Bridging gaps in bioenergy

Deploying system analysis to investigate potential biomass supply, demand and greenhouse gas mitigation scenarios from a national, European and global perspective

Bridging gaps in bioenergy - Deploying system analyses to analyze potential future biomass supply, demand and greenhouse gas mitigation from a national, European and global perspective

Ric Hoefnagels, Department of Innovation, Environmental and Energy Sciences, Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Utrecht, The Netherlands.

ISBN: 978-90-8672-059-0

Printing: Proefschriftmaken.nl, ’s-Hertogenbosch

Cover Design: Renske Diek

Created using ArcGIS® software by ESRI with the following data sources:

Commercial Shipping Activity, supporting data from Halpern, B.S., S. Walbridge, K.A. Selkoe et al. (2008), A global map of human impact on marine ecosystems. Science 319(5865), pp.948-952.

ESRI Data & Maps for ArcGIS (2012)

Bridging gaps in bioenergy

Deploying system analysis to investigate potential biomass supply, demand and greenhouse gas mitigation scenarios from a national, European and global perspective

Bruggen slaan in bio-energie

Inzet van systeemanalyse voor het onderzoeken van mogelijke biomassa aanbod, vraag en broeikasgas mitigatie scenario's vanuit een nationaal, Europees en mondiaal perspectief

(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 14 februari 2014 des ochtends te 10.30 uur

door

Eric Theodorus Augustinus Hoefnagels

geboren op 14 februari 1982 te Geldrop

Promotor: Prof. dr. A.P.C. Faaij

Co-promotor: Dr. H.M. Junginger

“The ideal country in a flat world is the one with no natural resources, because countries with no natural resources tend to dig inside themselves. They try to tap the energy, entrepreneurship, creativity, and intelligence of their own people-men and women-rather than drill an oil well.”

Thomas L. Friedman, The World Is Flat: A Brief History of the Twenty-first Century (2005)

“De aarde is rond, net als een pannenkoek. Die is ook rond.”

Herman Finkers (1995)

Table of contents

Units and Abbreviations

AC	All chemicals
AR	Average recovery ratio
ar	As received
ARA	Antwerp, Rotterdam and Amsterdam region
bbl	Oil barrel (159 L)
BIT-UU	Biomass Intermodal Transportation model - Utrecht University
BLM	Biomass Logistics Model
BU	Bottom-Up
C&D	Construction and demolition
CBS	Central Agency for Statistics
CCS	Carbon Capture and Storage
CES	Constant elasticity of substitution
CGE	Computable general equilibrium
CH_4	Methane
CHP	Combined heat and power
CIF	Cost, Insurance and Freight
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalent
CRF	Cumulative radiative forcing
CTL	Coal to liquid
DART	Dynamic Applied Regional Trade model (CGE)
DDGS	Distiller's Dried Grain with Solubles
DME	Dimethyl ether
DNDC	DeNitrification-DeComposition model
DWT	Dead weight tonnage
EC	European Commission
ECMT	European Conference of Ministers of Transport
EJ	Exa joule ($1 \times 10^{\wedge 18}$ joule)
EPPA	The Emissions Prediction and Policy Analysis model
EU	European Union (EU27)
FAME	Fatty Acid Methyl Ester
FAO	Food and Agriculture Organization of the United Nations
FIA	Forest Inventory and Analysis
FIE	Fertilizer induced emissions
FOB	Free on Board
FT	Fischer-Tropsch
FTE	Full Time Equivalent

GDP	Gross domestic product
GGL	Green Gold Label
GHG	Greenhouse gas
GHG-LCA	Lifecycle assessment of GHG emissions
GIS	Geographic Information System
GJ	Gigajoule (1 x 10^{9} joule)
GMA	Grocery Manufacturers' Association
GS	Growing stock,
GT	Gross tonnage
GTAP	Global Trade Analysis Project
GWP	Global warming potential
ha	Hectare (10 000 square meters)
HFO	Heavy Fuel Oil
IAM	Integrated Assessment Models
IBSAL	Integrated Biomass Supply and Logistics model
IEA	International Energy Agency
ILUC	indirect land use change
INL	Idaho National Laboratory
IPCC	Intergovernmental Panel on Climate Change
JEC	Joint Research Centre-EUCAR-CONCAWE collaboration
L	Liter
LCA	Lifecycle assessment
LEITAP	Modified GTAP model (CGE) from LEI Wageningen UR
LHV	lower heating value
lign.	Lignocellulosic
LUC	Direct land use change
MDO	marine diesel oil
Mg	Megagram (1 x 10^{6} gram) (1 ton)
MJ	Mega joule (1 x 10^{6} joule)
MSW	Municipal solid waste
N_2O	Nitrous oxide
NAICS	North American Industry Classification System
NG	natural gas
NGCC	Natural Gas Combined Cycle
NGO	Non-governmental organization
NGS	Non-growing stock
NREAP	National Renewable Action Plans
OD	Origin - Destination
OPEC	Organization of the Petroleum Exporting Countries
PC	Pulverized Coal
PE	Partial equilibrium

PJ	Peta joule (1 x 10^15 joule)
POME	Palm Oil Mill Effluent
ppm	Parts per million
RED	Renewable Energy Directive
RES	Renewable energy sources
RF	Residue factor
RME	Rapeseed methyl ester
SAM	Social accounting matrix
SRC	Short rotation coppice
SRES	Special Report Emissions Scenarios
TCF	Time correction factor
Tg	Teragram (1 x 10^12 gram) (million ton)
TPES	World Energy Model
TPO	Timber Product Output
U.S.	United States
UCS	Union of Concerned Scientists
UNFCCC	United Nations Framework Convention on Climate Change
WEM	World Energy Model
WLO	welfare, prosperity and quality of the living environment
WOW	Wet organic waste
WPE	Wood pellet equivalent (17.6 MJ kg^{-1})
WTT	Well-to-Tank
WTW	Well-to-Wheel
y	Year

Chapter 1

Introduction

1.1 The role of bioenergy in a changing energy system

The world total primary energy supply (TPES), required to meet the final demand for electricity, heat, transport fuels and non-energy use (i.e. as feedstock for materials, e.g. bitumen and plastics) is dominated by fossil resources including coal, lignite, crude oil and natural gas. Fossil fuels make up 82 % of the world TPES in 2011 (448 EJ y^{-1} of a total of 549 EJ) [1]. The current energy system is considered unsustainable for multiple reasons.

Firstly, the extraction and use of fossil resources is the largest source of anthropogenic greenhouse gas (GHG) emissions followed by emissions from land use change [2]. Since the industrial revolution, carbon dioxide (CO_2) concentrations have increased with 40 %, whereas methane and nitrous oxide (N_2O) increased with 150 % and 20 % respectively. Note though that the main sources of anthropogenic CH_4 and N_2O emissions are agriculture activities including the increasing number of ruminants (CH_4) [2] and the use and production of nitrogenous fertilizers (N_2O) [2, 3].

Secondly, fossil resources, especially oil and gas, are unevenly distributed among geographic regions with a large mismatch between regions where resources are becoming increasingly concentrated [4] and regions where most demand originates. Almost half of proven natural gas reserves are available in three countries (Russia, Iran, Qatar) and about 70 % of the proven oil reserves are available in OPEC (Organization of the Petroleum Exporting Countries) countries [5]. This imbalance in supply and demand results in economic and political dependencies of importing countries on export regions, resulting in concerns about costs of energy imports, security of supply and possible geopolitical conflicts. Thirdly, mining, transport and preprocessing required to supply fossil fuels, are becoming increasingly energy and resource intensive as resources are more difficult to exploit. For example, the production of tar sand oil, shale gas can increase the GHG footprint of fossil fuels substantially [6, 7]. Furthermore, the IEA estimated that only one third of the currently proven reserves of fossil resources can be used until 2050 to limit temperature rises to 2 °C compared to pre-industrial levels without carbon capture and storage (CCS) applied [5, 8].

Lastly, despite the economic growth in industrial countries driven by access to fossil fuels, billions of people still do not have access to modern energy carriers such as electricity. According to the IEA, 38 % of the world population is still relying on traditional fuels for cooking and heating, mainly wood, agriculture residues, animal dung and charcoal [5, 9]. These traditional uses of bioenergy are causing health problems because of indoor air pollution [9].

The transition towards a sustainable energy system requires strongly reduced GHG emissions, decreased dependencies on fossil fuels and decoupling of economic growth and since energy consumption. This is one of the largest and complex challenges that societies in both industrial and developing countries are currently facing [10]. So far, negotiations in the context of the United Nations Framework Convention on Climate Change (UNFCCC) have failed to establish binding agreements to reduce GHG emissions beyond the Kyoto Protocol, which ended in 2012. Furthermore, the proposed efforts by national governments for 2020 are insufficient to limit global temperature increase to 2 °C [11]. Global scenario assessment studies show that, if serious efforts will be taken to mitigate climate change, it will require large scale substitution of fossil energy carriers with renewable energy including wind, hydropower, solar energy and bioenergy.

Bioenergy is a versatile energy source that can substitute fossil energy carriers in electricity, heat and liquid transport fuels in transport sectors [9, 12]. Furthermore, biomass can be used to substitute non-energy uses of fossil energy carriers, e.g. the replacement of coking coal in steel industries and the production of bio-based products [9, 13, 14].

Bioenergy contributes 10 % to the world TPES today, [1] with an estimated supply of 50 EJ y^{-1} in 2008 [9] (Figure 1-1). Traditional uses of bioenergy, i.e. used residentially in developing countries for cooking and heating purposes, are still largest (37 to 43 EJ y^{-1}) [9]. Modern uses of bioenergy, including electricity generation, combined heat and power (CHP), centralized or high temperature heat generation and transport fuels account for 11.3 EJ y^{-1}, but is growing rapidly since the last decade. Key drivers are policies on climate change mitigation, price increases and volatility of fossil energy carriers and energy supply security [15-18].

The IPCC reviewed 137 scenario assessment studies on the deployment levels of renewable energy [19]. For bioenergy, the maximum primary demand was projected to be 300 EJ y^{-1} in 2050 with a median of 155 EJ y^{-1} under stringent mitigation scenarios (< 440 ppm CO_2). However, also under less stringent scenarios (440 – 600 ppm CO_2), the median of bioenergy demand projections still is increasing to 120 EJ y^{-1} in 2050. According to Chum et al. [9], the most likely range of primary bioenergy deployment in 2050 is 80 EJ y^{-1} to 190 EJ y^{-1}. Upper levels are 265 EJ y^{-1} to 300 EJ y^{-1} (Figure 1-1). Modern bioenergy demand makes up the largest share of these projections. For example, in the IEA World Energy Outlook New Policy scenario, aimed to keep global temperature rises below 3.6 °C compared to pre-industrial levels, modern bioenergy demand will more than double to 2035 [5, 20].

In contrast to the traditional uses of bioenergy, modern bioenergy demand is largest in populated industrialized and developed regions and here one finds strong support for renewable energy. In these regions are often limited biomass resources available with the exception of organic wastes. Forestry products and residues are mainly available in regions with high forestry cover, forest industries and forest plantations such as Western Canada, Scandinavia, Russia or the southeast of the U.S. [21]. The largest potential for dedicated energy cropping can be found in regions that currently have relatively low intensity agriculture management with subsequent high yield improvement potentials and relatively low population density [22, 23]. The strong expansion of bioenergy deployment with a magnitude of 150 to 300 EJ on global scale will therefore imply substantial increases in international bioenergy trade. The transition in bioenergy, from a local source of energy towards a global tradable energy commodity at large scale, started a decade ago [9, 24] and is still growing rapidly. In 2000, solid biomass trade was around 57 PJ and dominated by fuelwood and wood waste (81 % of total solid biomass traded). In a decade, an international biomass market has been created and global solid biomass trade increased over 5 fold to 302 PJ in 2010 of which 102 PJ wood pellets [15, 25]. Trade of solid biomass has been mainly driven by the economic margin between the cost of supply, including feedstock production and supply logistics and the market price in importing countries. The EU has been the key region for trade of solid biomass, mainly driven by renewable energy support policies. Over the last decade, also liquid biofuel production has grown exponentially to 2.5 EJ y^{-1} in 2011 with two thirds of ethanol, mainly produced in North and South America, and the remaining was biodiesel, mainly produced and consumed in the EU [26]. Before 2000, hardly any biofuels were traded, but has since then grown exponentially to 119 to 129 EJ y^{-1} in 2009 [17].

With the rising demand for bioenergy in an international market, bioenergy has also become subject to growing concerns regarding the potential negative ecological, socio-economic and environmental impacts induced by land use for energy crop production, removal of forestry products and residues and agriculture residues. Many of these concerns are related to direct land use change (LUC) and indirect land use change (ILUC) [27, 28]. Direct land use change occurs when bioenergy crops are cultivated on land that was previously not used for cropland production, e.g. natural vegetation areas such as forests. Indirect land-use change, or displacement, occurs when the previous land use activity, e.g. food crop production, shifts to other land induced by land use change for energy crop production [29, 30]. Other key concerns include possible threats to biodiversity, water resources and food supply security [31, 32]. Sustainable production and supply of bioenergy has therefore become a key concern in the role of bioenergy within transition towards a sustainable energy supply system.

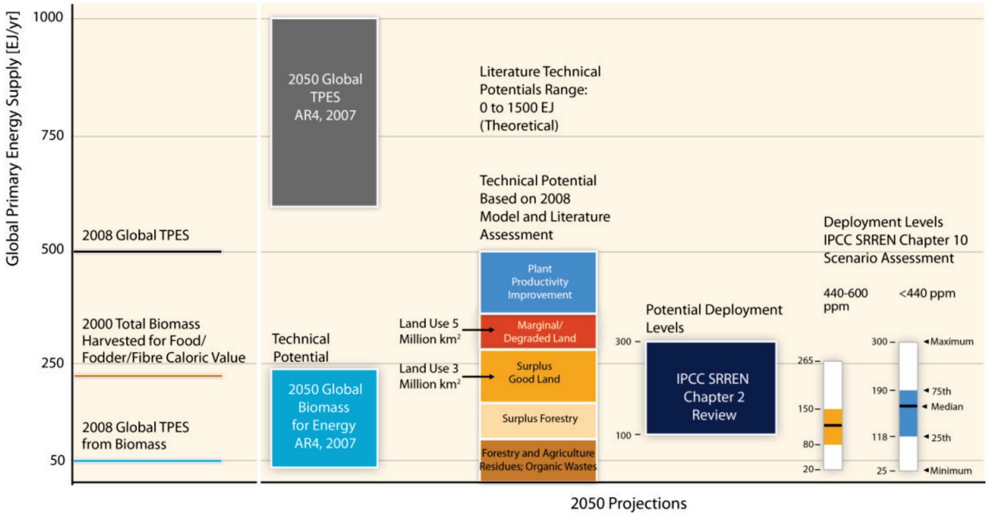

Figure 1-1 Reproduced from Chum et al. [9]. Left side (horizontal lines): the TPES from biomass in 2008, the equivalent energy content of the world biomass harvested for food, feed, and fibre in 2000 and the global TPES in 2008. From left to right: (1) estimates of the global TPES in 2050 and estimates of the technical biomass potential in 2050 according to the IPCC AR4 [33], (2) the ranges found in literature on the global technical potential of biomass in 2050 and the upper bound technical potential according to Dornburg et al. [34] for five resource categories in the stacked bar chart, (3) the deployment levels of terrestrial biomass in 2050 according to expert reviews of available literature and (4) the potential deployment levels of biomass in 2050 in the IPCC SRREN Chapter 2 and (5) Chapter 10 [35].

In the EU, member states have agreed on legally binding targets of 20 % renewable energy in gross final energy consumption in 2020 as reported in the Renewable Energy Directive (RED) (2009/28/EC) [36]. According to the National Renewable Action Plans (NREAPs), bioenergy is expected to remain the largest source of renewable energy generation and projected to contribute 54 % to the RED target in 2020 [37, 38]. Long term targets beyond 2020 are being negotiated and depend on ambitions to mitigate climate change, but are expected to increase the shares of renewable energy (including bioenergy) substantially. With the RED, also sustainability requirements for biofuels were introduced. These include, amongst others, minimum GHG saving performances as one of the key sustainability criteria. So far, solid and gaseous biomass used for electricity, heating and cooling are exempted from EU wide sustainability criteria. The EU recommends to follow the criteria for biofuels [39]. Also for solid biomass, minimizing GHG emissions is considered the most relevant criterion in sustainability certification schemes [40].

1.2 Gaps in knowledge and research needs

The future role of bioenergy in the transition to a sustainable energy system is characterized by a number of important research gaps and uncertainties.

1.2.1 The greenhouse gas performance and energy efficiency of liquid biofuels: the impact of input assumptions and methodological choices

The substitution of fossil fuels with liquid biofuels is considered a key option to improve energy supply security and mitigate GHG emissions in the transport sector. However, the GHG saving performance of liquid biofuels compared to fossil fuels has become subject to increasingly fierce debate. The GHG performance, following a lifecycle approach (GHG-LCA) and energy efficiency of biofuels can vary widely and is difficult to calculate due to the large number of, partially uncertain, parameters and impacts, as well as methodological issues. This has also led to numerous reviews on the GHG performance of biofuels [41], focused on biodiesel [42], or ethanol [43] or the methodology and tools applied [44, 45]. Partly, variations in outcomes are the result of the biofuel production systems (the combination of the biomass feedstock and conversion system) [46]. However, even for similar pathways, variations in the GHG performance are caused by :

- Differences in data used and data quality;
- The setting (geographic location, environment, year) in which production is assumed to take place;
- The method used to account for co-products [47];
- Calculation of nitrous oxide (N_2O) emission caused by changes in land use changes and by the application of nitrogen fertilizers [48];
- Assumptions on changes of above- and below ground biomass, soil organic carbon, litter and dead wood due to land-use change [27, 28, 49];
- The choice of reference system for land use, fossil fuel counterparts and co-products. if energy and GHG emission credits are given to the use of co-products as animal feed or energy;
- Time factor [50, 51][1].

Given the wide variation in outcomes in GHG balances, GHG savings and energy efficiency of biofuels, it is important to compare a wide range of biofuel production systems using a consistent set of system boundaries in time (current systems versus production systems that are currently not commercially available) and space (e.g. Eastern Europe, Western Europe). Furthermore, it is important to explicitly assess the impact of the differences in input assumptions of biofuel production and reference systems, co-product uses and allocation methods and possible effects and uncertainties in N_2O emissions induced by feedstock cultivation for biofuel production.

[1] In this thesis, pulse emissions from land-use change are accounted for by straight line amortization. Straight line implies that emissions that occur in the beginning have the same impact as emissions that occur at the end of the time horizon. According to the IPCC decay function of CO_2 however, 36.4% of CO_2 emitted will still be in the atmosphere after 100 years [50]. Emissions that occur at the beginning of the time period therefore have a larger impact on global warming than emissions that occur later. In order to correct for pulse emissions that occur during initial stages of biofuel production, a time correction factor (TCF) was developed by Kendall et al. [52] based on the cumulative radiative forcing (CRF) method of the IPCC [53]. An alternative option would be to apply discount rates to GHG emissions that occur in different times.

Lastly, there are two different frameworks in which LCA can be conducted: attributional LCA and consequential LCA. The attributional framework follows an accounting principle and covers all material and energy flows within the lifecycle chain of the product without considering the changes the product implies to the wider environment. Attributional LCA thus is static and independent of its environment [44], using allocation procedures (e.g. energy, mass, market value) to account for co-products [30]. Attributional LCA is applicable to product system assessments and carbon accounting [30].The purpose of consequential LCA is to assess the potential consequences of system changes implied by the product assessed. Consequential LCA, being context specific, marginal and dynamic, is therefore more appropriate for (policy) impact assessments [44]. However, this requires detailed insight in marginal changes that can become very complex, especially if multiple outputs are produced. Models are therefore needed that address these marginal changes as explained in the next section.

1.2.2 Lack of comprehensive and consistent insights in environmental and economic effects of bio-based economy scenarios at the national level

To assess the possible impact of bioenergy deployment, the different approaches can be categorized in four main categories [54]: computable general equilibrium (CGE), partial equilibrium (PE), Bottom-Up (BU) and Integrated Assessment Models (IAM). IAMs link models from different disciplines (e.g. economic models, energy system models, climate models) into a comprehensive assessment framework to assess the consequences of societal and economic changes on biosphere and atmosphere. Because IAMs rely heavily on bioenergy [51], IAMs should ideally encompass the complex system changes in a dynamic and interdependent environment while taking into account the geo-spatial , technological and temporal specific characteristics of bioenergy production systems. So far, the aggregation level of IAMs is too high to provide sufficiently detailed insights in bioenergy deployment, policy decisions, required changes, opportunities and risks for the short and medium term. These models are therefore mainly relevant for long term (decades, up to 2100) projections and insights in long term policy actions [54]. For short and medium term projections, policy makers and other stakeholders use individual models that focus on different aspects of the possible consequences of bioenergy deployment, policy decisions, required changes, opportunities and risks. However, on an individual basis, these models do not provide a comprehensive and consistent assessment of the complex, interlinked and dynamic environment of which bioenergy is embedded in the current and future energy system [9, 51, 54].

The transformation towards a sustainable energy system with large scale substitution of fossil energy carriers with renewable energy sources requires major investments in renewable energy capacity and infrastructure. A scenario analysis for the EU-27 shows that capital investments of about € 60 to 70 billion are required annually between 2011 and 2020 to meet the binding renewable energy targets of 20 % renewable energy in gross final energy generation by 2020. Compared to current investments in renewable energy, this results in an annual gap of € 26 billion to € 35 billion [55]. These investments generate new economic activities and direct and indirect macro-economic and employment impacts. Ragwitz et al. [56] have assessed the possible economic effects of renewable energy policy scenarios to 2020. They concluded that economic growth can be stimulated in by renewable energy policies with possible gross direct and indirect positive impacts on employment and added value (partly) depending on rises in energy cost from investments in renewable energy that are required to 2020. Note that net effects that take into account budget shifts and replacements of conventional energy technologies are significantly smaller due to the dampening effects and shifts in investments from conventional to renewable energy systems. Furthermore, these positive economic effects are strongly related to cost reductions by technological learning and economies of scale as well as efficient deployment of renewable energy. Note that on the longer term, beyond 2020, rising fossil fuel prices and decreasing cost of renewable energy production systems, including bioenergy, will potentially result in stronger positive economic impacts.

With bioenergy expected to contribute more than half of the 20 % renewable energy targets in the EU-27, as confirmed by the NREAPs [37, 38], major investments are needed in heat, electricity and transport fuels production capacity from biomass. Furthermore, bio-based chemicals are expected to become increasingly important [57]. The complexity of bioenergy, with many possible conversion pathways, a possible large role of international trade, multi-sectoral and multifaceted socio-economic effects makes it difficult to quantify the overall economic and employment impacts on national economies of large scale bioenergy deployment [9].

The Netherlands is located strategically with one of world largest sea ports and high quality hinterland connections to other EU member states. However, domestic resources are limited. For this reason, the Netherlands have already become one of the largest importing and exporting regions of raw materials, intermediates and final products [58] including bioenergy [59]. Shifts in the uses of imported (e.g. crude oil) and indigenous fossil resources (e.g. natural gas), to alternative energy sources can result in (major) sectoral shifts in the Dutch economy. If the cost of bio-based resources can be reduced in the future [60] and be further processed into high value added products (e.g. bio-based chemicals), to replace fossil resources that are likely to become more expensive in the future, this is likely to result in net positive effects on the national trade balance and economy [61]. However, the domestic potential of low cost biomass resources is low in the Netherlands, with its relatively high labor cost and high land prices [62] and small land surfaces and forest cover. The Netherlands have therefore already become one of the largest importing regions of solid biomass [15, 16]. Increasing domestic demand at the national level, will most likely result in increasing imports of biomass for energy purposes. To assess these effects requires a multidisciplinary (modeling) framework that takes into account the interactions among sectors and among countries through international trade of biomass and fossil energy carriers. At the same time, this modeling framework should be able to address the technological detail and technology changes that underlie these sectoral changes.

Despite recent efforts to incorporate biomass for bioenergy and the related details in macro-economic models, there are still large uncertainties and shortcomings to these models including technology representation, types of crops used and by-product and co-products produced [63]. Furthermore, bio-based chemical industries are not covered in these models.

1.2.3 The cost and potential of alternative wood fiber sources for wood pellet production in key exporting regions

The global demand for wood pellets is increasing, and the southeast of the U.S. is rapidly becoming the most important exporting region, with over 1 Tg of exports in the first quarter of 2013. At the same time, NGOs in particular in the US and Europe have been criticized for the use of primary forestry products (primarily pulp wood quality) for energy purposes, raising ecological concerns and pointing out possible poor GHG mitigation performances [64, 65]. This stresses the need for diversification of sustainable wood fiber sources for pellet production. According to the updated Billion Ton study [66], over 72 Tg dry wood could to be available from residues and wood wastes for bioenergy production for under 44 $ Mg^{-1} in the United States (U.S.). Many of these wood fiber sources do however not comply with the high quality standards of wood fibers for pellet production or are too expensive to mobilize, for example due to the geographically dispersed supply. Assessing the potential of alternative wood fiber sources requires empirical testing of candidate materials and a detailed assessment of cost and supply potentials taking into account the geographic dispersed supply into account. Also the possibilities to develop supply chains for limited resources in parallel or the need for feedstock mixing with other residues or conventional feedstocks need to be investigated. These aspects are not covered in the available biomass resource assessments available for the southeast of the U.S. or specific states [66-69].

1.2.4 Biomass deployment at the European level: prospects of supply, demand and trade of biomass resources to 2020

Bioenergy is expected to remain the largest source of renewable energy to 2020 with over 54 % of renewable energy in 2020 projected to be generated from biomass resources [38] providing almost 12 % of gross final energy consumption in the EU [37]. Therefore, bioenergy generation has to increase with 44 % between 2010 and 2020 with an expected growth of 90 % in bio-based electricity, 22 % in production of heat from biomass and 129 % growth in production of biofuels [38]. Residential uses of solid biomass are mainly based on domestic biomass resources. However, industrial sectors (i.e. for centralized heat, combined heat and power (CHP) or electricity generation in co-firing or dedicated electricity plants) where the largest growth is anticipated, have become increasingly dependent on imported biomass, in particular wood pellets [15, 16, 25]. Imports of wood pellets in the EU increased from 1.9 Tg in 2009 to 4.6 Tg in 2012 and are foreseen to increase to 15 Tg to 30 Tg in 2020 depending on economic factors, policies and the availability of domestic biomass resources [15, 16, 25]. Although many EU member states consider increasing imports of biomass, so far few EU member states have quantified the expected amounts of imported biomass. Likewise few countries have indicated possible countries to import from in their national renewable action plans (NREAPs) [70]. However, there is little information about the role of imported biomass. This can be explained by uncertainties in the volumes available, costs, the impact of sustainability criteria, the demand in competing importing regions and the competition with other renewable energy technologies. Bioenergy is a renewable, but not infinite source of energy and with the increasing demand and international trade of bioenergy, safeguarding the production and use of biomass in a sustainable way has become increasingly important [71]. Imports of biomass from third countries or from other EU member states, could improve the cost-effectiveness of renewable energy generation as well as supply security. On the other hand, it could as well shift import dependencies from fossil resources towards bioenergy [72].

To assess the potential role of biomass at the EU level, an integral analysis is required that encompasses the complexities of international biomass supply and biomass demand markets that are not provided in the NREAPs. The dynamic characteristics of the future biomass supply potentials and costs, international competition for resources with food, feed and fiber markets and developments in agriculture and bioenergy conversion systems as well as developments in other renewable energy systems, e.g. wind or photovoltaic are key variables to be included. Despite the large role of bioenergy in future scenarios and the expected continuation of growth in international bioenergy trade, there are only few studies that assess the implications of regional imbalances in bioenergy demand and supply and potentials of bioenergy trade. Recently, the World Energy Model (WEM) used for the IEA World Energy Outlook 2012, has been extended with a bioenergy trade module [5, 20]. At the EU level, biomass trade in context of the RES 2020 targets have been assessed by van Stralen et al. [38]. However, this study does not take the competition between bioenergy and other renewable energy sources into account. Furthermore, the geospatial features of actual biomass transport networks should be considered [73].

1.2.5 Detailed breakdown of cost and greenhouse gas structures of international solid biomass supply chains

Biomass logistics include all operations required from moving biomass from the location of production (agriculture land, forest or by-product in biomass processing industries, e.g. a sawmill) to inside of the conversion facilities that deliver final energy carriers. Biomass, in its raw form, often has unfavorable characteristics including high moisture content, low bulk densities and low energy densities and seasonal and geographic variations in supply. For example, energy crops and agriculture residues are only available in harvest seasons. Furthermore, the geographic locations of modern bioenergy demand are often remote from the location of biomass production. Especially for long distance, intercontinental transport (e.g. from the U.S. and Europe), preprocessing of biomass is required early in the supply chain to improve handling and reduce logistic costs. For this reason, wood pellets have become the main traded commodity of solid biomass [15, 25].

A reliable and efficient biomass supply system thus requires a complex series of logistic operations including harvest and collection, storage, handling, pre-treatment, and transportation [73, 74]. These logistic operations can add substantially to the total cost of biomass supply. For example, in production chains for domestic ethanol production, logistic operations contribute 20 % to 50 % of the total cost energy production [9] and up 40 % to 60 % to the total cost of ethanol production [74]. For international supply chains, these cost can be even higher [75]. Raw biomass feedstocks often have unfavorable characteristics for transport and handling due to their bulky nature and relatively low energy densities, high moisture, and poor flowability characteristics [76]. Pre-processing, e.g. drying, chipping, densification, is therefore required to reduce the cost and increase stability during long distance transport. Large scale users of biomass require a complex feedstock supply system consisting of 'many-to-few' and 'one-to-one' collection-handling-preprocessing-storage-delivery logistics possibly over long distances and hence imply additional cost, energy use and greenhouse gas (GHG) emissions to the biomass delivered [73, 77]. An economically and ecologically sustainable feedstock supply system therefore requires optimizing all logistic processes, including preprocessing, transport route and modes of transport, handling and storage in which the optimum design depends on the geo-spatial features and sizes of supply and demand, the available modes of transport and the type of end use [73]. Furthermore, it is increasingly important to understand how the economic and ecological impacts of the logistics supply systems will alter the competition between domestic uses and exports. Especially since on the long term, bioenergy trade might increase to the levels of current coal trade (1142 Tg in 2011) as anticipated by global bioenergy models [20]. Note that these large increases in bioenergy trade might also be the result of oversimplified representations of the implied cost, required infrastructure changes and required logistic operations.

Optimization of biomass logistics requires an integral approach that covers all logistic operations required to move biomass from the field of production up to the conversion plant taking into account the optimal locations and type of pre-treatment, e.g. densification to wood pellets (pelletization) and optimal use of available transportation networks including intermodal transportation. Several models have been developed to assess biomass logistics. Models, such as the Integrated Biomass Supply and Logistics model (IBSAL) [78] and the Biomass Logistics Model (BLM) developed by Idaho National Laboratory (INL) [74, 79-81] can simulate how a variety of feedstocks move from biomass standing in the field to the biorefinery, including logistic operations within the plant. However, many of these models focus on part of the logistic chains independently. Furthermore, most studies focus on a single regions or continents and lack infrastructure specifications for larger regions [73], e.g. intercontinental transportation. Studies that cover intercontinental biomass transportation are often limited to a limited number of predefined supply chains, e.g. Sikkema et al. [75] and Hamelinck et al. [82].

1.3 Objectives, research questions and thesis outline

This thesis aims to bridge some of the key knowledge gaps on the deployment of bioenergy at the national and European level with inclusion of international biomass trade. The main objective of this thesis is to improve the inclusion of bioenergy chains in economic, environmental and energy assessment tools next to modeling approaches to enable generation of improved insights in the potential direct and indirect impacts with respect to mitigation and economics of bio-based substitution of fossil energy carriers. To this purpose, the following research questions are addressed in this thesis:

I. What are the current and potential future cost and GHG balances of domestic and international bioenergy production chains?
II. How can system analyses contribute to the improved description and analysis of domestic and international bioenergy production chains in (established) energy and economic models and to what extent can different modelling approaches complement each other?
III. What are the prospects of bioenergy in fulfilling national and European renewable energy targets, what is the role of international biomass trade, key trade regions and potential resources and what factors affect biomass trade and deployment?

These research questions are addressed in Chapters 2 to 6 as indicated in Table 1-1. In each chapter, cost or GHG balances of the bioenergy production chain are determined, but each chapter focuses on different aspects. Chapter 2 demonstrates the impact of methodological choices and input assumptions on the energy and GHG balance of biofuel production systems. Chapter 3 demonstrates a spreadsheet based tool to deliver consistent inclusion of bioenergy production chains in sufficient detail, combined with a calculation of physical flows based on the monetary output of the LEITAP model including biomass and biomass trade, performance of different bioenergy and material options and their GHG performance. Chapter 4 focuses on the economic potential of low-value wood sources and wood wastes for wood pellet production taking the geographic dispersed supply into account. Chapter 5 uses the GIS based biomass transport model, called BIT-UU model, to calculate the logistic cost and GHG balances of Intra-European biomass supply chains combined with extra-EU supply chains that are included in the energy model Green-X. Green-X is a dynamic toolbox that covers electricity, heat and transport sectors that models the future deployment of renewable energy in the EU27. Current and future energy policy instruments can be evaluated (e.g. quota obligations, feed-in tariffs, tax incentives, investment incentives and emission trading). The model calculates the deployment of renewable energy at country and technology level and associated capital expenditures, consumer expenditures and fossil fuel and GHG avoidance compared to the reference scenarios on a yearly basis up to 2030. The model is widely used for impact assessments of renewable energy policies in Europe and is often updated with renewable energy country profiles in [83]. Chapter 6 combines the GIS based BIT-UU model with the logistic operations engineering model BLM to determine the cost and GHG emissions of intercontinental supply chains of solid biomass.

Table 1-1 Overview matrix of research questions covered within each chapter

Chapter		Research questions		
		I	II	III
2	Greenhouse gas footprints of different biofuel production systems	●		
3	Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level - a combined approach for the Netherlands	●	●	●
4	The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S.	●		
5	International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union	●	●	●
6	Lignocellulosic feedstock supply systems with intermodal and overseas transportation	●	●	

Chapter 2 covers the impact of key input assumptions and methodological choices on the lifecycle GHG and energetic performance of 1st generation (from starch, sugar, oil crops) and 2nd generation (from lignocellosic crops, residues and wastes) biofuel production systems from domestic supply sources in Europe and internationally sourced biomass. This chapter compares the results for different key parameters on a consistent basis. These include co-products allocation or system expansion, N_2O emissions from crop cultivation, conversion systems and co-product applications and direct land-use change emissions.

Chapter 3 aims to quantify possible direct and indirect economic effects of bioenergy deployment at the national level for the Netherlands. This is done by using the macro-economic computable general equilibrium (CGE) model LEITAP, capable of quantifying direct and indirect effects of a bio-based economy. A spreadsheet tool is developed for the inclusion of biomass conversion technologies in electricity, heat, transport fuels and chemical and the related physical flows of biomass, energy and GHG emissions. With the combined approach, five scenarios are assessed for bioenergy deployment in the Netherlands that differ in trade orientation (regional versus global orientation) and the rate of technology development.

Chapter 4 quantifies the economic potential of low-value wood resources that can be used for wood pellet production in the South East of the U.S.. This region has become one of the key supply regions for extra-EU wood pellet supply and is still expected to grow, but is also using increasing amounts of primary forest resources for wood pellet production. For three wood resources that are currently underutilized or used for inferior purposes (e.g. as furnace fuel), a resource potential has been conducted to determine the economic supply potential. These include primary forestry residues from premerchantable thinning operations and land clearing activities, secondary forestry residues from pole mills and post-consumer wood wastes from discarded wooden transport pallets.

Chapter 5 demonstrates a geographic explicit approach to determine the cost and GHG emissions of intermodal solid biomass transport (road, rail, inland waterways, sea) in the EU. The resulting routes between each possible region in the EU have been used in the renewable energy model Green-X. For this purpose, the GIS based biomass intermodal transport model BIT-UU and a bioenergy trade module for Green-X are developed. This enables the assessment of renewable energy scenarios in Europe taking biomass trade into account. Scenarios of renewable energy deployment in the EU to 2020 are used to demonstrate the capabilities of the model.

Chapter 6 presents an approach to assess the economics, energy and GHG emissions and related uncertainties of the logistic process operations of international supply chains with intercontinental shipping of lignocellusic biomass. The logistic operations Biomass Logistic Model (BLM) is combined with the GIS based BIT-UU model to address for the geospatial features of biomass transport. Because the BIT-UU model has been developed for the EU, as described in Chapter 5, it is extended with ocean shipping routes and inland transport networks of the U.S.. With the developed modeling framework, case studies of herbaceous and woody biomass, produced in the U.S. Midwest and U.S. Southeast, respectively, and shipped to Europe for conversion to Fischer-Tropsch (FT) diesel have been assessed.

Chapter 7 summarizes the results and findings from Chapters 2 to 6 and provides answers to the research questions. Also, this chapter presents the final conclusions on the developed tools and insights with respect to the substitution of fossil energy carriers with biomass and related direct and indirect economic and mitigation effects. Finally, chapter 7 provides recommendations for further research.

References introduction

[1] International Energy Agency (IEA). Key World Energy statistics. 2013th.Paris; OECD/IEA. 2013. 81 p.

[2] IPCC. Climate Change 2013: The Physical Science Basis. Working Group I Contribution to the IPCC 5th Assessment Report - Changes to the Underlying Scientific/Technical Assessment. Final Draft (Accepted).Intergovernmental Panel on Climate Change (IPCC). 2013, 7 June 2013. IPCC-XXVI/Doc.4.

[3] Reay DS, Davidson EA, Smith KA, Smith P, Melillo JM, Dentener F, et al. Global agriculture and nitrous oxide emissions. Nature Climate Change 2012; 2(6): 410-6.

[4] IEA. Oil Supply Security - Emergency Response of IEA Countries. Paris, France; International Energy Agency (IEA). 2007. 383 p.

[5] IEA. World Energy Outlook 2012. Paris; International Energy Agency (IEA). 2012.

[6] Brandt A, Farrell A. Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources. Clim Change 2007; 84(3): 241-63.

[7] Howarth R, Santoro R, Ingraffea A. Methane and the greenhouse-gas footprint of natural gas from shale formations 2011; 106(4): 679-690.

[8] Leaton J, Ranger N, Ward R, Sussams L, Brown M. Unburnable Carbon 2013: Wasted capital and stranded assets. Carbon Tracker, Grantham Research Institute on Climate Change and the Environment, LSE. 2013. 40 p.

[9] Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, et al. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, United Kingdom and New York, NY, USA.; Cambridge University Press. 2011.

[10] Holdren JP. Science and Technology for Sustainable Well-Being. Science 2008; 319(5862): 424-34.

[11] Blok K, Niklas H, Kees van dL, Harrison N. Bridging the greenhouse-gas emissions gap. Nature Climate Change 2012; 2: 471-4.

[12] Cornelissen S, Koper M, Deng YY. The role of bioenergy in a fully sustainable global energy system. Biomass Bioenergy 2012; 41(0): 21-33.

[13] Chen GQ, Patel MK. Plastics derived from biological sources: present and future: a technical and environmental review. Chem Rev 2012; 112(4): 2082-99.

[14] Shen L, Worrell E, Patel M. Present and future development in plastics from biomass. Biofuels, Bioproducts and Biorefining 2010; 4(1): 25-40.

[15] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. Renew Sust Energ Rev 2012; 16(5): 3176-99.

[16] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, et al. Wood pellet market and trade: a global perspective. Biofuel Bioprod Bior 2013; 7(1): 24-42.

[17] Lamers P, Hamelinck C, Junginger M, Faaij A. International bioenergy trade - A review of past developments in the liquid biofuel market. Renewable and Sustainable Energy Reviews 2011; 15(6): 2655-2676.

[18] Cocchi M, Nikolaisen L, Junginger M, Goh CS, Heinimö J, Bradley D, et al. Global Wood Pellet Industry Market and Trade Study. IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. 2011. 190 p.

[19] IPCC. Special Report on Renewable Energy Sources and Climate Change Mitigation - Final Release. Working Group III - Mitigation of Climate Change. 2011.

[20] Kranzl L, Daioglou V, Faaij A, Junginger M, Keramidas K, Keramidas K, et al. Chapter 8. Medium and long-term perspectives of international bioenergy trade. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[21] Smeets EMW, Faaij APC. Bioenergy potentials from forestry in 2050: An assessment of the drivers that determine the potentials. Clim Change 2007; 81(3-4): 353-90.

[22] Hoogwijk M, Faaij A, de Vries B, Turkenburg W. Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. Biomass Bioenergy 2009; 33(1): 26-43.

[23] Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC. A bottom up quickscan and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 2007; 33: 56-106.

[24] Faaij APC. Bio-energy in Europe: changing technology choices. Energy Policy 2006; 34(3): 322-42.

[25] Lamers P, Marchal D, Heinimö J, Steierer F. Chapter 3: Global Woody Biomass Trade for Energy. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[26] Lamers P, Rosillo-Calle F, Pelkmans L, Hamelinck C. Chapter 2: Developments in international liquid biofuel trade. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[27] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land Clearing and the Biofuel Carbon Debt. Science 2008; 319(5867): 1235-8.

[28] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, et al. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land Use Change. Sciencexpress 2008.

[29] Gnansounou E, Panichelli L, Dauriat A, Villegas JD. Accounting for indirect land-use changes in GHG balances of biofuels - Review of current approaches. Lausanne; EPFL. 2008. REF. 437.101.

[30] Tipper R, Hutchison C, Brander M. A Practical Approach for Policies to Address GHG Emissions from Indirect Land Use Change Associated with Biofuels. Greenenergy 2009; Technical Paper - TP-080212-A.

[31] Dornburg V, Van Vuuren D, Ven VD, Langeveld H, Meeusen M, Banse M, et al. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy and Environmental Science 2010; 3(3): 258-67.

[32] Fargione JE. The ecological impact of biofuels. Annual review of ecology, evolution, and systematics 2010; 41: 351.

[33] IPCC. Climate Change 2007: Synthesis Report. Contributions of Working Groups I, II and II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press. 2007. 104 p.

[34] Dornburg V, Van Vuuren D, Van De Ven G, Langeveld H, Meeusen M, Banse M, et al. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy and Environmental Science 2010; 3(3): 258-67.

[35] IPCC. Special Report on Renewable Energy Sources and Climate Change Mitigation - Final Release. Working Group III - Mitigation of Climate Change. 2011.

[36] European Commission. Directive 2009/28/EC of the European Parliament and of the Council - on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Brussels, Belgium; European Commission. 2009. 62 p.

[37] Scarlat N, Dallemand J, Banja M. Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. Renew Sust Energ Rev 2013; 18(0): 595-606.

[38] van Stralen JNP, Uslu A, Dalla Longa F, Panoutsou C. The role of biomass in heat, electricity, and transport markets in the EU27 under different scenarios. Biofuel Bioprod Bior 2013; 7(2): 147-63.

[39] European Commission. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling - Report from the Commission to the Council and European Parliament. Brussels, Belgium; 2010, February. COM(2010)11 final.

[40] Van Dam J, Junginger M, Faaij APC. From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. Renewable and Sustainable Energy Reviews 2010; 14(9): 2445-72.

[41] Naik S, Goud VV, Rout PK, Dalai AK. Production of first and second generation biofuels: a comprehensive review. Renewable and Sustainable Energy Reviews 2010; 14(2): 578-97.

[42] Malça J, Freire F. Life-cycle studies of biodiesel in Europe: A review addressing the variability of results and modeling issues. Renewable and Sustainable Energy Reviews 2011; 15(1): 338-51.

[43] von Blottnitz H, Curran MA. A review of assessments conducted on bio-ethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. J Clean Prod 2007; 15(7): 607-19.

[44] Plevin RJ, Delucchi MA, Creutzig F. Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers. J Ind Ecol 2013.

[45] Hennecke AM, Faist M, Reinhardt J, Junquera V, Neeft J, Fehrenbach H. Biofuel greenhouse gas calculations under the European Renewable Energy Directive – A comparison of the BioGrace tool vs. the tool of the Roundtable on Sustainable Biofuels. Appl Energy 2013; 102(0): 55-62.

[46] Kendall A, Yuan J. Comparing life cycle assessments of different biofuel options. Curr Opin Chem Biol 2013; 17(3): 439-43.

[47] Dam J, Faaij APC, Gustavsson L, Turkenburg WC. A unified methodology and tool to evaluate greenhouse gas balances and cost-effectiveness of various biomass energy systems. Published in Thesis 2009.

[48] Smeets EMW, Bouwman LEXF, Stehfest E, Vuuren DPv, Posthuma A. Contribution of N2O to the greenhouse gas balance of first-generation biofuels. Global Change Biol 2009; 15(1): 1-23.

[49] Wicke B, Sikkema R, Dornburg V, Faaij A. Exploring land use changes and the role of palm oil production in Indonesia and Malaysia. Land Use Policy 2011; 28(1): 193-206.

[50] Clift R, Brandao M. Carbon storage and timing of emissions - Briefing Note. Surray, UK; University of Surray. 2008.

[51] Creutzig F, Popp A, Plevin R, Luderer G, Minx J, Edenhofer O. Reconciling top-down and bottom-up modelling on future bioenergy deployment. Nature Clim.Change; advance online publication.

[52] Kendall A, Chang B, Sharpe B. Accounting for time-dependent effects in biofuel life cycle greenhouse gas emissions calculations. Environmental Science and Technology 2009; 43(18): 7142-7.

[53] IPCC. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [(eds.)]. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

[54] Wicke B, Hilst F, Daioglou V, Banse M, Beringer T, Gerssen-Gondelach S, et al. Opportunities and limitations of model collaboration for the assessment of biomass supplies and impacts Submitted.

[55] Klessmann C, Rathmann M, de Jager D, Gazzo A, Resch G, Busch S, et al. Policy options for reducing the costs of reaching the European renewables target. Renew Energ 2013; 57(0): 390-403.

[56] Ragwitz M, Schade W, Breitschopf B, Walz R, Helfrich N, Rathmann M, et al. EmployRES - The impact of renewable energy policy on economic growth and employment in the European Union. Karlsruhe; 2009.

[57] Daioglou V, Faaij A, Saygin D, Wicke B, Patel M, van Vuuren DP. Energy Demand and Emissions of the Non-Energy Sector. Energy Environ Sci 2013.

[58] Weterings R, Harmelen Tv, Gjaltema J, Jongeneel S, Manshanden W, Poliakov E, et al. Towards a Future Proof Energy System for the Netherlands (in Dutch: Naar een Toekomstbestendig Energiesysteem voor Nederland). TNO. 2013, 1 Maart. 150 p.. TNO 2013 R10325.

[59] Goh CS, Junginger M, Junginger M, Faaij A. Monitoring sustainable biomass flows in a bio-based economy: General methodology development. Submitted to Biofuels, Bioproducts & Biorefining 2013.

[60] Batidzirai B, Hilst F, Meerman H, Junginger M, Faaij A. Optimisation potential of biomass supply chains with torrefaction technology. Submitted.

[61] Brehmer B, Boom RM, Sanders J. Maximum fossil fuel feedstock replacement potential of petrochemicals via biorefineries. Chem Eng Res Design 2009; 87(9): 1103-19.

[62] van der Hilst F, Dornburg V, Sanders JPM, Elbersen B, Graves A, Turkenburg WC, et al. Potential, spatial distribution and economic performance of regional biomass chains: The North of the Netherlands as example. Agricultural Systems 2010; 103(7): 403-17.

[63] Wicke B, Verweij P, Meijl Hv, Vuuren Dv, Faaij A. Indirect land use change: Review of existing models and strategies for mitigation. Biofuels 2012; 3.

[64] Lamers P, Junginger M. The ‘debt’is in the detail: A synthesis of recent temporal forest carbon analyses on woody biomass for energy. Biofuels, Bioproducts and Biorefining 2013.

[65] Lamers P, Thiffault E, Paré D, Junginger M. Feedstock specific environmental risk levels related to biomass extraction for energy from boreal and temperate forests. Biomass Bioenergy 2013.

[66] Perlack RD, Stokes BJ, (Lead Authors). U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. Oak Ridge, TN; Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy under contract DE-AC05-00OR22725. 2011, August. 227 p.. ORNL/TM-2012/224.

[67] Conner RC, Adams TO, Johnson TG. Assessing the Potential for Biomass Energy Development in South Carolina. Asheville; United States Department of Agriculture Forest Service - Southern Research Station. 2009.

[68] Harris RA, Adams T, Hiott V, Lear DV, Wang G, Tanner T, et al. Potential for Bioamss Energy Development in South Carolina. South Carolina Forestry Commission. 2004. ID: 58.

[69] Staudhammer C, Hermansen LA, Carter D, Macie E. Wood to energy: using southern interface fuels for bioenergy. USDA Forestry Service - Southern Research Station. 2011. 89 p.

[70] Ragwitz M, Steinhilber S, Breitschopf B, Resch G, Panzer C, Ortner A, et al. D23 Final Report: RE-Shaping: Shaping an effective and efficient European renewable energy market. Karlsruhe, Germany; 2012. 112 p.

[71] van Dam J, Junginger M. Striving to further harmonization of sustainability criteria for bioenergy in Europe: Recommendations from a stakeholder questionnaire. Energy Policy 2011; 39(7): 4051-66.

[72] Atanasiu B. The role of bioenergy in the National Renewable Energy Action Plans: a first identification of issues and uncertainties. 2010, November 2010. 22 p.. Biomass role in achieving the Climate Change & Renewables EU policy targets. Demand and Supply dynamics under the perspective of stakeholders. IEE 08 653 SI2. 529 241.

[73] Miao Z, Shastri Y, Grift TE, Hansen AC, Ting KC. Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. Biofuel Bioprod Bior 2012; 6(3): 351-62.

[74] Cafferty KG, Searcy EM, Jacobson JJ. Biomass Logistics Model: Analyzing biomass supply systems. Submitted.

[75] Sikkema R, Junginger M, Pichler W, Hayes S, Faaij APC. The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. Biofuels, Bioproducts and Biorefining 2010; 4(2): 132-53.

[76] Searcy M, Hess JR, Tumuluru J, Ovard L, Muth DJ, Jacobson JJ, et al. Chapter 5: Optimization of Biomass Transport and Logistics. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[77] Hamelinck CN, Suurs RAA, Faaij APC. International bioenergy transport costs and energy balance. Biomass Bioenerg 2005; 29(2): 114-34.

[78] Sokhansanj S, Kumar A, Turhollow AF. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass Bioenergy 2006; 30(10): 838-47.

[79] Hess JR, Wright CT, Kenney KL. Cellulosic biomass feedstocks and logistics for ethanol production. Biofuel Bioprod Bior 2007; 1(3): 181-90.

[80] Searcy EM, Hess JR. Uniform-Format Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass. 2010. INL/EXT-10-20372.

[81] Cafferty KG, Jacobson JJ, Muth DJ, Bryden KM. Model based biomass system design of feedstock supply systems for bioenergy production. IDETC/CIE 2013 2013; DETC2013-13556.

[82] Hamelinck CN, Suurs RAA, Faaij APC. International bioenergy transport costs and energy balance. Biomass Bioenergy 2005; 29(2): 114-34.

[83] Teckenburg E, Rathmann M, Winkel T, Ragwitz M, Steinhilber S, Resch G, et al. Renewable Energy Policy Country Profiles - 2011 version. 2011. 343 p. D9.

Chapter 2

Greenhouse gas footprints of different biofuel production systems

Keywords: Allocation; Biodiesel; Ethanol; Greenhouse gas balance land-use change; Life-cycle Assessment (LCA)

Abstract: The aim of this study is to show the impact of different assumptions and methodological choices on the life-cycle greenhouse gas (GHG) performance of biofuels by providing the results for different key parameters on a consistent basis. These include co-products allocation or system expansion, N_2O emissions from crop cultivation, conversion systems and co-product applications and direct land-use change emissions. The results show that the GHG performance of biofuels varies depending on the method applied and the system boundaries selected. Key factors include selected allocation procedures and the location of production and related yields, reference land and soil N_2O emissions.

Published in: *Renewable and Sustainable Energy Reviews* (2010) 14 (7): 1661-1694. Co-authors: Edward Smeets (Utrecht University), André Faaij (Utrecht University)

2.1 Introduction

The impact of the replacement of conventional transportation fuels by biofuels on greenhouse gas (GHG) emissions and fossil energy use is subject of fierce debate. Life-cycle Assessments (LCAs) come to widely ranging conclusions that are the results of differences in (data) quality, the setting in which production is assumed to take place, the method used to account for co-products and the assumptions on changes of above- and belowground biomass, soil organic carbon, litter and dead wood due to (in)direct land-use change [1] and [2]. Also the choice of reference system is an important aspect if energy and GHG emission credits are given to the use of co-products as animal feed or energy [3] and [4]. Several studies have suggested that the use of protein-rich by-products from grain ethanol manufacture as animal feed may play a large role in offsetting (in)direct land-use change effects and related GHG emissions [5]. Overall, calculating the performance of biofuels on GHG emissions and fossil energy use is difficult, due to the large number of, partially uncertain, parameters and impacts, as well as methodological issues. The goal of this chapter is to investigate the energy requirements and GHG emissions of various transportation biofuels relative to conventional fossil fuels for the current situation and specific cases for the future.

The goal of this chapter is to investigate the GHG and energy balance of biofuels using a consistent set of system boundaries in time and space so that the results of each chain are comparable. Specific attention is paid to the implications of selecting different reference systems for land use and related changes in carbon stocks, use of co-products and allocation methods, the selected time period and the emissions of nitrous oxide (N_2O) that are caused by changes in land use and by the use of nitrogen fertilizers.

A wide range of energy crops and conversion technologies can be used to produce biofuels. We have selected the most commonly used combinations of energy crops, conversion technologies, and key producing world regions or potentially promising world regions (Table 2-1). Data are derived from recent, state-of-the-art life-cycle studies on biofuel production chains that that report underlying assumptions and procedures used for allocation and reference systems transparently. The main references are shown in Table 2-1. Details on these production routes can be found in in the online supplementary information.

Table 2-1 Selected biofuels and corresponding energy crops, conversion technology, key producing regions and the fossil oil based reference fuel.

Biofuel type	Energy crop	Key producing regions	Conversion technology	Reference fuel	Main references
Ethanol	Maize	US, West Europe, East Europe	Fermentation	Gasoline	[4, 11, 22]
Ethanol	Wheat	US, West Europe, East Europe	Fermentation	Gasoline	[4, 11, 22]
Ethanol	Sorghum	US, West Europe, East Europe	Fermentation	Gasoline	[44]
Methyl ester	Palm fruit	South-East Asia	Transesterification	Diesel	[4, 11, 22, 26]
Methyl ester	Rapeseed	West Europe, East Europe, Canada	Transesterification	Diesel	[4, 11, 22]
Ethanol	Sugar cane	Brazil	Fermentation	Gasoline	[22, 31]
Ethanol	Sugar beet	West Europe, East Europe	Fermentation	Gasoline	4, 11, 22]
Methyl ester	Soybean	US, Brazil	Transesterification	Diesel	[4, 11, 22]
Methyl ester	Jatropha	Africa, India	Transesterification	Diesel	[11, 45]
Ethanol	Switchgrass	US, West Europe, East Europe	Hydrolysis & Fermentation	Gasoline	[11, 46]
Ethanol	Miscanthus	US, West Europe, East Europe	Hydrolysis & Fermentation	Gasoline	[11, 46]
Ethanol	Eucalyptus	Brazil	Hydrolysis & Fermentation	Gasoline	[11, 47]
FTdiesel	Switchgrass	US, West Europe, East Europe	Gasification & FT-synthesis	Diesel	[11] [46]
FTdiesel	Miscanthus	US, West Europe, East Europe	Gasification & FT-synthesis	Diesel	[11] [46]
FTdiesel	Eucalyptus	Brazil	Gasification & FT-synthesis	Diesel	[11, 47]

Differences between regions are incorporated by differences in crop yield, soil conditions and fertilizer application rates. The performance of conversion technologies is assumed the same across all regions, unless indicated otherwise.

Section 2.2 describes the methodology, the methodological aspects and assumptions that are included. Section 2.3 shows results for the energetic and GHG performance of the biofuel production systems considered for different methodological choices and input variables. In Section 2.4 the results are discussed and Section 2.5 finalizes with the conclusion. Detailed input and result data is provided in the appendices of the online version.

2.2 Methodology

The energy and greenhouse gas balances are quantified and compared to the fossil reference system as described in Figure 2-1. The biofuels production chains are divided in four processes: (i) biomass production or cultivation, (ii) pre-treatment, storage and transport of the bioenergy crops to the conversion plant, (iii) conversion of bioenergy crops to biofuels and (iv) transport and distribution to gas stations.

Detailed calculations are included to estimate the GHG emissions and energy use of the different production steps of the biofuel and conventional fuel chains considered (following Bergsma et al. [6]).

For biofuels production, the following energy use or emission categories are distinguished:

- Biomass production:
    - The production of fertilizers.
    - The production and use of agro-chemicals.
    - Energy use from agriculture machinery.
    - The use of fertilizers. Nitrous oxide (N_2O) emissions are thereby crucial, as further discussed in Section 2.2.6.
    - The transportation of the feedstock to a biofuels production plant.
    - Biomass production induced direct or indirect changes in land use.
- Biomass to biofuels conversion:
    - The use of energy for biomass pre-treatment.
    - The use of energy for the conversion of biomass to biofuels. A crucial issue is the methodology that is used to include co-products from conversion, see further Section 2.2.4.
    - The production of chemicals.

For the fossil reference systems, the following emissions are taken into account:

- emissions from mining/extraction;
- emissions from transport;
- emissions from conversion to primary energy carrier; and
- emissions from distribution and end use.

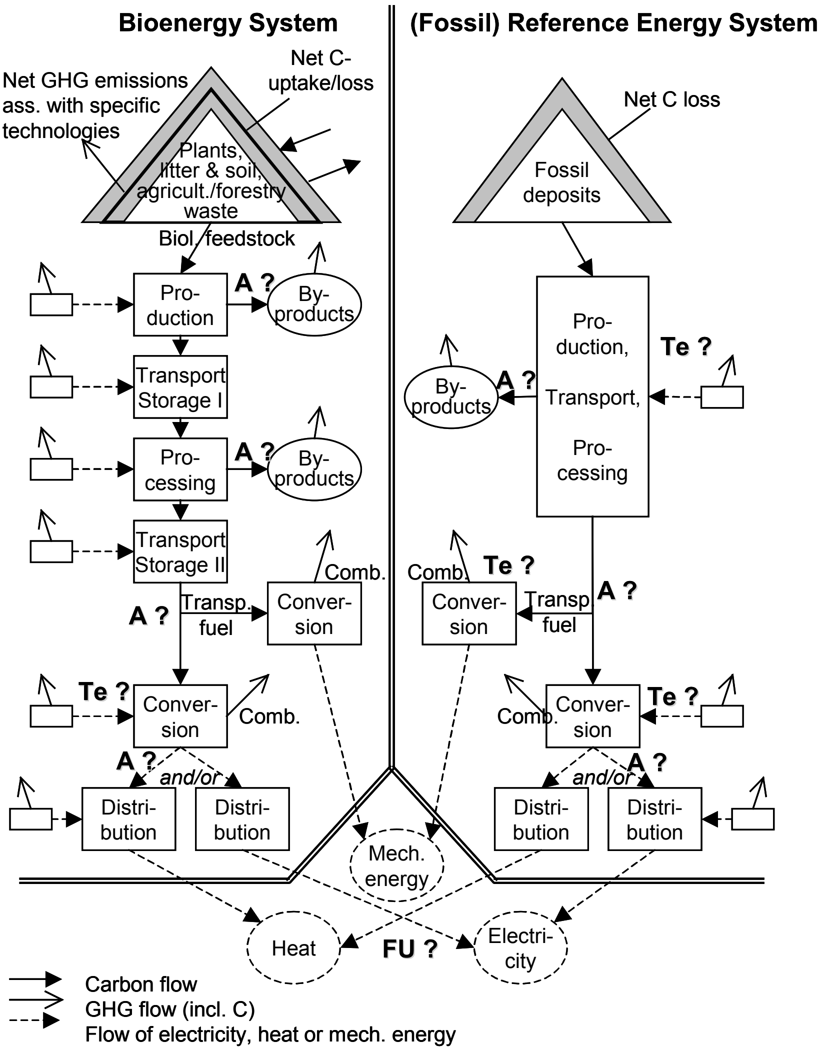

Figure 2-1 The bioenergy and reference system as graphically presented in [20]. The question marks indicate examples of special methodological interest for allocation methods (A?) of which four are applied in this study, choice of functional unit (FU?) and choice of technology (Te?).

Specific attention is paid to the impact of direct and indirect changes in land use and the resulting impact on GHG emissions from changes in above- and belowground biomass, soil organic carbon, litter and dead wood and on N_2O emissions, but also to the methodology used to include co-products from conversion. Several other parameters are also varied to investigate the impact of uncertainties and different production chains on the results, such as the type of energy used during conversion, the fertilizer application rate, the transportation distance, etc.

The life-cycle performance of fossil gasoline and diesel in the Europe is derived from the JEC WTW study [4] based on data from CONCAWE. The GHG and energy balances are also used as starting point in the calculations and are supplemented with other data sources.

2.2.1 System boundaries and functional units

2.2.1.1 Functional unit

For this chapter, two functional units for comparison are used. The functional units for energetic performance are MJ_{prim}/MJ_{fuel} and MJ_{prim}/ha land. For the GHG mitigation performance the functional units are g CO_2eq/MJ_{fuel} and g CO_2eq/ha land. The biofuel substitutes considered in this chapter have similar combustion characteristics compared to conventional fossil fuels. This justifies a direct comparison of fuels based on their calorific value.

2.2.1.2 Energy and greenhouse gas balances

This chapter considers the significant GHGs for biofuel production: carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). A 100-year time horizon is considered for the global warming potential (GWP) of these GHGs based on the fourth assessment report of the IPCC [7]. The GWP is 1, 25 and 298 for CO_2, CH_4 and N_2O, respectively.

The GHG reduction potential is calculated relative to the fossil references (diesel and gasoline):

$$\text{GHG reduction} = \frac{\text{GHG emission fossil chain} - \text{GHG emission bio chain}}{\text{GHG emission fossil chain}} \qquad \text{Eq. 2-1}$$

The demand for energy utilities for feedstock production, transport or biofuel production are expressed per unit of energy delivered, i.e. the energy that is used by the consumers. The measure for the energetic performance of the biofuel and fossil reference systems in this chapter is primary energy which is the total amount of energy available in the natural state of these fossil resources [8]. Unless stated otherwise, all energy units in this chapter are expressed in lower heating value (LHV).

2.2.2 Time horizon and time factor

This chapter includes first-generation biofuels that are currently being produced on commercial scales, but also second-generation biofuels that are not yet produced commercially at a large-scale, such as ethanol from lignocellulosic biomass and synthetic diesel. Results are generated for the present situation and in specific cases also for the future.

Time is also an important factor in calculations of the annual life-cycle performance of biofuels. Both energy inputs and outputs and emissions occur at different points in time. For example emissions from land use due to changes in aboveground biomass occur mainly during the short period when the land is converted for cultivation. The chosen time scale for amortization of these emissions can change the results drastically. In this chapter, specific attention is paid to the timeframe across which the changes in the above- or belowground biomass, soil organic matter, litter and dead wood are combined with annual emissions using amortization. For example, the IPCC uses a default value of 20 years [9], while Greenpeace aims for a 10-year period [10].

2.2.3 System boundaries

The focus in this chapter is on the GHG emissions and fossil primary energy use of biofuels and conventional fuels. Biofuels are assessed by taking into account the energy requirements and GHG emissions from the production of resources (cradle) to the final end use phase (grave), i.e. including the production of the feedstock, the conversion of the feedstock into biofuels and the transportation of the biofuels to Western Europe. Both direct and indirect GHG emissions and fossil primary energy use are considered. Direct emissions are emissions that occur at energy conversion or utilization processes or due to the direct effects of land-use changes. Indirect emissions are emissions that occur upstream from the production of utilities and raw materials utilized for the production of biofuels or occur due to the indirect effects of land-use changes. Emissions that occur from the construction, operation and maintenance of equipment and infrastructures related to biofuels production, i.e. third order emissions, are not taken into account in this chapter.

2.2.4 Co-products

The production of biofuels often results in the production of large quantities of co-products. For example, for the production of 1 kg ethanol from maize using dry milling, 1.25 kg DDGS (Destiller's Dried Grain with Solubles) is co-produced [11]. DDGS can be used for animal feed, but also for energy purposes, e.g. via anaerobic digestion. Another example is the production of diesel from soybeans, which co-generates 4.2 tonne of dry soy meal (generally used as animal feed) per tonne of diesel [12]. A list of co-products and their applications assumed in this chapter are given in the appendix (Table A 2-1).

The way in which co-products from biofuel production are included in the LCAs is a crucial factor [2] and [13]. Two main approaches are commonly applied in LCA studies:

1. Allocation, whereby the emissions due to energy crop production and processing are (partially) allocated to the co-products of biofuel production on the basis of either: weight, energy content or market value of these products. The advantage of the first two is that they are relatively easy to apply and allocation factors do not change over time like economic indicators or substituted product types do. The default and typical values reported in the draft proposal "Directive on the promotion of renewable energy", as published in January 2008, are based on allocation based on energy basis for co-products and subtraction for co-generation of heat and electricity. The main disadvantage is that this method does not accurately reflect the real impact of the use of co-products, e.g. the use of by-products for fuel or feed.

2. System boundary expansion. Allocation can be avoided by taking account of the emissions that are avoided when the co-products replace other products. This approach is also recommended by the guidelines for LCA issued by the International Organisation for Standardization ISO 14040-14049 guideline series [14]. A disadvantage of this methodology is that it increases the scope of the LCA chapter, as it requires an estimation of the avoided emissions.

In this chapter both allocation (mass, energy content and market value) and system expansion approach are applied to account for co-products.

2.2.5 Direct and indirect land-use change

Direct land-use change occurs when bioenergy crops are cultivated on land that was previously not used for cropland or farming. This includes natural vegetation areas such as forests, but could also be set aside land or degraded land. Indirect land-use change occurs when the previous activity which used the land previously shifts to other land induced by crop production for bioenergy purposes. These effects are also known as 'leakage' or 'displacement' as they occur outside the system boundary, but can be allocated to action that occurs within the system [15] and [16]. Both direct and indirect land-use change can have a significant impact on the GHG balance of biofuels, due to the GHG emissions from changes in above- and belowground biomass, soil organic carbon, litter and dead wood [10], [17], [18] and [19].

2.2.5.1 Direct land-use change

Changes in above- and belowground carbon per hectare of bioenergy crop are estimated for the five carbon pools that defined by the IPCC: above- and belowground biomass, soil organic carbon, litter and dead wood. The total change in carbon stock soil over the total period *T* is calculated using Eq. (2-2) in which the carbon stock change factor can change for each specific year *i* [20]:

$$\Delta Carbon\,stock\,soil\,(tC/ha) = \sum_i Carbon\,stock\,change\,factor\,(t/ha*yr)*T_i(yr) \qquad \text{Eq. 2-2}$$

The methodology and data to estimate the changes in the above- or belowground biomass, soil organic matter and litter are taken from the literature, whereby the IPCC Guidelines for National Greenhouse Gas Inventories [9] are used as starting point. The IPCC approach is compared with data and methodologies from other sources e.g. [10], [17] and [18].

2.2.5.2 Indirect land-use change

Indirect land-use change effects are difficult to estimate as it requires a detailed understanding of the dynamics of agricultural markets and agricultural land use. Most studies use general or partial equilibrium models to analyse the dynamics of commodity prices, land availability and sectoral changes as a result of bioenergy production [15]. However, this method is also being criticized. Hutchison et al. [16] claim that the limitations of forecasting models as a result of uncertainties in degrees of freedom in forecasting, feedback loops and interaction complexity result in model outcomes that do not generate policy relevant information and lacking evidence. Alternative suggested methods are, amongst others, the risk adder approach [21] and the approach from Ecometrica [16]. In case of the risk adder approach, a default conservative value was estimated for the conversion of a high carbon content natural system to arable land of 300 t CO_2/ha and a time frame of 20 years. This results in 15 t CO_2/(ha year) of which 25 % or ~4 t CO_2/ha has to be allocated to biofuels annually from a German perspective.[2] The method suggested by Ecometrica is based on the land-use changes reported by the FAO between 2000 and 2005 and allocation of marginal increases in output. They calculated the indirect effect at 0.286 t CO_2/t crop additional production[3] of which part is allocated to by-products by energy content. By using the same land-use change emission factor for all biofuel production systems, i.e. allocating land-use change emissions equally to all biofuels, different yields of energy crops are neglected. This factor might therefore be more negative for second generation fuels with limited co-products produced and higher yields per ha because this method does not take differences in yield into account.

This chapter does not suggest a method for indirect land-use change emissions. Rather we explore the impact of some scenarios including direct land-use change effects and the impact per type of biofuels.

2.2.6 Emissions from fertilizer use

In this chapter data on the N_2O emissions from bioenergy crop production will be calculated using:

- The results of the JEC WTT study [11] which are based on the DNDC model for N_2O emissions, of which the results are also included in the in the EU "Directive on the promotion of renewable energy"
- The IPCC Tier 1 method for fertilizer induced emissions (FIE). Most biofuel LCA-studies apply the Tier 1 method from the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [9] to account for direct N_2O emissions from fertilizer application. This method assumes that 1 % of the N input from N-fertilizers and manure result in N_2O-N emissions. This approach is based on fertilizer–induced emission (FIE). FIE is defined as the direct emission from a fertilized plot, minus the emission from an unfertilized control plot (all other conditions being equal to those of the fertilized plot), expressed as a percentage of the N input.

---

[2] 50 % will be 2nd generation biofuels from residues (no leakage), 50 % of energy crops will be produced on former set aside land resulting in 25 % of energy crop production that induces displacement of land indirectly (Fehrenbach et al. 2008).

[3] According to the FAO, 16 % of deforestation effects can be allocated to agricultural activities. Tipper, Hutchison et al. [16] estimate the contribution of biofuels based on the total feedstock fraction from agriculture used for biofuels between 2000 and 2005 (6.6 %) resulting in 124 Mton CO_2 eq. Based on the increase in crop output between 2000 and 2005 (263 Mton), the GHG emissions from deforestations allocated to agricultural activities in this period (11,777 Mton CO_2). 11,777 Mton CO_2*16 %/263 Mton additional feedstock * 25 years.

- The spatial explicit method developed by Smeets et al. [22]. The IPCC Tier 1 approach for direct emissions largely ignores the variability of emissions caused by differences in environmental conditions, crop type and its management. Furthermore, the FIE represents the anthropogenic emission caused by N application, although the emission from control plots may differ from the emission of the original vegetation in pre-agricultural times. The N_2O emission from zero-fertilizer plots may exceed that from soils under natural vegetation. In other cases it may be lower; for example, when cropland replaces tropical rainforest [23]. Smeets et al. [22] calculated the N_2O emissions from various reference land-use types and land used for the cultivation of 1st generation bioenergy crops.

2.2.7 Fossil references

Similar to land-use change, allocation of energy and emissions of the refinery processes to fossil fuels is based on arbitrary allocation principles [4]. Moreover, there is a wide range in the GHG and energy performance of crude oil from different sources. As easily accessible oil reserves become scarcer, oil extraction processes that require more energy and emit more GHG emissions are becoming more important. An example is that use of tar sands in Canada, which leads to higher emissions than high quality conventional oil resources [24]. In addition to conventional oil, this chapter includes two non-conventional sources of liquid fossil fuels: oil from tar sands in Canada and FT-diesel from coal (CTL). Future marginal production scenarios have not been analyzed in this chapter.

2.3 Results

2.3.1 Biofuel production

For each biofuel chain, the base case results are calculated. These are consistent with the JEC methodology and background data [4] and [11] including allocation for by-products by energy content. The results are displayed in Figure 2-2. This reference is selected because it is also used to calculate the default and typical values (plus underlying assumptions) as reported in the “Directive on the promotion of renewable energy” [25]. It should be noted however that the EC database is updated when more up-to-date figures are available. Later and earlier versions of the default values in the directive might therefore be different from the results presented in this report (Figure 2-3).

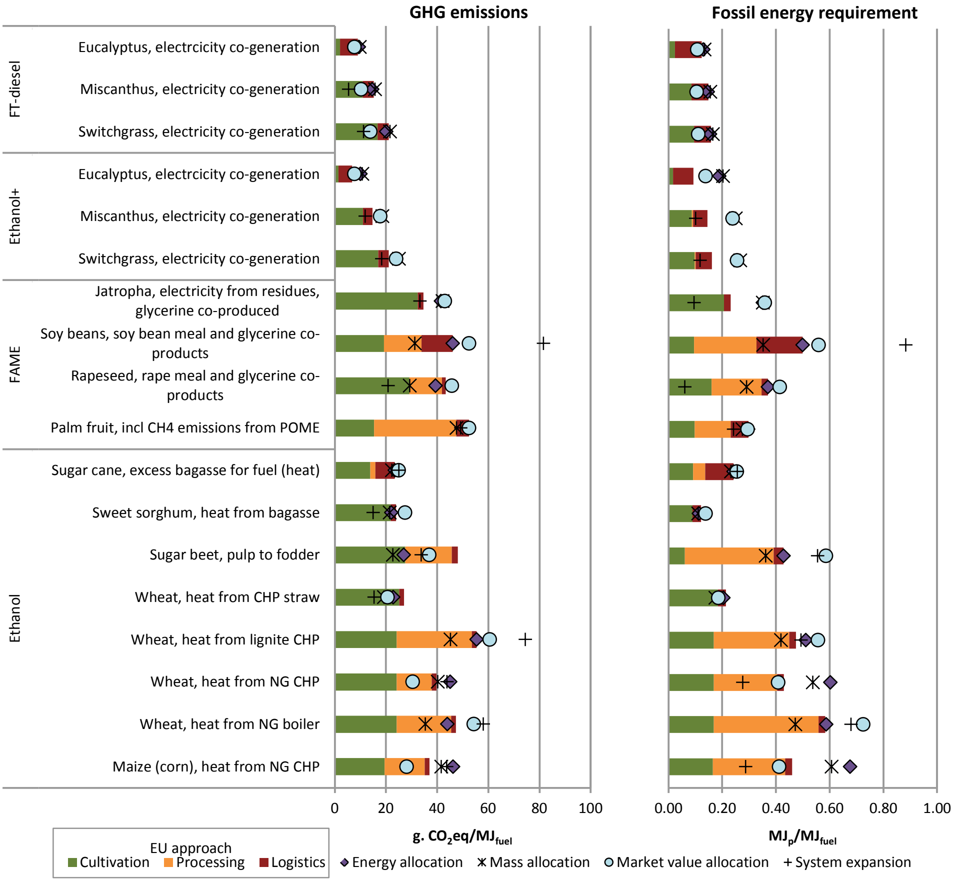

Figure 2-2 Fossil energy requirement and GHG emissions from biofuel production for the base cases. Allocation of co-products by EU default (energy allocation for co—products, subtraction for co-generation of electricity and heat), energy, mass and market value. No reference land use selected (no LUC). JRC DNDC model for N_2O emissions from sugar cane, wheat, sugar beet, maize and rapeseed. IPCC model for miscanthus, palm fruit, soy beans, switchgrass, eucalyptus and jatropha.

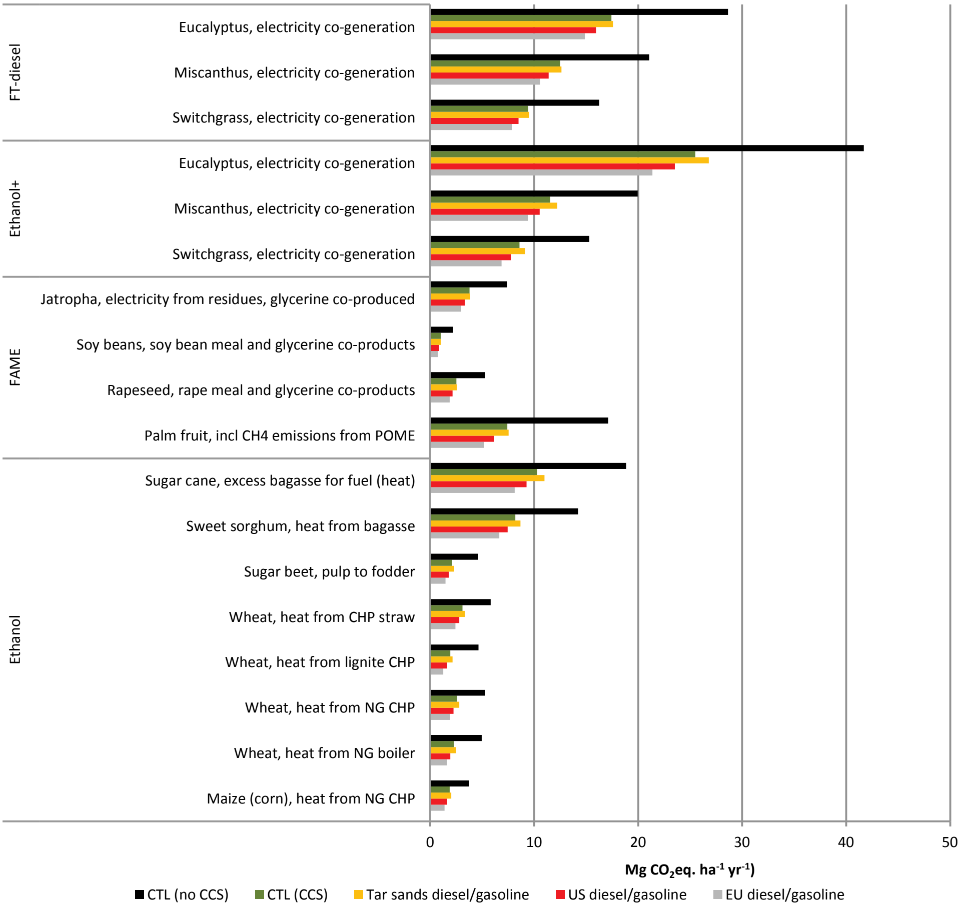

Figure 2-3 Lifecycle greenhouse gas emissions saved per hectare land for different fossil reference fuel types: for the EU [11], the US (GREET, [40]), Canadian tar sands [41], Coal to liquids with and without carbon capture and storage [42]. Input assumptions similar to the EU method for allocation of Figure 2-2.

2.3.2 By-product use and allocation

Figure 2-4 shows the GHG and energy requirements for ethanol production from wheat in the EU. These results are exemplary to show the variation in biofuel production chains, use of co-products and allocation procedures. Process heat and electricity are generated from natural gas (boiler or CHP plant), a lignite CHP plant, biogas from anaerobic digestion of DDGS or straw combustion. In case of straw combustion, additional fertilizers are required. In case of DDGS for energy purposes, the residues are used for fertilizers. These options are based on JEC [4] and [11].

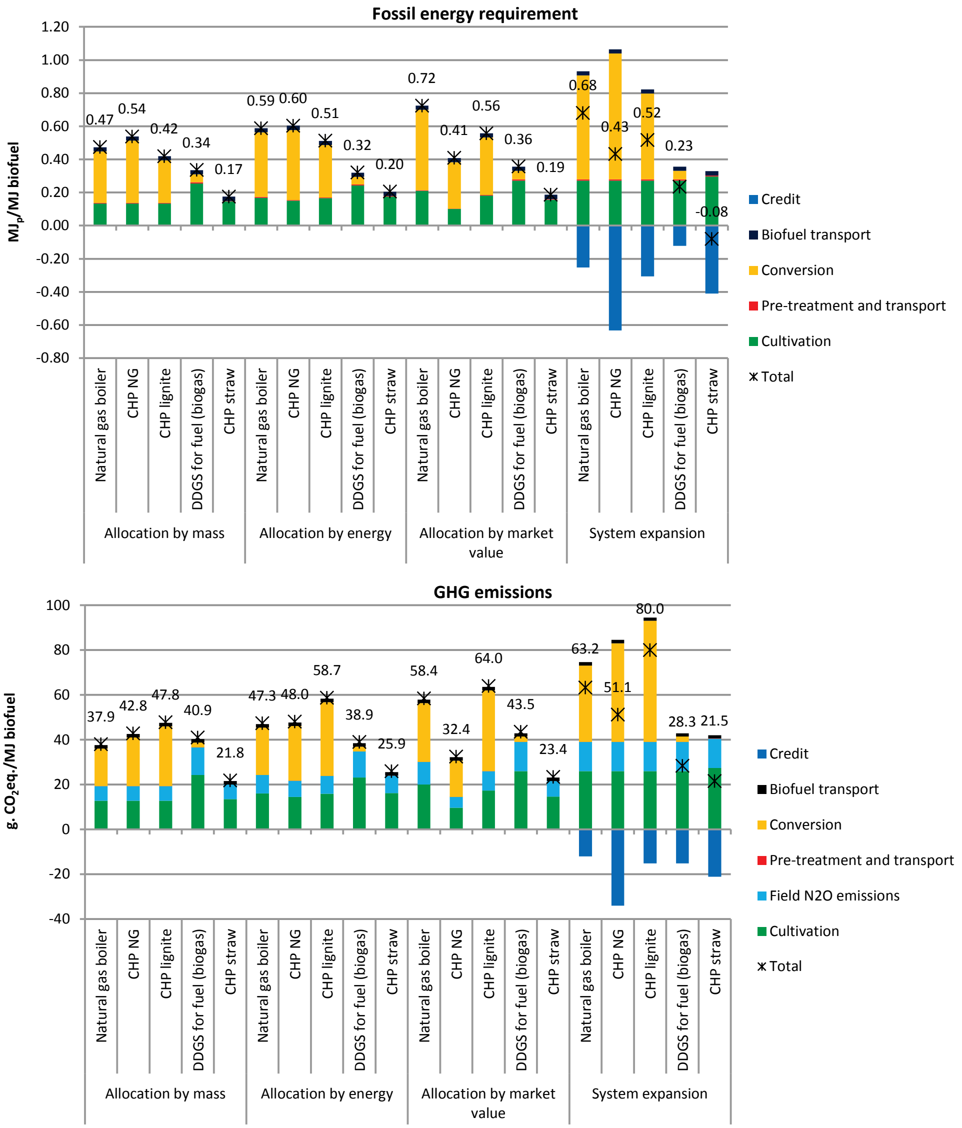

Figure 2-4 Ethanol production from wheat (EU, dry milling) with DDGS used for fodder and for process heat and electricity, DNDC model for N_2O emissions. The results for other locations and for other biofuel production systems are provided to the online version.

If allocated by mass, the NG boiler system performs better than the NG CHP system as co-produced electricity cannot be allocated for on mass basis. If straw is used for process heat, the system has the best GHG and energetic performance for all allocation procedures. From an environmental perspective, it is better to use DDGS as biofuel. From an economic perspective however, the added value of DDGS is higher if it is sold as animal fodder. This is better represented by allocation by market value.

2.3.3 Reference land

2.3.3.1 Emissions from land-use change

The amount of greenhouse gases released from converting reference land into cropland for biofuel crops varies strongly per type of reference as displayed in Figure 2-5. The difference in peatland emissions between Fargione et al. [18] and Wicke et al. [26] is mainly due to the years of emission accounting of 25 and 50 years in Wicke et al. [26] and Fargione et al. [18], respectively.

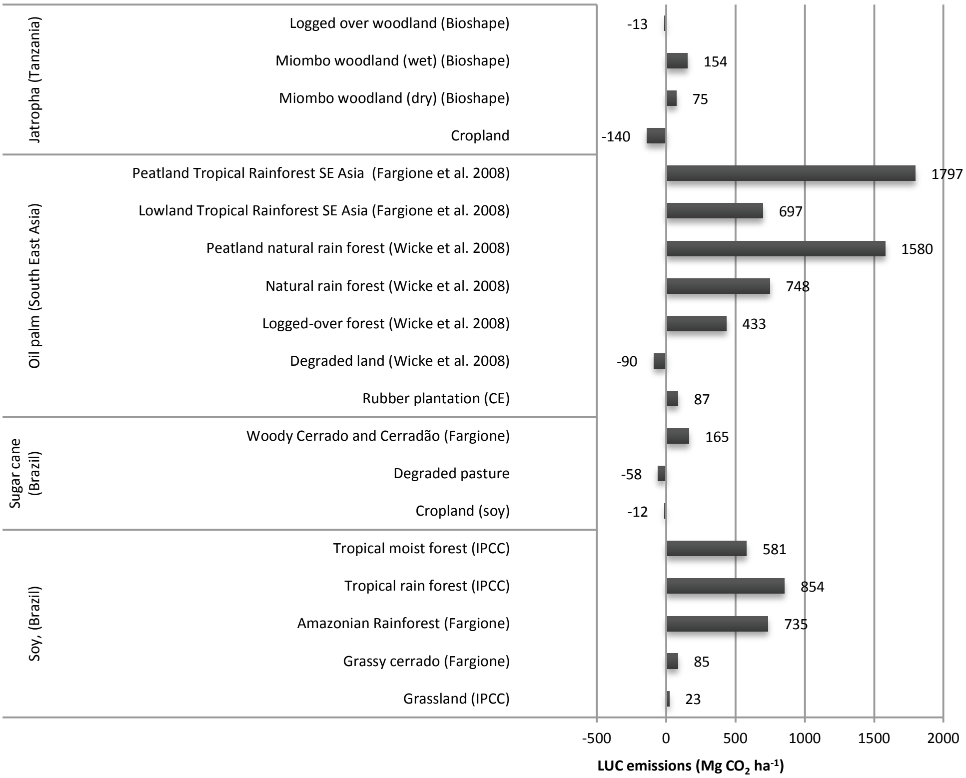

Figure 2-5 Net GHG emissions due to land use change. Based on IPCC [9], Fargione *et al.* [18], Wicke *et al.* [26], Bioshape [10]. For emissions from peatland, 20 years of emissions were allocated to land use change due to palm oil production whereas Wicke *et al.* [26] assume 25 years and Fargione *et al.* [18] assume 50 years.

Soy for European markets is mainly imported from Brazil and Argentina. For reference land we used the IPCC Tier 1 method [9] and included data from Fargione et al. [18] for rainforest and Cerrado land as shown in Figure 2-5. It depends on the allocation method and the allocation period how much is added to the GHG performance of biofuel production.

2.3.3.2 GHG performance including land-use change emissions

Figure 2-6 shows the greenhouse gas emissions for palm oil biodiesel production for different land-use reference systems. If grown on degraded land, the carbon stored in the palm oil plantation will be higher than emitted from converting degraded land into cultivation land. If cultivation land is yielded from natural rain forests, palm oil diesel becomes a net producer of greenhouse gases when land use change emissions are combined with annual emissions by amortization over 20 years.

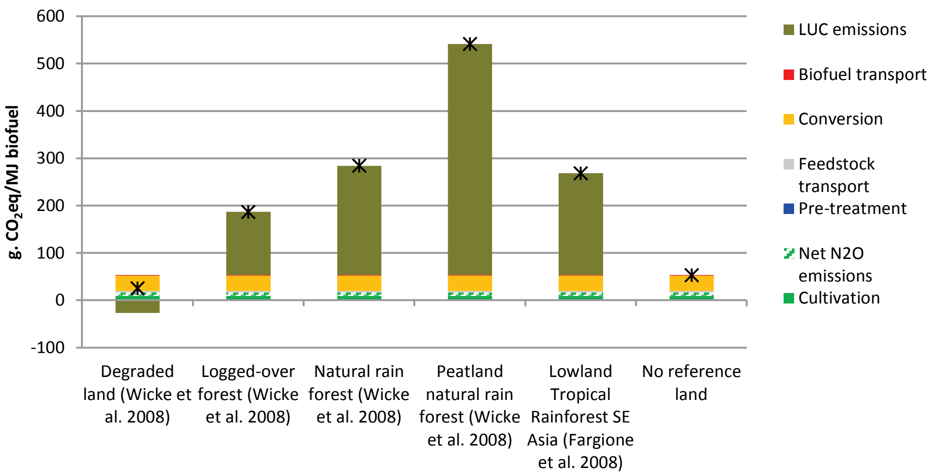

Figure 2-6 Greenhouse gas emissions from palm oil biodiesel production including land use change emissions for different land types. Amortized over 20 years.

2.3.3.3 System expansion, references for co-products

Utilization of biofuel co-products for food or feed purposes results in avoided crop cultivation and related land use. If reference land use is taken into account for biofuel crop cultivation, it should also be taken into account, reference land for co-product references should also be included.

To illustrate the impact of taking reference land for co-products into account, Figure 2-7 shows the GHG performance of ethanol production from wheat and grain with DDGS either used for animal feed or for energy purposes. DDGS likely replaces Brazilian soy bean meal [4]. Substitution of soy bean meal also results in reduced soy oil production which has to be produced from sources. Marginal vegetable oil is likely to be South-East Asian palm oil, the cheapest alternative to soy oil [10] and [27].

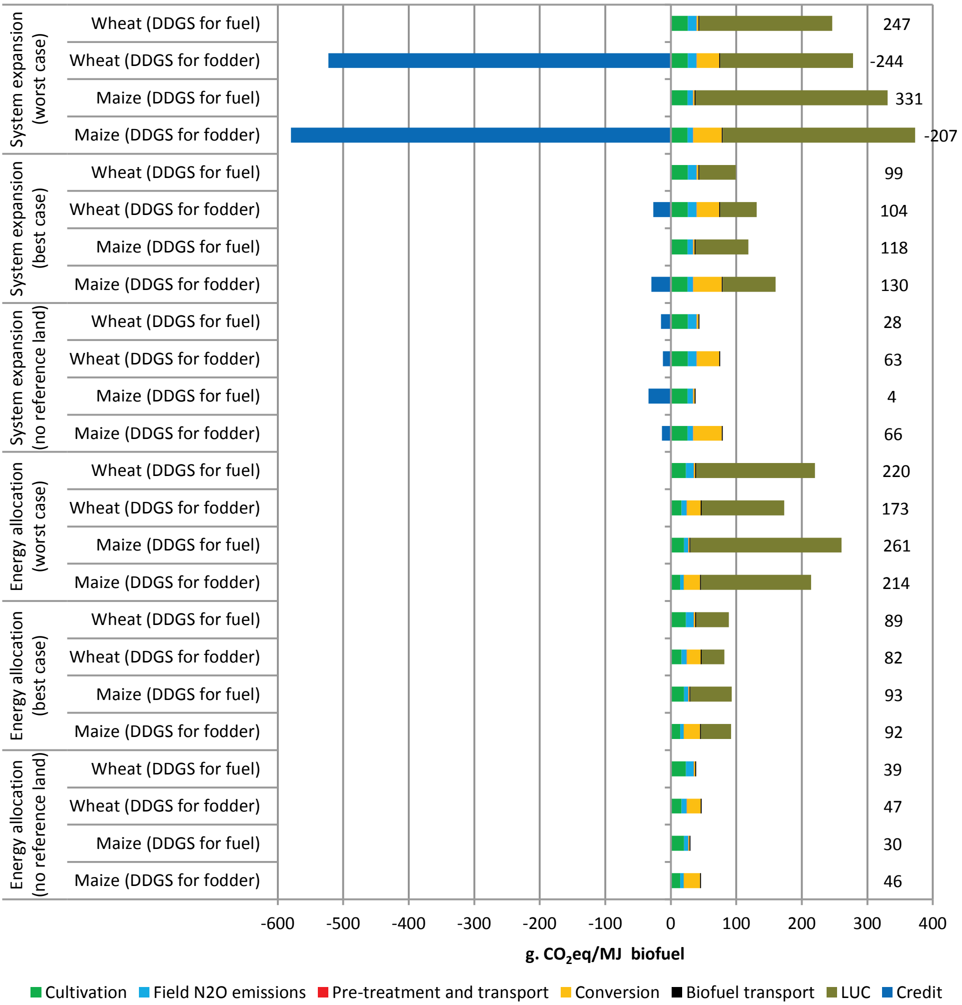

Figure 2-7 GHG performance for ethanol production from wheat and maize in Europe including land use change emissions for feedstock and for co-product references (DDGS replaces soy bean meal. The avoided soy oil production is assumed to be replaced by palm oil).

Similar to Croezen and Kampman [10], we assume a worst case and best case for reference land. For the best case, maize and wheat are cultivated on former set aside land, reference land for soy bean cultivation and palm fruit cultivation is grassland and degraded land, respectively. For the worst case, maize and wheat are cultivated on former pasture land. Reference land for soy beans and palm fruit are natural rain forest and peatland natural rain forest, respectively.

The results in Figure 2-7 illustrate the effect of assuming different allocation procedures and reference land types. GHG emissions from ethanol production range from −244 to 247 g CO_2 equiv./MJ biofuel for wheat and −207 to 331 g CO_2 equiv./MJ biofuel for maize. The worst cases result in such high credits for co-products as reference land for maize and wheat include relatively low levels of organic carbon whereas land-use change emissions from natural rain forest and peatland natural rainforest are extremely high (Figure 2-5).

2.3.4 Ethanol sugar cane in Brazil

This section covers a direct comparison for ethanol produced from sugar cane in Brazil. The results of other biofuel production chains are summarized in Figure 2-8. For both cases, we defined a default, worst and best case for the current and future (2030) situation. The assumptions are given in Table 2-2.

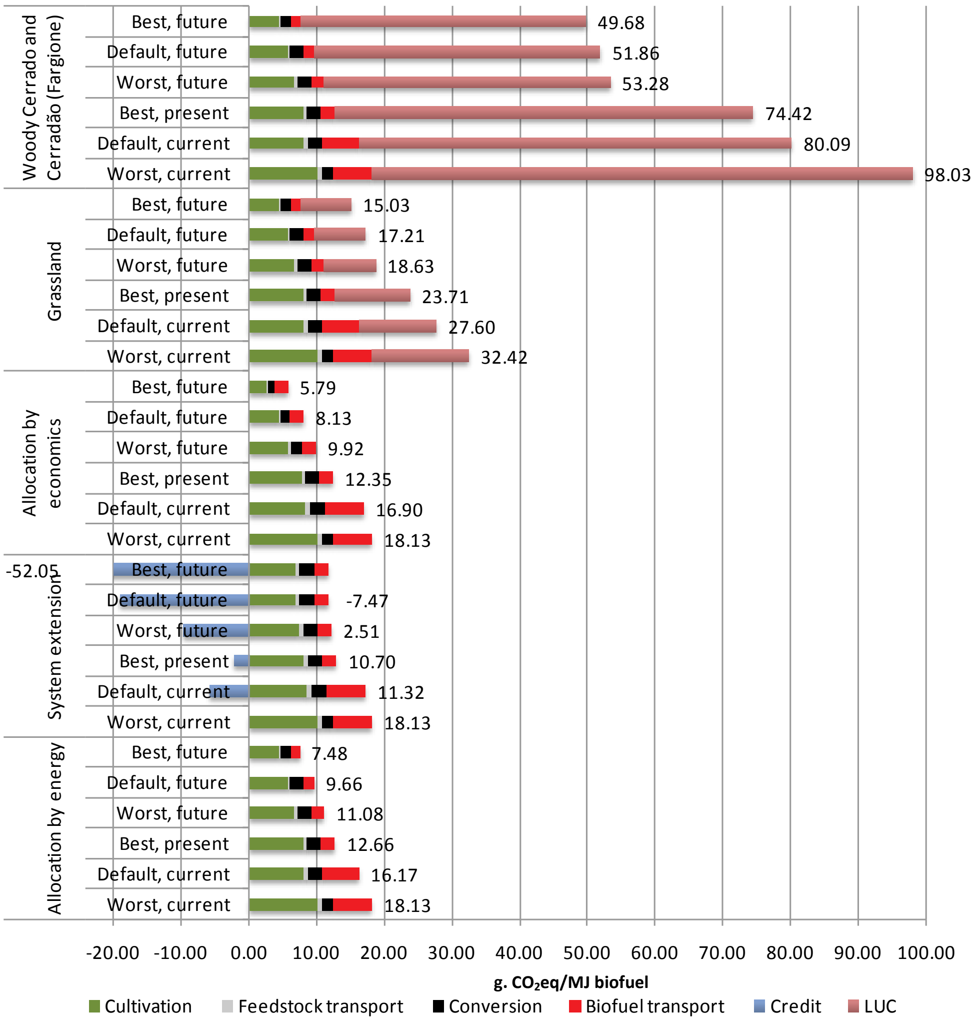

Figure 2-8 Ethanol from sugar cane, Brazil. Based on [18, 31, 43].

Table 2-2 Ethanol production from sugar cane, parameters for analysis.

Parameters	Present Worst	Present Default	Present Best	Future Worst	Future Default	Future Best
Harvest system	Partial cane burning	Partial cane burning	Partial cane burning	Partial cane burning	No cane burning	No cane burning
Share of mechanical harvesting	35%	35%	35%	35%	100%	100%
Trash recovery	No	No	No	No	Yes, 50%	Yes, 50%
Cogeneration	N/A	Bagasse boiler	Combustion, partial steam extraction	Combustion, partial steam extraction	Combustion, partial steam extraction	Gasification, steam-injected gas turbine
Ethanol yield (GJ ha^{-1} yr^{-1})	103.4	129.2	133.7	195.7	195.7	195.7
Ethanol yield (m^3 ha^{-1} yr^{-1})	4.9	6.1	6.3	9.2	9.2	9.2
Electricity surplus (kWh Mg^{-1} cane 73 % moist)			10.0	59.0	110.0	300.0

The worst, average and best case for current ethanol production and the projected performance for worst, average and best case are included. These cases are derived from Smeets et al. [28], include variable parameters for allocation methods, N_2O emissions related to sugar cane cultivation and land-use change emissions. The assumptions are summarized in Table 2-2.

The present, average case is based on Scenario 1 from Macedo et al. [29]. Similar to Smeets et al. [30], we assume for the worst case that no additional bagasse is available for bioenergy. For the default case, bagasse is assumed to be used for heat generation, which is the current major practice in Brazil [31]. The best case is based on Scenario 2 from Macedo et al. [29].

For the future cases, we used the projections from Smeets et al. [30]. Based on an annual sugar cane yield of 100 tonne/ha (73% moist) and including 50% trash recovery which is used for electricity and heat generation.

Similar to the JEC study [11], we assume ethanol to be produced to the harbour by truck (700 km) where it is loaded on a product tanker for sea transport (10,186 km). Final transport to road fuel depots takes place by truck over a distance of 150 km [11].

Indirect energy and GHG emissions from the production of chemicals and utilities are calculated based on the JEC database. Results are therefore different from Macedo et al. [29]. This implies mainly higher indirect emissions for electricity for the production of e.g. fertilizers using the EU-mix instead of Brazil where 83% comes from hydropower [32].

2.4 Discussion

The results of this chapter are based on a wide range of sources for which selected methodologies are applied to calculate the life-cycle energy and GHG performance of biofuels in a consistent way. This section covers the uncertainty of the input data selected for this chapter, the impact of normative choices made for this chapter (e.g. selected conversion chains and co-product use) and the uncertainties of the methodology applied.

2.4.1 Input data

The emphasis of this chapter is on the impact of methodological assumptions for estimating the life-cycle energy and GHG performance of biofuel production systems rather than the absolute performance of each production chain. Input data includes a selection of state-of-the-art studies with site and chain specific data (e.g. yields, N_2O emissions, carbon stocks) reported transparently as part of the LCA calculation steps had to be repeated for this chapter.

2.4.1.1 Yields and conversion

The main source for LCA data on biofuel production was the Well-to-Wheel study from JEC [4] and [11] which is also used to calculate the typical and default values of the EU directive on biofuels. For ethanol from sugar cane, the updated study form Macedo et al. [31] was used whereas the JEC study [11] is based on the precursor of this study [29]. The default results for sugar cane ethanol are therefore slightly different from the results of the EU directive.

Limited data is available on the life-cycle performance of ethanol from sweet sorghum, ethanol from energy cane and biodiesel from jatropha. There is still limited experience with these feedstocks for biofuel and empirical data on the life-cycle performance of these systems is therefore scarce. For jatropha, data on crop cultivation is derived for Tanzania from Croezen and Kampman [10] with optimistic yield projections (6 Mg seeds/(ha year). It should be noted that these plantations are not yet mature and empirical studies show that yields obtained are only half of the projected yields [33].

2.4.1.2 Carbon stock change and reference land

Input data for above- and belowground carbon of reference land and crop land for palm oil in South-East Asia was available from [18] and [26], for Jatropha in Tanzania [10] and Sugar cane in Brazil [18] and [34]. For other crop types, the IPCC Tier 1 method was used to estimate carbon stock changes due to land-use change. Although the IPCC Tier 1 method is not site specific, the most important regions where land-use change is likely to occur are developing regions such as Brazil and South-East Asia. More detailed data is available on these areas from existing studies [10], [18] and [26]. In Europe, set aside land or existing cropland is expected to be used for energy crop cultivation [4] and [10].

2.4.1.3 N_2O emissions from crop cultivation

For N_2O emissions from crop cultivation, three model types were used: the DNDC model results from JEC [11], the N_2O model from Smeets et al. [22] for first-generation biofuels and the IPCC Tier 1 method. For 2nd generation crops such as switchgrass, miscanthus and eucalyptus, only the IPCC Tier 1 model could be used as data on these energy crops was missing in the other model studies. Also for soy bean and palm fruit cultivation, the IPCC model was used for the JEC study [11]. This implies that the GHG performance of all production chains can only be compared consistently using the IPCC Tier 1 model.

2.4.2 Normative choices and methodology

2.4.2.1 Chain selection and location

The selected energy crops in this chapter include the most commonly used energy crops, conversion routes and production locations. However, also alternative crops such as algae and alternative biofuels such as hydrogen or DME, or (hybrid) electric vehicles could become important in the future. A comparison of these chains would require a Well-to-Wheel analysis which is beyond the scope of this chapter.

The selected locations for dedicated crop cultivation in this chapter include the most common sites. Main differences per location are fertilizer use, soil properties (e.g. organic carbon) and crop yields. Site specific data on yields and N_2O emissions was available for the locations selected [22], however limited data was available on organic carbon levels and reference land per location.

2.4.2.2 System boundaries

For this chapter, system boundaries are extended to account for energy and GHG credits from the use of co-products. For all co-products, multiple end uses are defined based common practice [4]. The results are also shown if allocation methods are used rather than system expansion to show the implications of allocation procedures. It should be noted that system expansion requires arbitrary choices.

Issues arise if co-products replace products that are also produced from processes with multiple outputs. For example, if rape meal replaces soy bean meal, less soy oil will be produced. This has to be replaced with other products in which one could finally end up in endless system enlargements and modelling the world [35].

In this chapter, the life-cycle performances of biofuels are compared on a well-to tank basis based on the assumption that the performance of the considered biofuels and the fossil references is in range when used in internal combustion engines. Some studies indicate that ethanol blends results engine efficiencies improvements (MJ_{th}/km) up to 7.5 % [36] which results in improved energetic and GHG performance of bioethanol. These factors are not taken into account in this chapter.

2.4.2.3 Time correction factor

In this chapter, pulse emissions from land-use change are accounted for by straight line amortization. Straight line implies that emissions that occur in the beginning have the same impact as emissions that occur at the end of the time horizon. According to the IPCC decay function of CO_2 however, 36.4 % of CO_2 emitted will still be in the atmosphere after 100 years [37]. Emissions that occur at the beginning of the time period therefore have a larger impact on global warming than emissions that occur later.

In order to correct for pulse emissions that occur during initial stages of biofuel production, a time correction factor (TCF) was developed by Kendall et al. [38] based on the cumulative radiative forcing (CRF) method of the IPCC [39]. An alternative option would be to apply discount rates to GHG emissions that occur in different times. The latter method, however, requires the complexity of monetization of the different impacts of GHG emissions that are uncertain, even in physical quantities [38].

Both methods would result in larger impacts of emissions from land-use change on the GHG performance of biofuels, but are not considered in this chapter.

2.5 Conclusion

A life-cycle analysis has been conducted on the energy and GHG performance of different biofuel production systems from thirteen biomass feedstock types cultivated in different regions producing ethanol, biodiesel or FT-diesel. Rather than reviewing the performance parameters of biofuel production chains found, the focus of this chapter is on the impact of key parameters and procedures to estimate the energy and GHG performance of biofuel production chains. Included are different co-product allocation procedures, fossil energy reference systems, land-use reference systems and related land-use change emissions and carbon stock changes, site specificity and N_2O emissions from crop cultivation.

The highest biofuel yield for the biofuel production systems in this chapter is for ethanol from eucalyptus in Brazil (246 $GJ_{biofuel}$/ha year). The lowest yield was found for rapeseed diesel from rapeseed in East Europe (9.4 GJ $GJ_{biofuel}$/ha year). For all lignocellulosic crops (miscanthus, switchgrass and eucalyptus), yields are found to be higher than oil, sugar and starch crops.

The energy requirement for biofuel production is also lowest for FT-diesel production from eucalyptus in Brazil (−0.06 $MJ_p/MJ_{biofuel}$) due to high crop yields, limited fertilizer inputs and credits for co-produced electricity if system expansion is applied. The highest energy requirement is for maize ethanol using a natural gas boiler if system expansion is applied (0.89 $MJ_p/MJ_{biofuel}$). The performance of ethanol production from starch crops improves if steam is generated using CHP plants. If wheat ethanol is produced using a straw fired CHP plant, the system becomes a net producer of energy (−0.02 $MJ_p/MJ_{biofuel}$).

No clear winner can be selected for the GHG performance of the biofuel production chains included as the performance varies considerably depending on the allocation procedure applied and the type of reference land. If emissions from land-use change are excluded, the location of crop cultivation and related yields, fertilizer application and soil N_2O emissions are key factors that determine the GHG performance of biofuel production. GHG emissions from rapeseed methyl ester (RME) can be almost twice as high as fossil diesel (140 g CO_2eq/MJ RME) if cultivated in East Europe and if no reference land is selected for N_2O emissions. If both rapeseed cake and glycerine are used for energy purposes and if cultivated in Western Europe, GHG emissions are 17 g CO_2eq/MJ RME.

It depends on the type of reference land, if the carbon content of cropland is higher or lower than the reference situation. In case of degraded land for palm fruit cultivation in South-East Asia, logged over woodland in Tanzania and degraded pasture land for soy cultivation, more carbon will be stored if the land is converted for energy crop production resulting in additional GHG credits for biofuel production. If carbon intensive land such as natural rain forest and mainly peatland natural rainforest is converted to cropland, extreme quantities of carbon will be released. If peatland natural rain forest is converted into cropland for biodiesel from palm fruit, GHG emissions are more than three times higher than from fossil diesel if allocated over 20 years.

If land-use change emissions are taken into account for co-products from energy crops cultivated in Europe, but replacing soy bean meal in Brazil, these biofuel production systems can turn out to be robust GHG savers in case of system expansion. With maize cultivated in Europe and DDGS replacing soy bean meal cultivated on former natural rain forest land, extreme credits could be allocated to ethanol production resulting in negative GHG emissions of over 244 g $CO_2eq/MJ_{biofuel}$.

It should be noted that these cases are extreme and illustrate the impact of selected land-use reference systems rather than realistic cases. Moreover, if indirect land-use change would be taken into account, a worst case scenario for the Europe would potentially be a scenario with conversion of cropland in Europe that induces land-use change in South America rather than avoiding land use change in this region by co-products from Europe. Nevertheless, it shows the importance of reference systems for land use and the selected procedure for co-product allocation. If allocation methods are used rather than system expansion, land-use change emissions from co-product reference systems cannot be accounted for.

In context of the current debate on the sustainability of biofuel production systems, there is a growing need to improve insight in the energetic, but specifically the GHG life-cycle performance of biofuels. This study shows that a wide variation in performance can be found for the same biofuel type depending on reference land, location of crop cultivation and related yields and soil N_2O emissions and used allocation procedure for co-products.

System expansion is the preferred method to account for co-products. However, since this method also introduces some major difficulties when e.g. reference products are also produced in multiple output systems or when the reference system cannot be identified, also other allocation procedures should be applied.

Appendix Chapter 2

Table A 2-1 Co-products from biofuel production

Biofuel type	Energy crop	By-products[a]	Market price (€/tonne)	Application options considered[b]	Reference product[c]
Ethanol	Maize	Cobs & stalks		Ploughed back into the field	
		DDGS	148 [d]	1) Animal feed	Soy meal
				2) Fuel (CHP)	CHP (nat. gas)
Ethanol	Wheat	Wheat straw	29 [d]	1) Hydrolysis & fermentation to ethanol	Gasoline
				2) Fuel (CHP plant)	CHP (nat. gas)
		DDGS	148 [d]	(see ethanol from maize)	
Ethanol	Sorghum	Pressed stalk residues		1) Biofuel (process heat)	Natural gas
				2) Hydrolysis & fermentation to ethanol	Gasoline
Methyl ester	Palm fruit	Empty fruit bunches		Organic fertilizer	
		Shells		Biofuel (process heat)	
		Palm kernel meal	55 [d]	1) Animal feed	Wheat
				2) Biofuel (CHP)	CHP (nat. gas)
		Glycerin	646 [d]	1) Animal feed	Wheat
				2) Chemicals	Propylene glycol
Methyl ester	Rapeseed	Rape meal	127 [d]	1) Animal feed	Soy meal
				2) Biofuel (anaerobic digestion)	Natural gas
		Glycerin	646 [d]	(See Palm fruit)	
Ethanol	Sugar cane	Bagasse		1) Animal feed	Soy meal
				2) Biofuel (CHP)	National gen. mix, NGCC
Ethanol	Energy cane	(See sugar cane)			
Ethanol	Sugar beet	Leaves		Ploughed back into the field	
		Beet pulp & slop	6 [d]	1) Animal feed	Wheat
				2) Biofuel (process heat)	Natural gas
				2) Biofuel (anaerobic digestion)	CHP (nat. gas)
Methyl ester	Soybean	Soy bean meal	177 [d]	1) Animal feed	Soy meal
		Glycerin	646 [d]	(See Palm fruit)	
Methyl ester	Jatropha	Shell		1) Organic fertilizer	Synthetic fertilizer
				2) Biofuel (CHP)	CHP (nat. gas)
		Seed cake		1) Organic fertilizer	Synthetic fertilizer
				2) Biofuel (CHP)	CHP (nat. gas)
		Glycerin	646 [d]	(See Palm fruit)	
Ethanol	Switchgrass	Electricity	0.04 €/kWh	Electricity fed into the grid	National gen. mix, NGCC
Ethanol	Miscanthus	Electricity	0.04 €/kWh	(See switchgrass)	
Ethanol	Eucalyptus	Electricity	0.04 €/kWh	(See switchgrass)	
FTdiesel	Switchgrass	Electricity	0.04 €/kWh	(See switchgrass)	
FTdiesel	Miscanthus	Electricity	0.04 €/kWh	(See switchgrass)	
FTdiesel	Eucalyptus	Electricity	0.04 €/kWh	(See switchgrass)	

a) By-products come available from feedstock cultivation and harvesting and from conversion processes.
b) In case there are more options for the use of by-products, the options stated in this column will be included in the analysis.
c) The reference products are defined to allocate credits to the biofuel production chain in case of the system extension method.
d) Hamelinck and Hoogwijk [35]

References Chapter 2

[1] Porder S, Bento A, Leip A, Martinelli LA, Samseth J, Simpson T. Quantifying the environmental impacts of biofuel production: knowns and unknowns. In: Proceedings of the scientific committee on problems of the environment (SCOPE) international biofuels project rapid assessment; 2009.

[2] Larson ED. A review of life-cycle analysis studies on liquid biofuel systems for the transport sector. Energy for Sustainable Development 2006;10(2):109–26.

[3] VIEWLS. Shift gear to biofuels—results and recommendations from the VIEWLS project; 2005. p. 59.

[4] JEC. Well-to-wheels analysis of future automotive fuels and powertrains in the European context, in version 2c. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre (JRC/IES); 2007.

[5] van Dam J, Faaij APC, Hilbert J, Petruzzi H, Turkenburg WC. Large-scale bioenergy production from soybeans and switchgrass in Argentina: Part B. Environmental and socio-economic impacts on a regional level. Renewable and Sustainable Energy Reviews 2009;13(8):1679–709.

[6] Bergsma G, Vroonhof J, Dornburg V. The greenhouse gas calculation methodology for biomass-based electricity heat and fuels. Delft: CE; 2006.

[7] IPCC. IPCC fourth assessment report. Intergovernmental panel on climate change (IPCC); 2007.

[8] Horne RE, Matthews R. BIOMITRE technical manual. UK: Sheffield Hallam University Sheffield; 2004.

[9] IPCC. 2006 IPCC guidelines for national greenhouse gas inventories—agricul- ture forestry and other land use in volume 4. Intergovernmental panel on climate change (IPCC); 2006.

[10] Croezen H, Kampman B. Calculating greenhouse gas emissions of EU biofuels—an assessment of the EU methodology proposal for biofuels CO2 calculations. Delft: CE; 2008.

[11] JEC. Well-to-wheels study in version 3. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre (JRC/IES); 2008.

[12] Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H. Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Golden Colorado: National Renewable Energy Laboratory; 1998. p. 314.

[13] Quirin M, Gärtner SO, Pehnt M, Reinhardt GA. CO_2 mitigation through biofuels in the transport sector—status and perspectives. Heidelberg, Germany: Insti- tute for Energy and Environmental Research Heidelberg (IFEU); 2004.

[14] ISO. Environmental management—life cycle assessment—requirements and guidelines. Geneva, Switzerland: International Standard Organization (ISO); 2006.

[15] Gnansounou E, Panichelli L, Dauriat A, Villegas JD. Accounting for indirect land-use changes in GHG balances of biofuels—review of current approaches.. Lausanne: EPFL; 2008.

[16] Tipper R, Hutchison C, Brander M. A practical approach for policies to address GHG emissions from indirect land use change associated with biofuels. Green- energy, 2009. Technical Paper – TP-080212-A.

[17] RFA. The Gallagher review of the indirect effects of biofuels production..Sussex, UK: Renewable Fuels Agency; 2008.

[18] Fargione J, Hill J, Tilman D, Polasky S, Hawthorne P. Land clearing and the biofuel carbon debt. Science 2008;319(5867):1235–8.

[19] Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J., et al. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. Sciencexpress 2008.

[20] van Dam, J., (2009). Sustainability of bioenergy chains: the result is in the details. Copernicus Institute. Utrecht, Utrecht University: 395.

[21] Fehrenbach H, Fritsche UR, Giegrich J. Greenhouse gas balances for biomass: issues for further discussion. Issue paper for the informal workshop; 2008 [January 25, 2008 in Brussels].

[22] Smeets EMW, Bouwman LEXF, Stehfest E, Vuuren DPV, Posthuma A. Con-tribution of N2O to the greenhouse gas balance of first-generation biofuels. Global Change Biology 2009;15(1):1–23.

[23] Stehfest E, Bouwman AF. N2O and NO emission from agricultural fields and soils under natural vegetation: summarizing available measurement data and modeling of global annual emissions. Nutrient Cycling in Agroecosystems 2006;74(3):207–28.

[24] Charpentier AD, Bergerson JA, MacLean HL. Understanding the Canadian oil sands industry's greenhouse gas emissions. Environmental Research Letters 2009;4(014005):p11.

[25] EC. Proposal for a Directive of the European Parliament and of the Council on the promoting of the use of energy from renewable sources. Brussels, Belgium: European Commission (EC); 2008. p. 63.

[26] Wicke B, Dornburg V, Junginger M, Faaij A. Different palm oil production systems for energy purposes and their greenhouse gas implications. Biomass and Bioenergy 2008;32(12):1322–37.

[27] Schmidt JH, Weidema BP. Shift in the marginal supply of vegetable oil. International Journal of Life Cycle Assessment 2007.

[28] Smeets EMW, Faaij APC. The impact of sustainability criteria on the costs and potentials of bioenergy production – Applied for case studies in Brazil and Ukraine. Biomass and Bioenergy 2010;34(3):319–33.

[29] Macedo IC, Leal MRLV, Da Silva JEAR. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. Brazil: Secretariat of the Environment of the State of Sao Paulo; 2004. p. 32.

[30] Smeets EMW, Junginger M, Faaij APC, Walter A, Dolzan P. The sustainability of Brazilian ethanol—an assessment of the possibilities of certified production. Biomass and Bioenergy 2008;32:781–813.

[31] Macedo IC, Seabra JEA, Silva JEAR. Greenhouse gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. Biomass and Bioenergy 2008;32(7):582–95.

[32] Oeko-Institut, GEMIS 4.5. 2008.

[33] Lane J. The blunder crop: a biofuels digest special report on jatropha biofuels development. Biofuels Digest 2009.

[34] Amaral W. Environmental sustainability of sugarcane ethanol in Brazil. ESALQ– USP; 2008.

[35] Hamelinck CN, Hoogwijk M. Future scenarios for first and second generation biofuels. Utrecht: Ecofys; 2007.

[36] Gnansounou E, Dauriat A, Villegas J, Panichelli L. Life cycle assessment of biofuels: energy and greenhouse gas balances. Bioresource Technology 2009;100(21):4919–30.

[37] Clift R, Brandao M. Carbon storage and timing of emissions—briefing note. Surray, UK: University of Surray; 2008.

[38] Kendall A, Chang B, Sharpe B. Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations. Environmental Science & Technology 2009;43(18):7142–7.

[39] IPCC. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, et al., editors. Climate change 2007: the physical science basis. Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007. p. 996.

[40] Wang M. The greenhouse gases, regulated emissions, and energy use in transportation

(GREET) model version 1.5. Center for Transportation Research Argonne National Laboratory; 1999.

[41] Brandt A, Farrell A. Scraping the bottom of the barrel: greenhouse gas emission consequences of a transition to low-quality and synthetic petroleum resources. Climatic Change 2007;84(3):241–63.

[42] Williams RH, Larson ED, Jin H. F-T liquids production from coal and coal + -biomass with CO2 capture and alternative storage options: aquifer CO2 storage vs CO2-enhanced oil recovery; 2006.

[43] Smeets E, Junginger M, Faaij A, Dolzan P, Walter A. The sustainability of Brazilian ethanol–An assessment of the possibilities of certified production. Biomass and Bioenergy 2008;32(8):781–813.

[44] Jungbluth N, Emmenegger M, Stettler FDC, Doka C, Chudakoff M, Dauriat A, et al. Life cycle inventories of bioenergy. Uster; 2007.

[45] Croezen H. A greenhouse gas analysis for the bioshape initiative. Delft: CE; 2008.

[46] Smeets EMW, Lewandowskia IM, Faaija APC. The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. Renewable and Sustainable Energy Reviews 2009;13(6–7):1230–45.

[47] Damen K. Future prospects for biofuel production in Brazil. A chain comparison of ethanol from sugarcane and methanol from eucalyptus in Sao Paulo State. Master thesis. NWS report NWS-E-2001-131, Unit Science Technology and Society, Utrecht.

Chapter 3

Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level—A combined approach for the Netherlands

Keywords: Bioenergy; Bio-based materials; Computable general-equilibrium model

Abstract: Biomass is considered one of the most important options in the transition to a sustainable energy system with reduced greenhouse gas (GHG) emissions and increased security of energy supply. In order to facilitate this transition with targeted policies and implementation strategies, it is of vital importance to understand the economic benefits, uncertainties and risks of this transition. This presents a quantification of the economic impacts on value added, employment shares and the trade balance as well as required biomass and avoided primary energy and greenhouse gases related to large scale biomass deployment on a country level (the Netherlands) for different future scenarios to 2030. This is done by using the macro-economic computable general equilibrium (CGE) model LEITAP, capable of quantifying direct and indirect effects of a bio-based economy combined with a spread sheet tool to address underlying technological details. Although the combined approach has limitations, the results of the projections show that substitution of fossil energy carriers by biomass, could have positive economic effects, as well as reducing GHG emissions and fossil energy requirement. Key factors to achieve these targets are enhanced technological development and the import of sustainable biomass resources to the Netherlands.

Published in: *Energy Policy* (2013) 59: 727-744. Co-authors: Martin Banse (LEI-Wageningen UR), Veronika Dornburg (Utrecht University), André Faaij (Utrecht University)

3.1 Introduction

The transition to a sustainable energy system with strongly reduced greenhouse gas (GHG) emissions and improved security of supply requires major changes. Substitution of fossil energy carriers by biomass is considered one of the most important options [1-3] and is expected to account for more than half of the 20 % renewable energy target of member states in the EU-27 in 2020 [4]. In the Netherlands, the energy transition platform 'Bio-based Green Materials' has set ambitious targets to replace 30 % of fossil primary resources with biomass in 2030 of which 60% substitution in the transport sector, 25 % substitution in chemical sectors, 25 % substitution in electricity and 17 % substitution in heat [5].

The transformation to an energy system – including large scale use of biomass for electricity, heat, transport fuels and materials – implies large investments and financial support in infrastructure and conversion capacity. Shifts in the use of imported and indigenous fossil resources, such as natural gas or oil, to imported, and domestic biomass resources, will also results in (major) sectoral shifts in the economy. Furthermore, investments in infrastructure and technology will generate new economic activities. This especially holds true when (low cost) imported biomass resources are converted into high value added products such as bio-chemicals and replace relatively expensive fossil-based resources that have to be imported [6]. On the other hand, the large scale use of bio-based materials can also induce negative effects such as (indirect) land use changes [7] or increased prices in competing markets [8]. A better understanding of these impacts is of vital importance for designing targeted policies and implementation strategies to optimise the economic benefits and reduce risks (costs) of large scale biomass deployment.

The Netherlands depend to a large extent on the import and export of raw materials, intermediates and final products. Therefore, a multidisciplinary modelling framework should be used to encompass the interactions among sectors within economies and among countries through international trade of biomass and fossil energy carriers. At the same time, this model should be able to address the technological detail and technology changes that underlie these sectoral changes. Recent concerns on the negative impact of biomass for bioenergy, including food prices and (indirect) land use change induced by biofuel production, has led to major efforts to incorporate biomass for bioenergy and the related technology details into macro-economic models [9]. Despite recent efforts to improve macro-economic models to estimate the global land use impacts of biofuel production, there are still large uncertainties and shortcomings to these models. One of the main shortcomings of these models is the representation of conversion technologies, type of crops used and by-products and co-products that are produced [9]. Furthermore, most of these models focus on biofuels for transport only whereas bio-based electricity, heat and, potentially, also bio-based chemicals are also important sectors for current and future uses of biomass resources.

The aim of this chapter is to provide quantitative insight on the economic and mitigation effects of the large-scale substitution of fossil-energy carriers with biomass in electricity, transport and chemical sectors on a national level for the Netherlands to 2030 using the macro-economic computable general equilibrium (CGE) model LEITAP. A spread sheet tool provides the required input data of the LEITAP model and to analyse and compare the results with bottom-up projections to identify key uncertainties and limitations of the selected approach.

Although imports of biomass from European and non-European countries are taken into account, the main focus of this is on national impacts related to bio-based substitution of electricity, chemicals and transport fuels. Possible positive or negative (indirect) effects outside the Netherlands are highly relevant, but to assess these effects, would require a larger regional or global scope with all related uncertainties on socio-economic, political and technological development.

3.2 Methodology

Detailed assumptions on the substitution of fossil electricity, transport fuels and chemicals with domestic and imported resources are implemented in the top-down computable general equilibrium model LEITAP to estimate the potential macro-economic and environmental impact for the Netherlands. To assure more comprehensive technology details, physical parameters in LEITAP have been updated with an Excel based spread sheet tool.

3.2.1 Scenarios

This analysis includes four main scenarios, partly consistent with the storylines and scenario variables of the IPCC SRES scenarios 'Global Economy,' 'Continental market,' 'Global cooperation,' and 'Regional communities' [1] and one additional scenario with a focus on bio-based chemicals. The scenarios vary over two key variables: (1) international cooperation & trade and (2) technological development rate (Figure 3-1). In the scenarios with more global orientation (GlobLowTech and GlobHighTech scenarios), it is assumed that biomass resources are available for the Netherlands at global level, whereas for the scenarios with more regional orientation, the biomass market is limited to European resources of biomass ('RegLowTech' and 'RegHighTech' scenarios). Conversion technologies in the scenarios with conservative technological development (LowTech) are assumed only to have technologies available that are already used commercially today. For the scenarios with enhanced technological development (HighTech), advanced conversion technologies, such as second generation biofuels and advanced bio-refinery concepts, are assumed to become available by 2015. The GlobHighTechAC scenario is similar to the GlobHighTech scenario, but includes, apart from bio-based hydrogen, also the chemicals bio-based ethylene and caprolactam to substitute 25 % of fossil raw materials in the chemical sectors in 2030. Scenario assumptions other than bioenergy are derived from WLO scenarios (welfare, prosperity and quality of the living environment) that project different futures for the Netherlands within the IPCC SRES scenario framework [10].

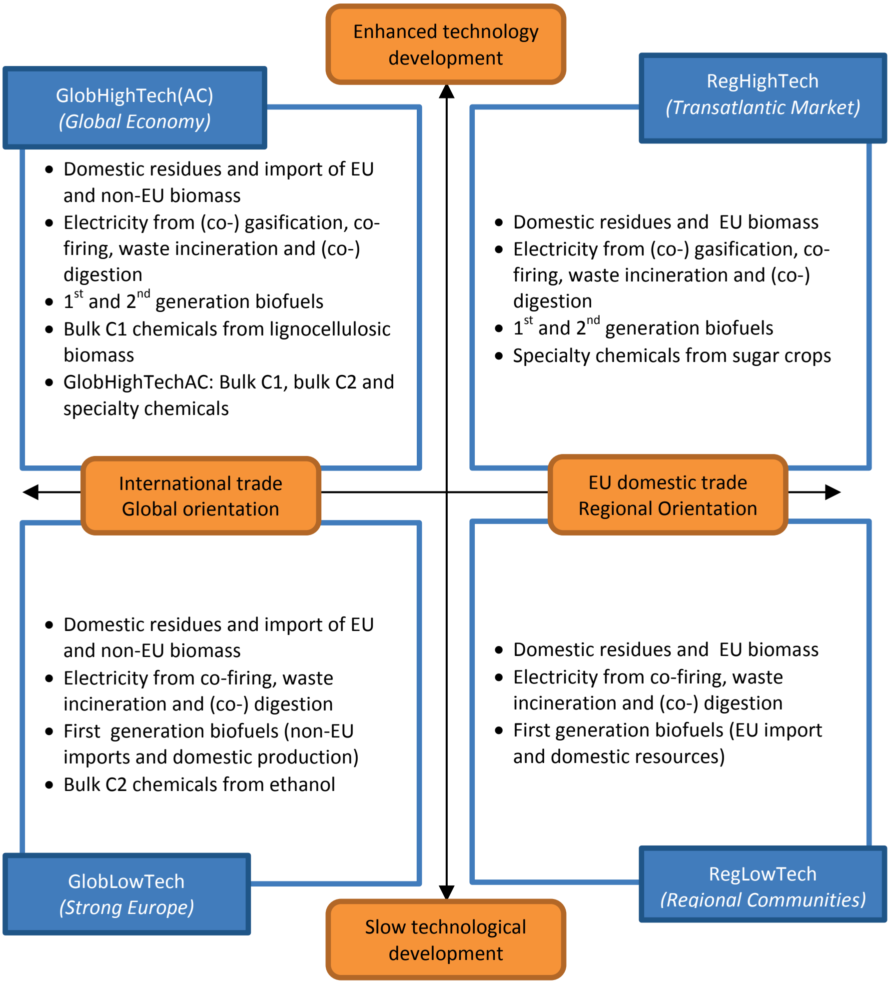

Figure 3-1 Scenarios and key biomass supply and conversion options per scenario.

The technologies depicted in Figure 3-1 represent the key conversion options per scenario. Table 3-1 summarizes all technologies available in the scenarios. The technical, environmental and economic performance of these technologies and related references for cost and efficiencies are provided in the Appendix and in Hoefnagels et al. [11].

Table 3-1 Fossil and biomass conversion technologies in the scenarios.

	RegLowTech	GlobTowTech	RegHighTech	GlobHighTech	GlobHighTechAC
Electricity					
Natural Gas Combined Cycle (NGCC)	x	x	x	x	x
NGCC Co-gasification (25 %)			x	x	x
Pulverised Coal (PC)	x	x	x	x	x
PC Co-firing (10 %), existing plants	x	x			
PC Co-firing (20 %), new plants	x	x			
Municipal Solid Waste	x	x	x	x	x
Biomass digestion	x	x	x	x	x
Fuels					
FAME (veg. oil)	x	x	x	x	x
FAME (oil and fat residues)	x	x	x	x	x
Ethanol from starch (wheat)	x	x	x	x	x
Ethanol from sugar (sugar beet)	x	x	x	x	x
Ethanol from sugar (sugar cane)	x	x	x	x	x
FT- diesel from lign. Biomass			x	x	x
Ethanol from lign. Biomass			x	x	x
Chemicals					
Ethylene					
Fossil based	x	x	x	x	x
Bio-based (sugar cane ethanol)		x			x
Caprolactam					
Fossil based	x	x	x	x	x
Bio-based			x		x
Hydrogen					
Fossil based (natural gas)	x	x	x	x	x
Bio-based (lign. biomass)				x	x

3.2.1.1 Electricity

The selected technologies include representative biomass conversion technologies and their fossil counterparts already being used or that are expected to become available before 2030. Co-gasification of biomass in natural gas combined cycle plants (NGCC) represents advanced electricity generation that is only available in the high-tech scenarios from 2015 onwards. Co-firing of biomass in pulverized coal plants (PC) is available in all scenarios. Incineration of organic waste (MSW) is also available in all scenarios, but the future growth potential is limited. Wet organic waste (WOW) is assumed to be converted into electricity and heat via gas produced from anaerobic digestion.

For renewable electricity generation, the total potential depends mainly on the replacement rate of existing central power generation units (pulverized coal and natural gas) and related co-firing potentials and co-generation in case of advanced biomass technologies in the HighTech scenarios. Similar to Hansson et al. (2009), it is assumed that existing coal-fired capacities have a 10 % fuel share of biomass, but for new capacities, 20 % is assumed to be feasible. Replacement rates of existing capacities are based on the long vintage (LowTech) and short vintage (HighTech) scenarios of van den Broek et al. [12]. Future capacities are mainly based on the WLO-projections for decentral generation units such as CHP [10] and own assumptions for central generation plants and biomass conversion units. Final energy demands are derived from the LEITAP projections. The resulting blending shares, as calculated with the spread sheet tool, in the scenarios are depicted in Table 3-2.

Table 3-2 Bio-based blending shares in the scenarios applied to the LEITAP model.

	RegLowTech	GlobLowTech	RegHighTech	GlobHighTech	GlobHighTechAC
Electricity (% energy output)					
2006	3 %	3 %	3 %	3 %	3 %
2010	5 %	4 %	5 %	5 %	5 %
2020	6 %	5 %	9 %	25 %	21 %
2030	7 %	6 %	8 %	29 %	20 %
Transport fuels (% energy output)					
2006	0.5 %	0.5 %	0.5 %	0.5 %	0.5 %
2010	5.75 %	5.75 %	5.75 %	5.75 %	5.75 %
2020	10 %	10 %	10 %	25 %	25 %
2030	10 %	20 %	20 %	60 %	60 %
Bio-based chemical (% energy for raw materials in the chemical industry)					
	Bulk[a]	Bulk[b]	Bulk	Bulk[d]	Bulk[e]
2006	N/A	N/A	N/A	N/A	N/A
2010	N/A	N/A	N/A	N/A	N/A
2020	N/A	N/A	4 %	9 %	13 %
2030	N/A	N/A	7 %	19 %	25 %
	Specialty[a]	Specialty	Specialty[c]	Specialty[d]	Specialty[f]
2006	N/A	N/A	N/A	N/A	N/A
2010	N/A	N/A	N/A	N/A	N/A
2020	N/A	4 %	N/A	9 %	13 %
2030	N/A	7 %	N/A	19 %	25 %

a) No bio-based chemicals in the RegLowTech scenario.
b) Bio-based production of bulk C2 chemicals, based on 10 % and 20 % replacement of fossil based ethylene by bio-based ethylene in 2020 and 2030 respectively.
c) Bio-based production of specialty chemicals, based on 50 % and 100 % replacement of fossil based caprolactam by bio-based caprolactam in 2020 and 2030 respectively.
d) Bio-based production of synthesis gas, replaces fossil based synthesis gas used for bulk and specialty chemicals. Note that the division between synthesis gas use for bulk and specialty chemicals is similar to the total use of fossil energy for chemicals (80 % and 20 %).
e) Bulk C1 and C2 chemicals, based on bio-based ethylene (25 % substitution of petroleum products in 2030) and bio-based synthesis gas (30 % substitution of natural gas in 2030).
f) Bio-based production of specialty chemicals, based on caprolactam (25 % substitution of petroleum products in 2030) and synthesis gas (30 % substitution of natural gas in 2030).

The biofuel blending targets, as reported in the National Renewable Action Plan of the Netherlands, include blending shares that increase from 4.25 % in 2011 to 5.5 % in 2014. The growth rate after 2014 is yet unknown, but the Netherlands is committed to reaching the 10 % blending target in 2020 [13]. We assumed that the blending targets for 2020 will be achieved in the LowTech scenarios and the RegHighTech scenario increasing to 20 % in 2030 in the GlobLowTech and RegHighTech scenario and remaining 10 % in the RegLowTech scenario. The GlobHighTech and GlobHighTechAC scenarios have very high biomass blending shares up to 60 % in 2030. These targets are consistent with the ambitions of the energy transition platform 'Bio-based Green Materials' as described in Section 1. The biomass blending shares in the scenarios are depicted in Table 3-2. However, if technical and economic barriers, such as disinvestments in refinery capital and limitations to combustion engines, are considered, these targets might be infeasible. Rabou et al. [5] concluded that 60 % substitution of transport fuels in 2030 is not feasible due to the limited flexibility of refining industries and estimated that 40 % substitution of fossil fuels by biofuels would be more realistic in 2030. For this , the high blending shares are still considered to show the implications of the ambitious targets of the energy transition platform.

The available biofuels in the scenarios differ per scenario. In the LowTech scenarios, there is no diffusion of 2nd generation biofuels whereas in the HighTech scenarios, 2nd generation biofuels including Fischer-Tropsch diesel and ethanol from lignocellulosic biomass become commercially available after 2015. First generation biofuels include biodiesel from vegetable oils (palm oil, rapeseed oil, jatropha) and oil and fat residues and ethanol from starch (wheat) and sugar (sugar beet, sugar cane) depending on the source of production. Diffusion of 2nd generation biofuels is modelled endogenously with the LEITAP model. The results of a scenario with all biofuels produced from lignocellulosic residues and energy crops (Advanced biofuels) is also included for 2030 (2030Adv.).

3.2.1.2 Chemicals

Due to the diversity and complexity and due to lack of cost and performance data of the chemical industry, it is impossible to model all bio-based chemicals that could potentially be produced. Therefore, three representative options are selected for the scenarios. Ethylene production from dehydration of sugar cane based ethanol represents the production of bulk, low-tech C2 chemicals in the GlobLowTech scenario and replaces oil-based ethylene that is mainly produced by steam cracking of naphtha [14]. Caprolactam, a precursor of nylon-6 [15], represents the production of high value added specialty chemicals in the RegHighTech scenario and is produced from sugar beet via synthesis of lysine [16]. The production of hydrogen from gasification of lignocellulosic biomass represents the production of advanced bulk syngas in the GlobHighTech scenario and replaces natural gas based hydrogen from steam methane reforming. In the GlobHighTechAC scenario, these three chemical representatives are all assumed to be produced. Blending shares in the chemical industry are based on replacement rates of individual chemicals (Table 3-2).

3.2.1.3 Heat

In the Netherlands, 2.4 % of the final heat demand was produced from renewable energy in 2006 of which 92 % was produced from biomass and organic waste and the remaining 8 % was produced from heat pumps, solar thermal and geothermal sources. Similar to the WLO scenarios [10] and the NREAP of the Netherlands [13], we assumed that heat from stand-alone solid biomass (mainly domestic wood stoves) remains constant to 2030 in the scenarios. Since heat is not represented explicitly in LEITAP, economic effects of biomass heat we considered heat from stand-alone sources outside the scope of this analysis, but heat from co-generation plants increases in the scenarios with increased production of electricity. The avoided primary energy and greenhouse gases from co-generation of heat are allocated to the electricity sector.

3.2.2 Model set-up

3.2.2.1 Overview

To quantify the economic impact of introducing biomass for bio-energy and bio-based materials at a national level, the macro-economic CGE model LEITAP was used in combination with an Excel based spread sheet tool to translate the physical-flow (e.g. tonnes of biomass) based scenarios to the balanced input—output matrices of all economic transactions within the economy in value terms (US$/yr) as used in LEITAP. Figure 3-2 summarizes the methodology applied and the data flows between the spread sheet tool and LEITAP. At first, the spread sheet tool is used to calculate bio-based blending shares (Table 3-2) that are applied to the LEITAP model. Finally, the relative growth per sector and the input of biomass commodities, as projected with the LEITAP model, are used for post-processing with the Excel spread sheet tool to calculate final and primary demand of bioenergy and bio-based chemicals, cost structures and greenhouse gas mitigation. Note that the total primary energy demand, including fossil energy, cannot be calculated because the Excel spread sheet tool only includes bio-based sectors and its fossil counterparts Figure 3-2.

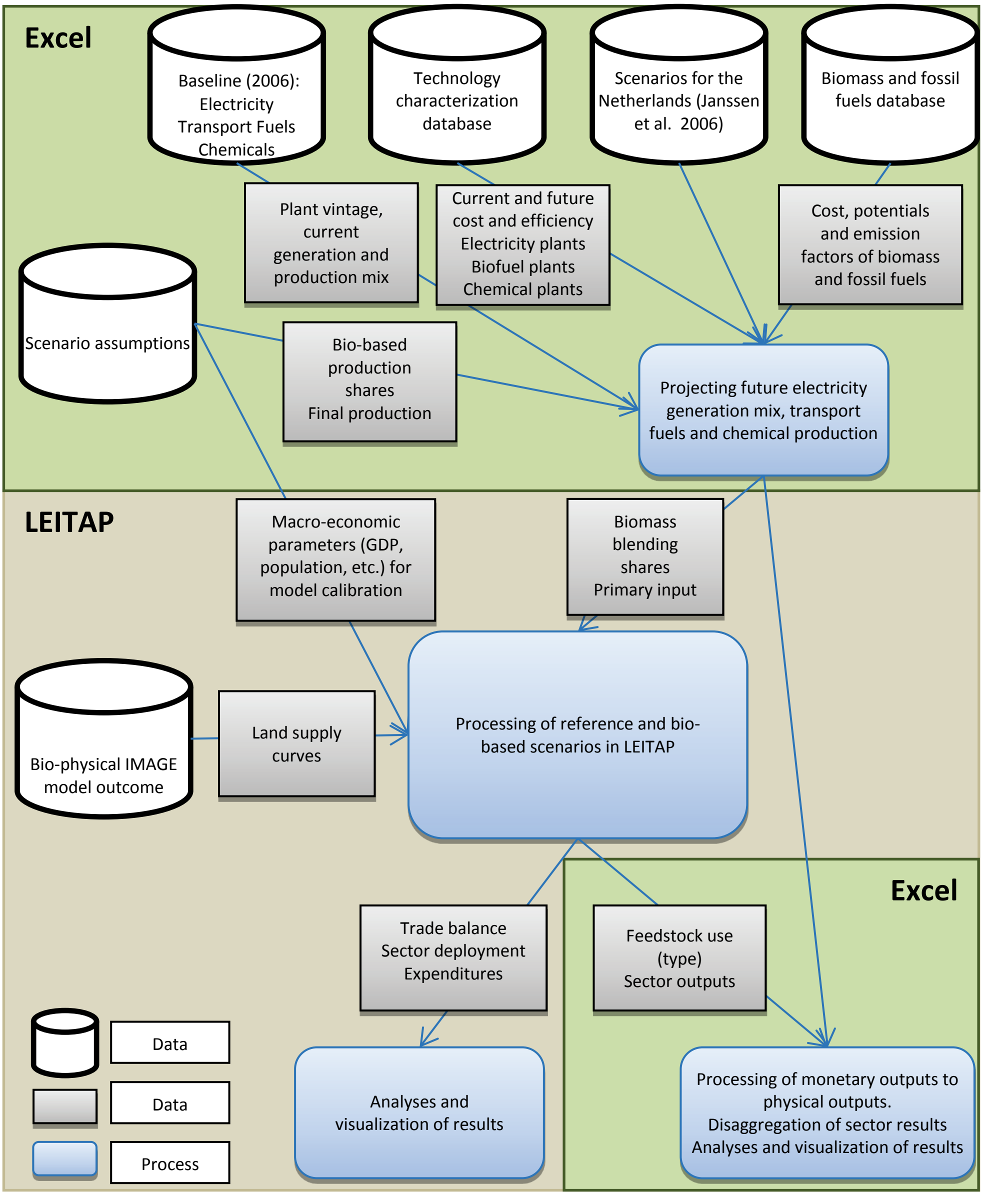

Figure 3-2 Applied model systems for estimating the macro-economic impact of large scale deployment of biomass on a national level.

3.2.2.2 Bioenergy and bio-based chemicals in LEITAP

The macro-economic impacts of large scale deployment of biomass in the Netherlands have been assessed using the CGE model LEITAP [17]. LEITAP builds on the CGE model GTAP-E [18], an Energy-Environment extended version of GTAP (Global Trade Analysis Project) version 6 [19]. The LEITAP model has a global coverage aggregated into 37 regions including all EU-27 countries, with Belgium and Luxembourg, Malta and Cyprus, Bulgaria and Romania and the Baltic countries aggregated in single regions. Outside the EU, countries are aggregated into regions that are important in the context of agricultural production and demand [17]. The 57 GTAP sectors are, in LEITAP, aggregated into 23 sectors with detailed sectors on land-using agricultural sectors and sectors that are relevant for energy consumption/production (e.g. crude oil, petroleum, gas, coal and electricity).

There are three approaches to represent biomass for bioenergy in macro-economic models: latent technologies and disaggregation of the social accounting matrices (SAMs) and implicit modelling [20]. Latent technologies, as applied in, e.g.. EPPA [21] and DART [22], represent technologies that are currently not active, but could become profitable if conditions change. Disaggregation of the relevant SAMs, as applied in GTAP-BIO [23] allows biomass to be modelled explicitly, but this approach is mainly limited by a lack of the data required to construct the related SAMs. With implicit modelling, as applied in LEITAP, the SAMs remain unchanged and biomass is embedded by extending the nested structure of the capital–energy composite as explained below.

The GTAP-E model includes energy-capital substitution by aggregating all energy-related inputs in the value added nest side [18]. For the assessment of biomass in the energy sectors, the value-added nested CES (constant elasticity of substitution) function of the GTAP-E model has been transformed in LEITAP into a multi-level nesting structure (Figure 3-3).

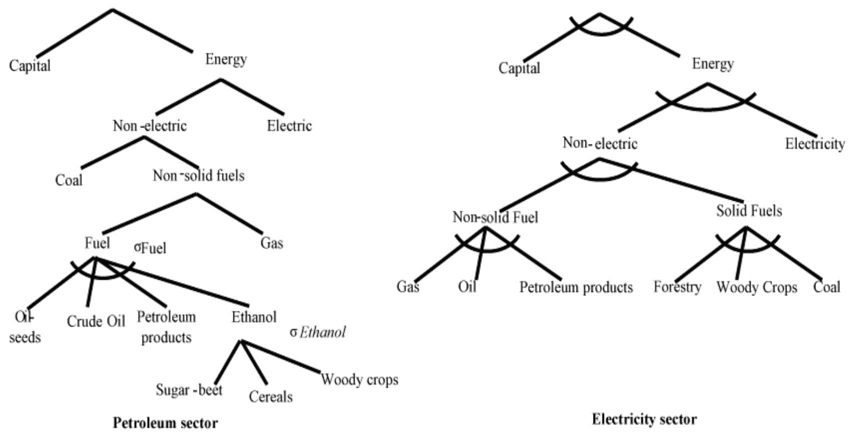

Figure 3-3 Capital-energy composite in the extended LEITAP in the petroleum and electricity sectors.

The LEITAP model builds on the GTAP 6 database with 2001 as base year. But, bio-based sectors have grown significantly since 2001. Therefore, the LEITAP model has been calibrated to the base year of this study (2006) by calibration of biomass utilization based on statistical data for ethanol [24], Eurostat and other sources. The approach to update the model is explained in detail in Banse et al. [17].

To assess future biomass deployment for bioenergy and bio-based materials using LEITAP, the blending shares of biomass in the different scenarios, are calculated with the spread sheet tool (Table 3-2) and are exogenously applied to the LEITAP model as minimum mandatory blending shares. These blending shares are calculated at sector level as described in detail in Hoefnagels et al. [11]. In the reference scenarios (noBD), no mandatory blending rates are assumed resulting in consumption far below the obligatory blending rates implemented in the policy scenarios. LEITAP calculates the mandatory blending rates which forces the bio-based industries to use more biomass than they would use under no mandates through subsidies on biomass inputs in these industries. These subsidies are however implemented as so-called budget neutral subsidies affecting the price of the final products, e.g. petrol with biofuels. The required amount of subsidies is financed as an equal consumer tax on products produced by the bio-based industries.

3.2.2.3 Monetary and physical quantities

The LEITAP variables are not expressed in absolute quantities (e.g. tons of wheat) but in relative changes for all endogenous variables which are described in values. However, the combined approach in this , that is based on physical quantities (e.g. tons or PJ), requires a 'conversion' of flows in monetary values into quantities and vice versa. Therefore, we measured the outcome of LEITAP in volume terms at constant base year prices using Eq. (3-1):

$$\Delta V_{i,t} = \Delta(Q_{i,t} * P_{i,\text{Base Year}}) \qquad \text{Eq. 3-1}$$

Vi,t is the volume of product *i* in period t expressed as the change in quantities valued at base year prices. With constant base year price $P_{i,Base\ Year}$, we set the relative changes in monetary flows *V* equal to the relative change in physical flows *Q*. Gross final electricity demand, the final demand of transport fuels and the share of 1st and 2nd generation biofuels are based on these assumptions and therefore have a large impact on the result.

3.2.3 Biomass potentials and bio-based substitution

3.2.3.1 Biomass potentials

The amount of biomass that can be used for bioenergy without direct or indirect negative impacts is uncertain and a subject of debate [1]. This study analysis includes biomass from domestic sources in the Netherlands and foreign sources from other EU-27 countries as well as non-EU countries. The main goal of this is to show the consequences of a different degree of use of biomass in the Dutch economy under alternative technology assumptions and a different degree of openness. In order to assess biomass scenarios, an appropriate macro-economic model has to capture two main elements. First, it should consider regional differences in land availability and the degree of intensity level of land cultivation. And second, it should be flexible to represent different biomass conversion technologies.

Earlier analyses concluded that a strong increase in biomass demand in the EU will not be met by EU-domestically grown biomass alone [17, 25]. Hence, a comprehensive analysis of the consequences of a growing demand for biomass requires good insights into the inter-linkages between domestic policies and global impacts in order to correctly assess the consequences for land use and the yield changes of biomass crops. Biomass crops will directly and indirectly affect the intensity of biomass production and the amount of land available for other land uses. The land availability per region and the yield level are very important drivers of the costs for biomass production. To capture the changes in land use and land intensity level, the LEITAP model has been linked to the bio-physical model IMAGE to introduce a land supply curve representing the process of land conversion and an endogenous change in yield levels [26, 27]. As a consequence, in land-abundant regions like South America, an increase in demand results in a large increase in land use, a modest increase in rental rates and only a small increase in land intensity level. Land scarce regions on the other hand, e.g. Japan, Korea or most European countries, experience a small increase in land use, a large increase in the rental rate, and a movement towards an increased intensity level of land use, if land demand increases.

There are, however, two important limitations to this modelling approach in the context of the scope and scenarios. First, the endogenously calculated potentials of biomass available for bioenergy only cover dedicated energy crops and forestry biomass, but not biomass residues and waste, a major source, mainly for electricity, heat and/or biogas production in the Netherlands [13]. Second, it is difficult to clearly distinguish between inter- and intra-European trade as defined in the 'National' scenarios (EU trade only) and 'International' scenarios (both intra and extra-European trade). In this , first the biomass blending shares are calculated bottom-up using the spread sheet tool based on biomass resource assessments for the Netherlands [5], Europe [28, 29] and globally [30, 31]. The total primary energy demand in the scenarios in Netherlands, relative to the total primary energy demand in the world, as projected to 2030 by the IEA for the World Energy Outlook [32], was used to represent the share of the global biomass potential available for the Netherlands resulting in global available supply potential shares of 0.5 % to 0.60 % in the Glob(al) scenarios. A detailed description of these supply potentials is provided in Hoefnagels et al. [11]. Finally, the required land use for bio-based production is projected endogenously with the LEITAP model.

3.2.4 Biomass trade

Whereas some countries are already (and might remain) self-sufficient on bioenergy resources, the Netherlands already depends largely on imported biomass. For example, in 2009 the Netherlands imported almost 1 million tons of wood pellets, of which over 80 %

were imported from non-European countries (mainly the US and Canada) [33]. Trade is therefore also considered in the national scenarios, but focused on intra-European resources. The international scenarios cover both inter and intra-European trade. The bioenergy trade scenario variable is modelled in LEITAP by altering the Armington elasticities. This parameter represents elasticity of substitution of product trade between countries, in this case biomass feedstocks [34]. To capture these differences in the degree of openness, we vary the trade elasticities (Armington elasticities) determining the composition of final demand between domestic and imported sources as a reaction to changes in the ratio of domestic and international prices. Under the 'National' (Reg) scenarios we apply lower values while under the 'International' (Glob) scenarios the level is increased with 50 % compared with those applied for the 'National' scenarios. The higher trade elasticities under the 'International' scenario will lead to a stronger increase in imports if domestic prices increase. The Armington elasticities are provided in Appendix Table A5 and changes in elasticities between the scenarios are treated the same for all regions in the LEITAP model.

3.2.5 Economic and environmental performance of fossil and bio-based technologies

The spread sheet calculation tool includes a database of fossil and bio-based energy conversion technologies and chemical production plants. The tool calculates the reduced fossil energy and GHG emissions due to the substitution of fossil energy carriers by biomass in electricity, transport fuels and chemical industries for the time frame 2006 to 2030 in the Netherlands. This is done for scenario specific technology pathways and final demands of energy and materials. The economic, energy and GHG performance are provided in the Appendix for fossil and biomass feedstocks (Table A 3-1), electricity (Table A 3-2), transport fuels (Table A 3-3) and chemicals (Table A 3-4). A detailed description of the individual technologies and the approach to calculate the energy and greenhouse gas mitigation performance are provided in Hoefnagels et al. [11]. The greenhouse gas emissions from bio-based and fossil production chains are calculated using Eq. (3-2). For co-generation plants (CHP), credits are given for electricity and heat based on individual fossil reference plants for electricity (NGCC plant) and heat (natural gas fired boiler). A detailed description of the approach and assumptions is provided in Hoefnagels et al. [11].

$$mCO_2 = m_{cult} + m_p + m_{td} - e_H - e_E - E_{co} \qquad \text{Eq. 3-2}$$

with: mCO_2 is the total emissions from fuel, electricity or chemical production; m_{cult} is emissions from mining, extraction or cultivation, collection and harvesting of raw materials; m_p is the emissions from processing (e.g. pelletization, transesterification); m_{td} is the emissions from transport (including inter-continental transport chains); e_H is the emission savings from co-generation of heat (natural gas boiler, η=90 %); e_E is the emission savings from co-generation of electricity (relative to a NGCC plant, η=58–63 %); E_{co} is the emission savings from co-products (e.g. glycerine by transesterification).The bottom-up CO_2 mitigation cost are calculated with the spread sheet tool and are expressed as the incremental cost of electricity, transport fuel or bio-based chemicals production relative to the fossil reference system divided by the difference in greenhouse gas emissions (expressed in CO_2eq) between the fossil reference system and the bio-based production system (Eq. 3-3).

$$MCO_2 = \frac{COP_{bio} - COP_{reference}}{mCO_{2reference} - mCO_{2bio}} \quad \text{Eq. 3-3}$$

MCO_2 is the greenhouse gas mitigation cost (€/t CO_2eq); COP_{bio} is the total cost of bio-based production (€/year); $COP_{reference}$ is the total cost of fossil reference production (€/year); mCO_2 reference is the total GHG emissions fossil reference production (t CO_2eq/year); $mCO_{2\,bio}$ is the total GHG emissions bio-based production (t CO_2eq/year).

The comparison of the life cycle GHG performance of fossil reference and bio-based electricity generation, transport fuel production and the production of chemicals are calculated on a 'cradle to factory gate' base. Transport to consumers, use and disposal phases are assumed to be similar to the fossil reference systems and are thus excluded. Possible carbon releases due to (indirect) land use change are not taken into account because the focus is on effects on the national level and because it is infeasible to estimate these effects with the models currently available. This analysis includes direct (first order) and indirect (second order) primary energy requirements and GHG emissions. The production of equipment, e.g. housing, (third order) energy requirements and emissions are not taken into account as only limited data is available and because the impact is relatively low [35].

In LEITAP, the substitution of first generation biomass conversion technologies with second generation biomass technologies in the high-tech scenarios is not modelled as a sudden shift from one technology to another. Technology changes follow a path of substituting without drastic changes in the composition of the feedstock in the biomass sector.[4] Thus, even in the GlobHighTech scenario, first generation biomass crops such as oilseeds continue to contribute to biofuel production at a significant level. Based on the macro-economic model applied here, the achieved results indicate that an economy fully based on second generation biomass inputs would require a longer time path for adjustment.

Apart from the assumption of a higher degree of substitutability of biomass with fossil inputs under the HighTech scenario, we also assume that the conversion efficiency is higher compared with the LowTech scenarios. This is implemented in the macro-economic

[4] Other modelling approaches such as a linear-programming model would allow for these immediate shifts in the mix of first and second generation biomass. However, these modelling approaches would neglect other important features such as the endogenous development of relative prices between different inputs.

model by different assumptions on the rate of input augmenting technical progress. Eq. (3-4) describes the relative change in industry's j demand for intermediate inputs i in region r qf in a linearized form, where i is the input, j the industry and r is the region:

qf(i,j,r) = -af(i,j,r) + qo(j,r) - ao(j,r)- ESUBT(j,r) * [pf(i,j,r) - af(i,j,r) - ps(j,r) - ao(j,r)]   Eq. 3-4

with *af(i,j,r)*, input augmenting technical progress; *qf(i,j,r)* is the demand for intermediate input; *ESUBT(j,r)* is the elasticity of substitution among (composite) intermediate inputs in production; *pf(i,j,r)* is the price of intermediate input; *qo(j,r)* is the output quantity; *ao(j,r)* is the sectoral productivity; *ps(j,r)* is the output price.

Under the LowTech scenario we assume that the technical progress is 'neutral' without affecting the composition of intermediate demand in different sectors, i.e. *af(i,j,r)* is zero and the increase in sectoral productivity *ao(j,r)* leads to a decline in demand for intermediate input which is equal for all intermediate inputs. Therefore, technical progress in fuel or chemical production will not affect the mix of biomass and fossil inputs. Under the HighTech scenarios this assumption is dropped, and technical progress in input-saving for biomass inputs in the bio-based sectors, i.e. *af(i,j,r)* differs from zero for biomass inputs in bio-based sectors.[5] This assumption will lead to a higher conversion rate for biomass inputs in the bio-based economy Table A 3-5.

3.3 Results

The results include value added in bio-based and agriculture sectors, composition and land use of imported biomass crops and effects of bio-based substitution on the trade balance of the Netherlands. These results are directly derived from the LEITAP model. For bio-based production and biomass demand, avoided primary energy and greenhouse gases, bottom-up cost structures and mitigation cost, the spread sheet tool was used in combination with the input shares of biomass commodities and growth of final demand per sector as projected with the LEITAP model (Table A 3-6). Also, results for 2030 are presented with input shares of biomass crops from the LEITAP model replaced with the pre-defined of the spread sheet tool and presented in the results for 2030 (2030Adv.). In these scenario results, all biofuels are produced from 2nd generation conversion systems in 2030.

3.3.1 Development of bio-based sectors

For the five scenarios assessed, Figure 3-4 depicts the amount of transport fuels, electricity and chemicals produced from biomass. Chemicals are included based on the

[5] Technically this is implemented by a rate of input-saving technical progress for biomass inputs j in the parameter af(i,j,r) which is equal to 50 % of the sectoral increase in productivity ao(j,r).

net calorific values of the final products and exclude energy use to produce these products. The results of the RegLowTech scenario show that under low technology development and with limited international biomass supply, bio-based production of electricity, transport fuels and chemicals would be limited to 115 PJ in 2030. In contrast, under a more advanced technology development and if global resources are available, as assumed in the GlobHighTech(AC) scenarios, bio-based production could be up to 644 PJ in 2030. When all biofuels are produced from lignocellulosic biomass in 2030 (2030Adv.), total production in the GlobHighTedAC scenario increases to 660 PJ due to increased co-generation of electricity from 2nd generation biofuels in 2030. The large difference between the GlobHighTech scenarios and the other scenarios is mainly due to the large share of biofuels (60 % biofuels in 2030, Table 3-2) in these scenarios. Co-generation of electricity in second generation transport fuel production systems and advanced chemicals (syngas), also adds over 50 % of total renewable electricity generation from biomass in the GlobHighTech scenario. Heat from co-generation increases to 13 PJ in all scenarios. Biomass heat from stand-alone plants, (7.4 PJ avoided primary energy in the WLO scenarios in 2030 [5](Janssen et al., 2006)) is not included in this .

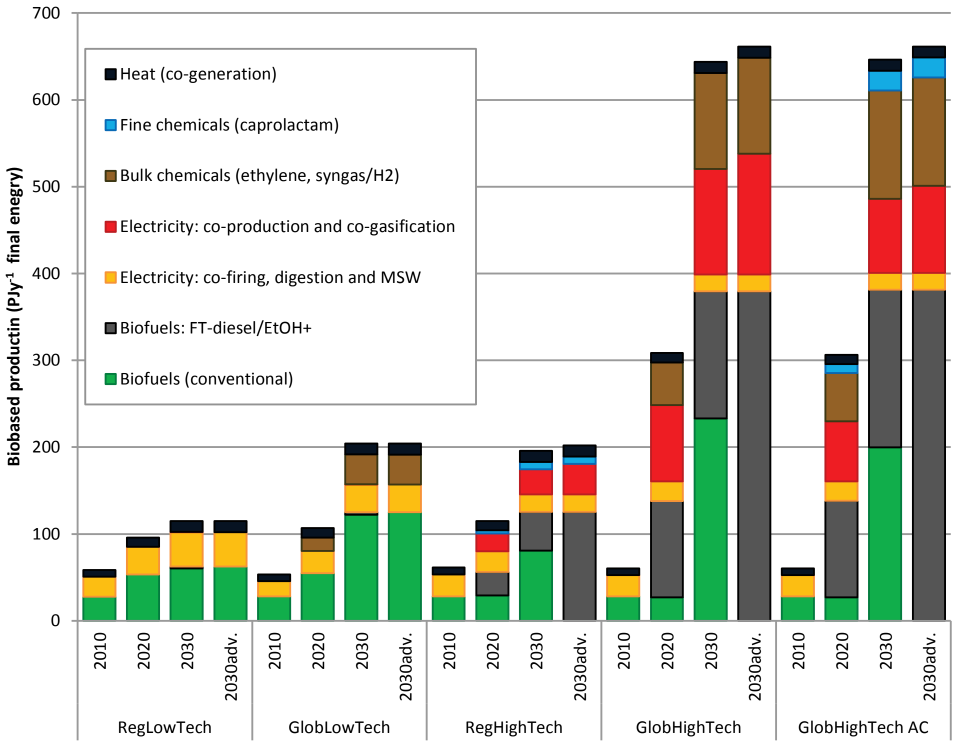

Figure 3-4 Bio-based production of electricity, transport fuels and chemicals in the scenarios (final energy).

In the NREAP of the Netherlands, the projected final contribution of renewable energy is projected to increase to 310 PJ in 2020 of which 155 PJ is produced from biomass or organic residues [13]. In this , the projected generation of electricity from biomass ranges from 26 PJ in the GlobLowTech scenario to 110 PJ in the GlobHighTech scenario in 2020 compared to 60 PJ electricity from biomass in the NREAP. The LowTech scenarios are more conservative on the share of co-firing in existing pulverized coal plants (10 %) compared to the NREAP. The NREAP, on the other hand, does not include co-generation of electricity with 2nd generation biofuel production and syngas based chemical production resulting in higher electricity generation in the High-tech scenarios.

Transport fuels from biomass in the NREAP in 2020 include 32 PJ from biomass and 6 PJ from other sources (mainly electricity). Although bio-based blending shares in the transport sectors for 2020 in the Lowtech and RegHighTech scenarios are similar to the blending targets in the NREAP (10 %), biofuel production in these scenarios is significantly higher (53–55 PJ in 2020) compared to the NREAP of the Netherlands as a result of increasing final demand of transport fuels as projected in this study (Appendix Table A6). Furthermore, double counting of biofuels from wastes or lignocellulosic biomass and residues under Article 21.2 of the Renewable Energy Directive [36], as considered in the NREAP to meet the 10 % blending target, was not taken into account in this study.

With up to 39 PJ heat generation from biomass in the NREAP, the amount of heat generation from CHP plants taken into account in this is relatively small (11 PJ heat in all scenarios in 2020). The increase of biomass heat generation in the NREAP is mainly related to heat from biogas (increasing from 2 PJ in 2005 to 12 PJ in 2020). In this study, biogas is assumed to be used in CHP plants (2.4 PJ electricity and 2.1 PJ heat in all scenarios in 2020).

3.3.2 Required biomass

To meet the bio-based substitution targets in the scenarios, large amount of biomass are required including biomass residues, forestry products and dedicated energy crops as depicted in Figure 3-5. In the scenarios calculated, biomass consumption for energy and bio-based chemicals is projected to increase from 124 PJ in 2010 to 182–191 PJ in 2020 under the RegLowTech scenario. In the LEITAP projections, considerable amounts of vegetable oils and sugar crops are still used for the production of biofuels in the HighTech scenarios (43 % vegetable oil based biofuel of total biofuel production in 2030, GlobHighTech). This is mainly due to diffusion constraints of second generation biofuels as projected with LEITAP. The total amount of required biomass is lower in the LEITAP projections compared to the 2030Adv. results, because vegetable oils have a higher biomass-to-biofuel conversion efficiency (η=~100 %) than lignocellulosic biomass (η=41–44 %).

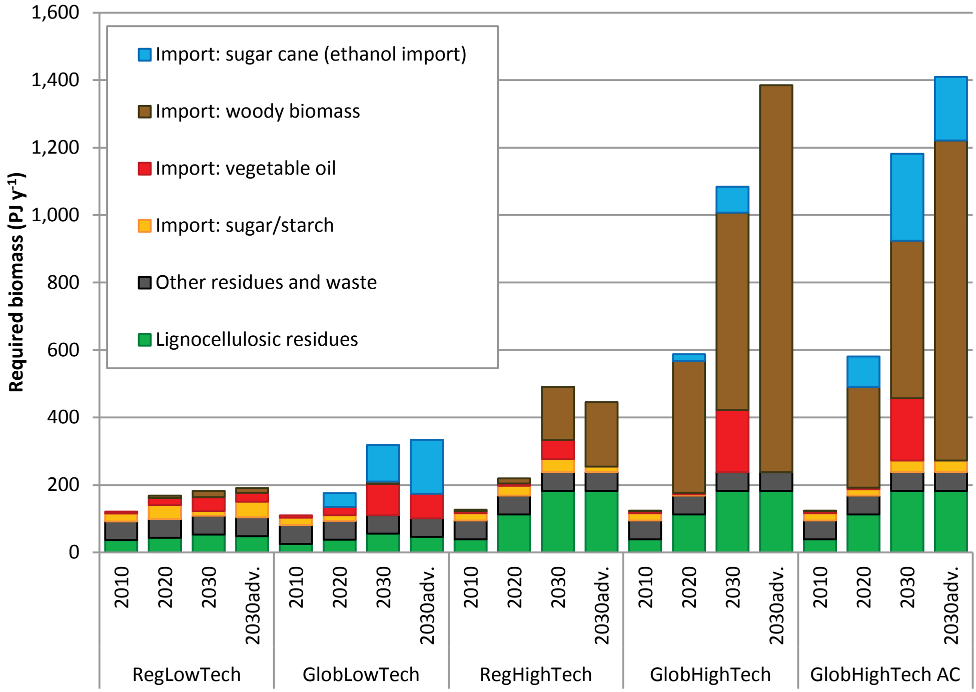

Figure 3-5 Biomass required for bioenergy and bio-based chemicals in the scenarios (PJ biomass feedstock).

Under more ambitious targets, biomass demand could increase to 1410 PJ in 2030 under the GlobHighTechAC scenario, an amount equivalent to 80 million tons of wood pellets. In 2009, the Netherlands imported almost 1 million tons of wood pellets [33] and future estimated imports of solid biomass for Europe as a whole is projected to increase to 80 million tons in 2020 [37]. Although the LEITAP model projects that the required biomass will almost entirely be imported to the Netherlands under all scenarios, the bottom-up resource assessments indicates that domestic residues could contribute for a major share and could be almost sufficient to meet the total demand for biomass in the RegLowTech scenario. Also the Dutch NREAP confirms that significant amounts of biomass could be mobilized from domestic resources in the Netherlands (189–245 PJ primary biomass, depending on the scenario in 2020).

3.3.3 Biomass trade, required land and trade balance

The domestic production of dedicated energy crops varies in the scenarios between 180 M€ (RegLowTech) and 720 M€ (GlobHighTechAC). Although this is substantial, these values are modest compared to the required imports of biomass to meet the demand for bioenergy and bio-based chemicals in the scenarios. Figure 3-6 and Figure 3-7 show the composition and total imports of biomass crops for all purposes to the Netherlands in monetary terms and estimated required land, respectively. Although these figures include also import for other sectors, e.g. food and feed, the main changes relative to 2006 are due to the use of biomass for bioenergy and bio-based chemicals that increase from 3 % in 2006 to over 50 % in 2030.

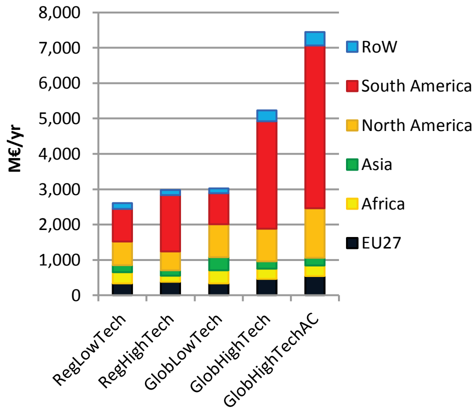

Figure 3-6 Composition of all biomass crops imported to the Netherlands in the different scenarios in 2030 (LEITAP projections).

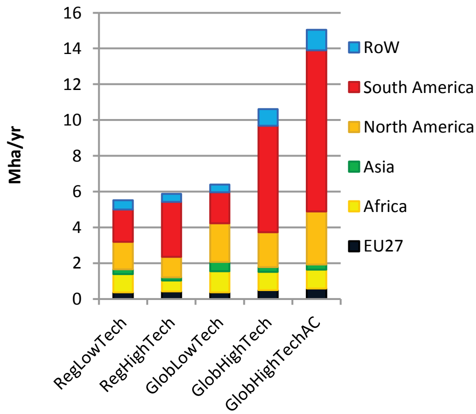

Figure 3-7 Estimated required land for all biomass crops imported to the Netherlands in the different scenarios in 2030 (LEITAP projections).

The largest shares of imported biomass in the national scenarios are still expected to originate from non-EU countries (mainly South America), even under the RegLowTech or RegLowTech scenarios. Under these two scenarios, the Armington elasticities are set at low levels and imports require large price differences between domestic and international markets. However, limited land availability and related high price of EU biomass sources, as projected in LEITAP, outweigh the Armington elasticities imposed on non-EU biomass sources. In case of the GlobHighTechAC scenario LEITAP projects that 93 % will be imported from non-EU countries and almost 7 % will be imported from EU countries. Total required land increases to 15 million hectares in the GlobHighTechAC scenario compared to 9.5 million hectares in a noBFD scenario in 2030. This implies that about 5.5 million additional hectares will be used for bioenergy crop production globally to meet the blending targets of biomass in the GlobHighTechAC scenario.

Most of the additional imports are projected to come from South America as a result of relatively large land reserves in these regions, especially in Brazil [38]. These export regions, including South America as one of the major sources of biomass, are subject to major concerns on the negative effects of biomass projection for biofuels on (in-)direct land use change and increasing prices for competing food and material markets. To analyse these effects, larger regions than the Netherlands should be taken into account. If the bio-based blending targets of the GlobHighTech and GlobHighTechAC scenarios would be implemented in more countries than the Netherlands however, the efforts required to guarantee the sustainable supply of biomass sources would be large. Moreover, an increased demand for ‘cheap’ biomass resources from other world regions would increase their price with repercussions for the profitability of bio-based technologies and the economic benefits that their increased deployment would bring.

All scenario results show a decline in the trade balance of the Netherlands (Figure 3-8) which is the result of LEITAP projecting increased GDP growth in the Netherlands as a result of the model calibration (up to 60 % GDP increases between 2006 and 2030). This growing GDP results in parallel growth in imports to the Netherlands, whereas Dutch exports increase by 12 % only. These macro-economic developments are not related to any bio-based scenario and are based on the model calibration process and the impact of biomass is better represented by the difference between the reference (no biomass policy) scenario and the bio-based scenarios. Recent economic developments, resulting in a small to negative GDP growth in 2009–2012, also indicate that the future increase in GDP might be much smaller than projected here. From these figures it can be concluded that, although the overall trend is not related to the bio-based scenarios and very uncertain, all bio-based scenarios have a positive effect on the trade balance of the Netherlands and reduce the decreasing trend of the trade balance. This positive difference ranges from 2000 M€ in the RegLowTech scenario to 7400 M€ in the GlobHighTechAC scenario in 2030. This positive difference in the trade balance is mainly the result of avoiding the import of (expensive) fossil energy carriers by importing relatively cheap bio-based energy carriers.

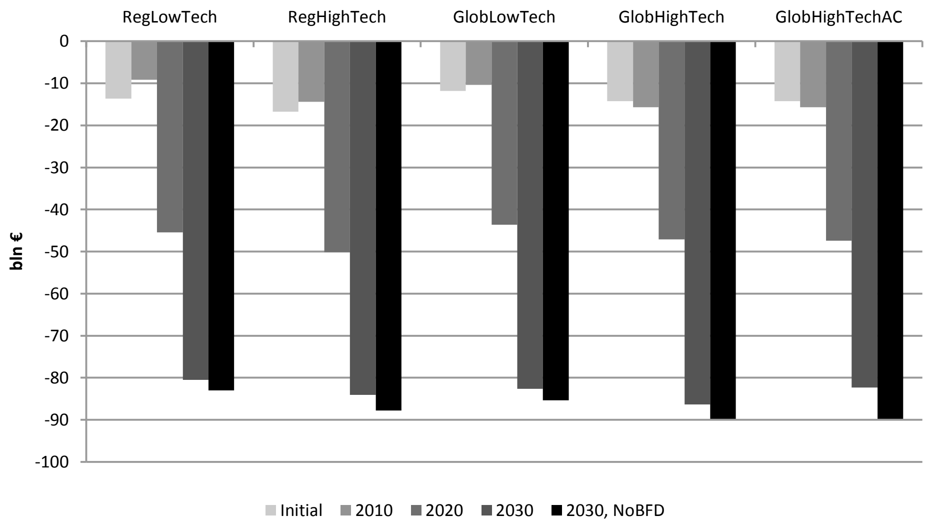

Figure 3-8 Trade balance of the Netherlands in bln €.

3.3.4 Fossil energy and greenhouse gas mitigation

Figure 3-9 and Figure 3-10 show the fossil primary energy avoided by bio-based substitution in 2030. Avoided fossil primary energy ranges from 136 PJ in the RegLowTech up to 790 PJ in the GlobHighTech scenario (2030Adv). GHG mitigation, as depicted in Fig. 10, ranges from 10 Mt CO_2 in the RegLowTech scenario to 46 Mt CO_2 in the GlobHighTech scenario (LEITAP projections) and 53 Mt CO_2 (2030Adv.) in 2030. The mitigation potential is higher in the scenarios with 100 % biofuels from lignocellulosic biomass (2030Adv.), as a result of the better environmental performance of second generation technologies.

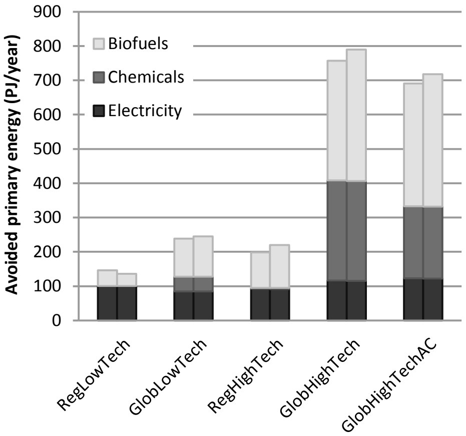

Figure 3-9 Avoided fossil primary energy in 2030, LEITAP projections (left columns), 100 % advanced biofuels in 2030 (2030Adv.) (right columns).

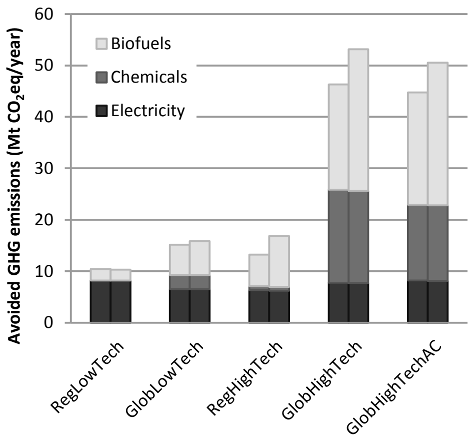

Figure 3-10 Greenhouse gas mitigation in 2030, LEITAP projections (left), 100 % advanced biofuels in 2030 (2030Adv.) (right columns).

The production of advanced bio-based chemicals and second generation biofuels, and related co-generation of electricity, results in large CO_2 reductions in the GlobHighTech and GlobHighTechAC scenarios of over 27 % compared to 2006 [39]. Despite efficient co-gasification of biomass in the HighTech scenarios, the difference between carbon mitigation in the electricity sector is low due to replacement of carbon-intensive coal in the LowTech scenarios vs. replacement of natural gas in the HighTech scenarios.

3.3.5 Required expenditures and mitigation costs

The total cost of the bio-based production of electricity, transport fuels and chemicals from biomass is calculated with the spread sheet tool. Although this tool includes detailed data on the techno-economic performance of biofuel conversion systems, bottom-up feedstock cost estimates are based on literature review and do not reflect price changes due to changes in supply and demand. It was however infeasible to use the projected commodity prices of the LEITAP model as the used version of the LEITAP model does not provide commodity specific prices. Figure 3-11 displays the total annualized costs of bio-based production, based on the specific cost parameters per technology (Appendix A) and the bio-based production rate (Figure 3-4). The total costs range between 1480 M€ (RegLowTech) and 9255 M€ (GlobHighTechAC, 2030Adv.). There are two important differences between the bottom-up costs as calculated with the spread sheet tool and the prices of bio-based production as calculated with LEITAP: (i) LEITAP calculates biomass prices whereas the BU-model is based on production cost of biomass; (ii) only the BU-model includes biomass residues from cheap, domestic sources. These residues represent a considerable share of the total biomass demand in the scenarios ranging from 17 % in the GlobHighTechAC scenario to 56 % in the RegLowTech scenario in 2030.

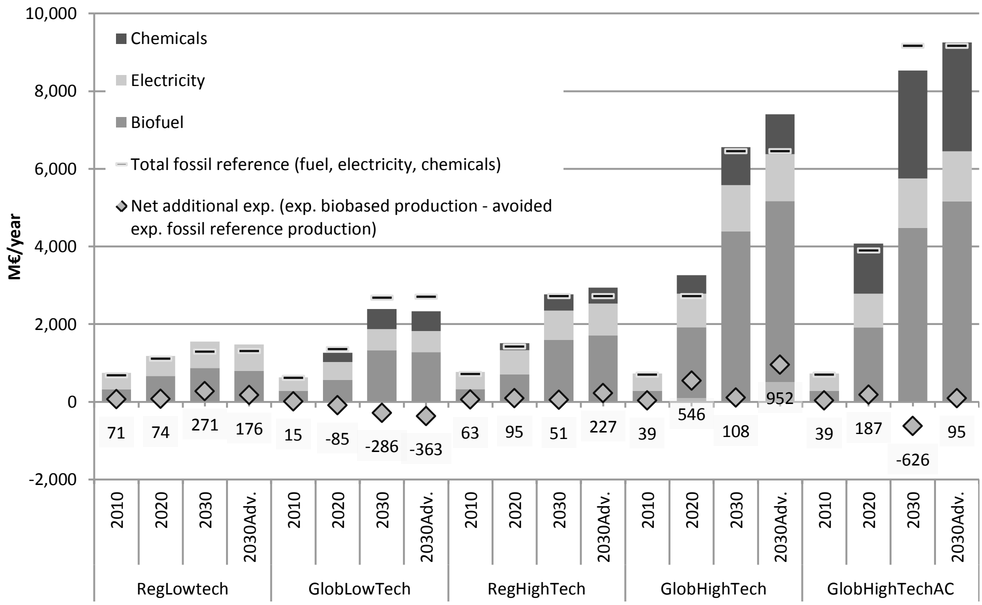

Figure 3-11 Development of required expenditures for bioenergy and bio-based materials (annualized) in the scenarios, calculated with the Excel tool relative to the fossil reference systems in million € per year and an assumed constant oil price of 75 US$/bbl.

3.3.6 Value added in agriculture and bio-based sectors in the Netherlands

In the scenarios, enforced biomass use and related demand results in additional added value of 26 to 335 M€ in the Dutch agricultural sector compared to scenarios without binding biomass blending targets (NoBFD) in 2030 (Figure 3-12). Depending on the scenarios, 3 % to 5 % of agricultural employment will be related to the production of biomass for bioenergy or bio-based chemicals in 2030 (Figure 3-13). Total employment in the agricultural sector is however projected to half regardless of the scenario mainly due to labour productivity improvement. Bio-based production will ease the burden of structural changes, but will not change the decreasing trend in employment in the agricultural sector in the Netherlands.

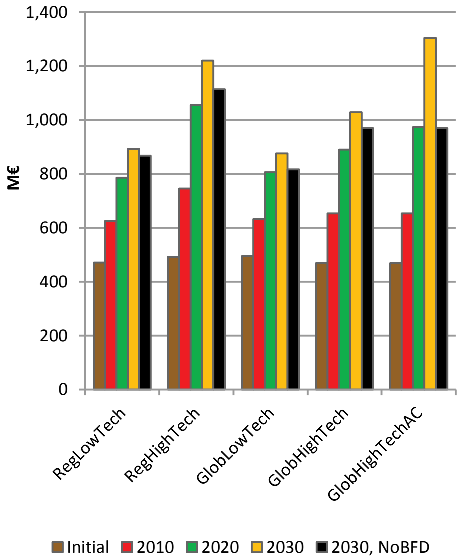

Figure 3-12 Agricultural value added in biomass production in the Netherlands.

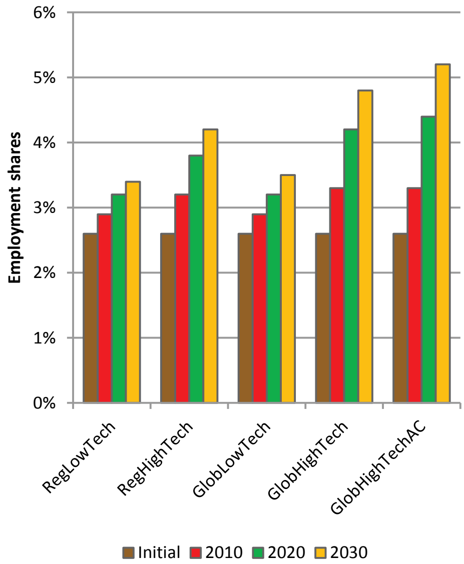

Figure 3-13 Share of employment in biomass production used for bioenergy and bio-based chemicals.

The added value in industries related to bio-based production, i.e. electricity, transport fuels and chemicals, is projected to increase in all scenarios (Figure 3-14). These figures include income from non-bio-based and bio-based sectors. The share of bio-based income in these industries, as depicted in Fig. 15, are the largest in the GlobHighTechAC scenario due to the quantities of bio-based production in the chemical industries. The results indicate that a shift to higher shares of biomass in these industries results in additional value added of up to 100 M€ (GlobLowTech) to 1300 M€ (GlobHighTechAC) compared to the reference scenario. Note that these sectors do not show the economy wide effects of subsidies that counter finance the higher price for bio-based production.

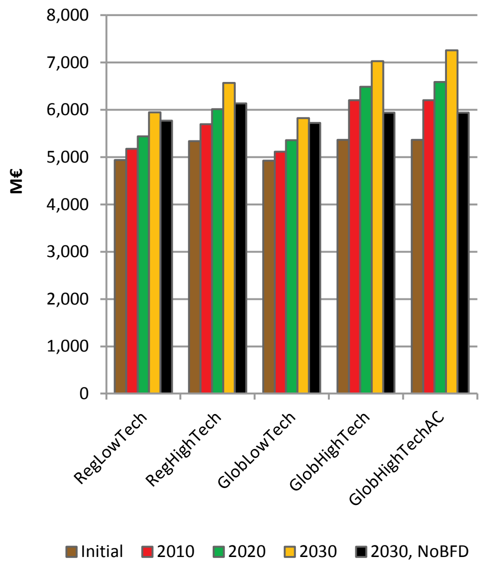

Figure 3-14 Total value added in petrol, electricity and fine chemical sectors in the Netherlands.

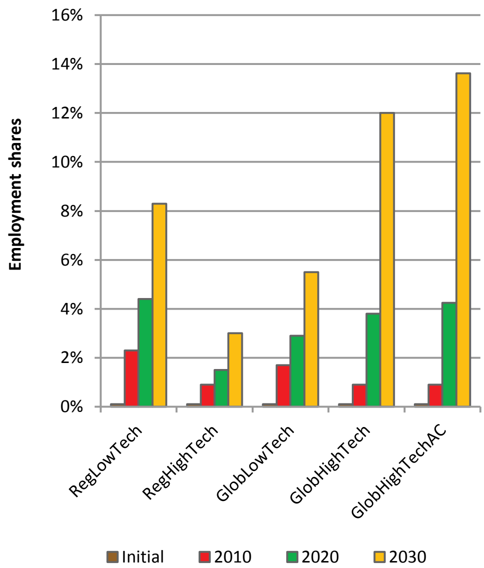

Figure 3-15 Share of employment in bio-based production relative to total employment in petrol, electricity and fine chemical sectors in the Netherlands.

3.3.7 Sensitivity analysis

The sensitivity analysis show the impact of higher and lower prices of fossil fuel on the income generated in bio-based industries, on the Dutch trade balance (Table 3-3) and the required tax burden, to meet the mandatory blending shares for biofuels (Table 3-4). Fossil fuel prices are assumed to range with −25 % and +50 % relative to the base case assumptions of crude oil 75 US$/bbl crude oil. All other assumptions are kept unchanged.

Table 3-3 Sensitivity scenarios: value added in bio-based industries and balance in total trade in the Netherlands for the GlobHighTech scenario.

	Year	GlobHighTech	GlobHighTech (oil = 112 US$/bbl)	GlobHighTech (oil = 56 US$/bbl)
		M€	% change	
Income in bio-based industries*	2010	6204	0.7 %	-0.3 %
	2020	6489	4.4 %	-2.1 %
	2030	7026	12.0 %	-4.8 %
Balance in total trade in the Netherlands	2010	-15664	1.4 %	-1.4 %
	2020	-47105	2.2 %	-2.5 %
	2030	-86314	6.1 %	-5.5 %

*) Electricity, petroleum products and chemical industries.

Table 3-4 Tax burden of using biomass inputs for liquid petroleum products in the Netherlands in 2030 for the base scenarios and sensitivity scenarios.

	RegLow-Tech	GlobLow-Tech	RegHigh-Tech	GlobHigh-Tech	GlobHigh-TechAC	GlobHighTech (oil = 112 US$/bbl)	GlobHighTech (oil = 56 US$/bbl)
Fuel consumption (mill. liters)	14218	14035	14364	14286	14160	13286	14786
Substitution share in %	10	20	20	60	75	62	60
Amount of biofuel (mill. liters)	1422	2807	2873	8572	10620	8237	8872
Subsidies, M €	578	347	828	293	421	121	521
€/liter of biofuel	0.407	0.124	0.288	0.034	0.040	0.015	0.059

The bottom-up mitigation costs, as depicted in Fig. 16, are sensitive to fossil fuel prices. For crude oil prices of 56 US$/bbl, the mitigation costs are lowest in the GlobLowTech scenario due to relatively cheap imports of sugar cane-based ethanol from Brazil that reduces the costs of ethanol for transport fuels and for ethylene production. For crude oil prices of 75 US$/bbl, apart from the RegLowTech scenario, all bio-based transport fuels and chemicals are competitive with their fossil counterparts, resulting in negative mitigation costs up to −19 €/t CO_2. For crude oil prices of 112 US$/bbl, which is almost similar to the projected oil price of the IEA World Energy Outlook 2009 for 2030 (115 US$2008/bbl) all scenarios have net negative mitigation costs up to −89 €/t CO_2 (GlobHighTechAC). Note that prices of electricity are sensitive to coal and natural gas price fluctuations. Also capital and O&M cost have proven to increase with increasing fuel prices. The relation between fossil fuel prices and capital cost and operation cost of fossil energy plants are not assessed here, but could have a net positive or negative influence on competitiveness of bio-based technologies.

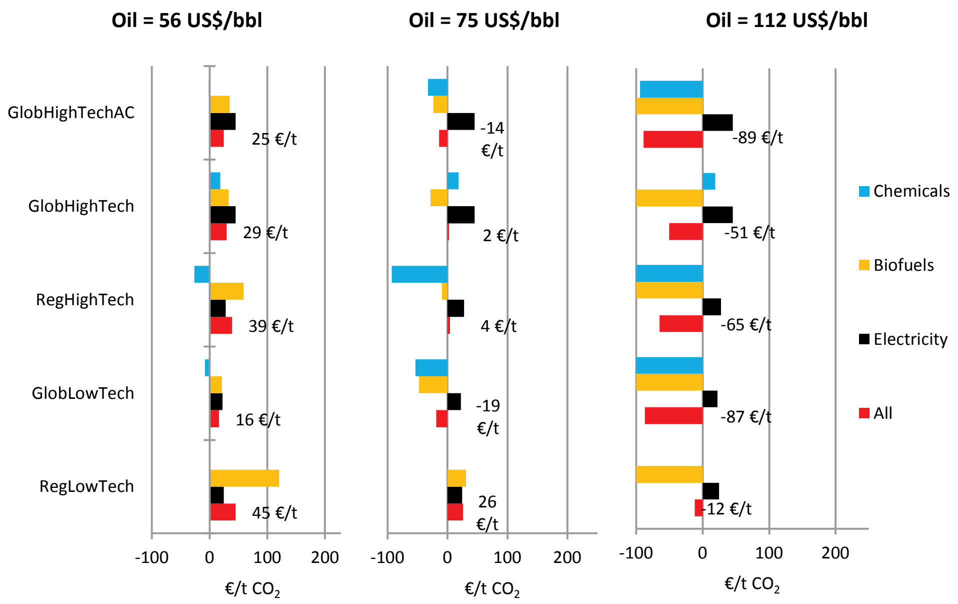

Figure 3-16 Specific greenhouse gas mitigation cost calculated with the spreadsheet tool for oil = 56 US$2006/bbl, 75 US$2006/bbl (base scenario), 112 US$2006/bbl.

Under higher fossil energy prices the Dutch trade balance will further deteriorate due to higher expenses for energy imports while lower energy prices will lower the Dutch trade deficit, but the net positive impacts of biomass will also increase due to the substitution of expensive crude oil imports to the Netherlands by biomass (Table 3-4). The lower profitability of biomass crops – due to lower fossil energy prices – will lead to higher subsidies on biomass inputs, even under the GlobLowTech scenario.

The increase in demand of biomass crops in the bio-based sectors to 2030, positively affects income generated in those sectors. Under the GlobHighTech scenario, with oil prices of 112 US$/bbl, total income in the bio-based industries is around 800 M€ higher as compared to the GlobHighTech base scenario. Lower energy prices reduce total income in the bio-based sector which is due to changes in the relative factor prices. With higher demand for biomass inputs in the bio-based industries the composition of biomass remains unchanged. However, the level of fossil energy prices determines the competitiveness of biomass inputs relative to fossil inputs in the bio-based sectors. The lower the fossil prices the more 'costly' the use of biomass inputs. Blending shares are set as minimum blending requirements for the bio-based sectors and without these mandatory minimum blending requirements less biomass would be used in all scenarios. Higher fossil energy prices increase the relative competitiveness of biomass inputs. The sensitivity analysis shows that under the GlobHighTech scenario with high fossil energy prices, the required subsidies become very low see following Table 3-4.

To estimate the cost of bio-based substitution in the scenarios, LEITAP calculates the amount of subsidies required to meet the blending targets and also the total cost of imported biomass based on the prices of these commodities. The net profits/required support levels to meet the bio-based blending targets in the different scenarios differ strongly depending on the technologies applied, the availability of biomass from non-EU regions, and the prices of fossil energy carriers. With crude oil price of US$75/bbl, the results in results in Table 3-4 show that the availability of high technology and of non-EU biomass resources would strongly reduce the cost of biofuel production. With reduced oil prices (56 US$/bbl), the subsidy in the GlobHighTech scenario increases to 0.059 €/L. With a higher crude price (US$112/bbl), the required subsidy decreases to 0.015 €/L which implies that hardly any subsidy is needed if competing with high fuel prices.

3.4 Discussion and conclusion

This analyses the effects of large scale substitution of fossil resources by biomass for energy and materials on mitigation of fossil energy and CO_2 emissions, trade balance, added value in relevant sectors and cost on a national level for the Netherlands. For this purpose, the macro-economic CGE model LEITAP was used to address multi-sector changes relevant for bio-based industries and changes in imports of fossil and bio-based energy carriers. Especially for an open economy, such as the Netherlands, these multi-regional interactions are important to address, as the Netherlands depends to a large extent on foreign trade. An Excel spread sheet tool was used to complement LEITAP with the required discrete sectoral details, such as technology substitution, technological change and physical flows of fossil and bio-based commodities. The scenarios differ mainly for two key variables: the rate of technological change and the degree of trade orientation. These variables result in different biomass shares limited by supply of imported biomass sources and the availability of advanced conversion technologies. Under the RegLowTech scenario, on the one hand, we assume low technology development and a focus on regional trade, whereas on the other hand, the GlobHighTech and GlobHighTechAC scenario includes enhanced technological development and further globalization of trade with single, or multiple, replacement of chemicals by biomass, respectively.

Overall, the results indicate that pursuing a substitution of fossil energy with biomass by up to 30 %, producing 660 PJ bio-based energy and bio-based chemicals in 2030, as aimed for by the energy transition platform 'Bio-based Green Materials' in the Netherlands, could result in major reductions in GHG emissions (up to 53 Mt CO_2eq) and decreased fossil-fuel dependency (avoiding 790 PJ primary fossil fuels) with synergetic positive impacts on economic activities in agriculture, energy and chemical industry sectors and the trade balance of the Netherlands. However, the magnitude of these positive impacts depends strongly on the rate of technological development and mobilization of international, sustainable biomass resources and the price of biomass sources relative to the price of fossil energy carriers. To achieve these targets, the estimated required biomass could be up to 1410 PJ as calculated with the spread sheet tool, of which 80 % has to be imported. The LEITAP results indicate that biomass will be imported mainly non-EU resources, with South America to become the major supplier of biomass.

Total final demand for energy and non-energy use increases in all scenarios ranging from 11 % between 2006 and 2030 in the RegLowTech scenario to up to 29 % between 2006 and 2030 in the GlobHighTechAC scenario based endogenous projections of the LEITAP model (Appendix Table A6). This does imply that, due to the increased final energy demand, the absolute mitigation of fossil primary energy demand between 2006 and 2030 is partly dampened by the absolute increase in primary energy demand. This shows the importance for energy efficiency measures and policies next to renewable energy support policies.

The results show that sub-sectoral changes, due to technological change, and due to changes in commodities, i.e. from fossil-energy carriers to renewable-energy carriers, have a major impact on the trade balance of the Netherlands and employment levels in bio-based industries. Combining the CGE model LEITAP with a spread sheet based BU-model illustrates the importance of improving the representation of bio-based energy and material conversion options and related commodities at the micro-level to account for macro-economic changes. The spread sheet tool provides detailed insights into the costs and performances of biomass-conversion technologies, future technology change and the impact of substitution of first generation technologies with advanced, second generation, biomass conversion technologies taking co-production of by-products and co-generation of energy into account. On the other hand, LEITAP provides insights into the multi-sector changes, global supply of biomass resources and new activities that occur due to shifts from fossil-energy carriers to biomass.

It should be emphasized that this focuses on the national impact of large-scale substitution of fossil resources by biomass. To guarantee for sustainable biomass supply with the large amounts of biomass required, more insight is required in global impact assessment, including, most importantly, direct and indirect land use change and impact on competing markets for biomass resources and resulting biomass prices. This requires, in the first place, an improved representation of biomass-conversion technologies including by-products such as DDGS or soy bean meal, mainly from first generation biofuels and second generation technologies with related co-generation of electricity or heat. Future versions of GTAP will likely include extended SAMs with disaggregated biomass sectors for bio-based electricity and biofuels. This research also indicates that bio-based chemicals or concepts of bio-refineries that produce multiple outputs from biomass such as chemicals and biofuels or electricity could become cost effective, have a positive impact on value added and the trade balance by substituting high-cost fossil-energy carriers with relatively low cost bio-based commodities that can be converted to advanced bio-based materials. In addition to bioenergy, it is therefore important to improve the representation of bio-based materials in economic models.

Regarding the modelling approach in this study, further improvements could be made which include:

- Capital expenditures of new technologies are not modelled adequately in LEITAP. This is of main importance for capital-intensive technologies that use relatively low price feedstock which might be used for second generation biofuel production. Further integration of these parameters would result in higher costs for these technologies, but would also result in cross-sector positive economic effects due to investments in complex, capital intensive technologies. Ragwitz et al. [43] found that investments in capital intensive renewable energy technologies in the EU-27 could have positive macro-economic impacts on the Netherlands. The latent technologies approach [20] would be more realistic for advanced technologies than the implicit approach used in LEITAP.
- The SAM (Social Accounting Matrices) database used for this was derived from GTAP 6 with 2001 as base year. One of the major limitations of this database is that in 2001, biomass use for bioenergy was still very moderate. Little data on trade and production of bioenergy is therefore included in this database. Although we have updated the bio-based sectors to 2006 using statistical data, newer versions of GTAP include the recent global activities in bio-based sectors that have increased significantly [20].
- Apart from a modified GTAP-E version that was used for this , first efforts are also made to include first generation biofuels by disaggregating the SAMs of GTAP to include biofuels, by splitting biodiesel from the vegetable and oil seeds sector and ethanol from the food processing and chemicals, rubber and plastics sectors (GTAP-BIO) [40, 41]. Also the GTAP-BIO model is based on GTAP 6 which implies little activities on biofuels in the base year (2001), limitations on data (e.g. country-specific figures on biofuel production) [20] and no representation of second generation technologies. However, future efforts to include current biomass trade and advanced conversion technologies that have increased significantly since the last update of the SAMs could be valuable to assess the impact of bioenergy under pre-conditions that more data is available in the future.
- Agricultural residues and by-products, such as meal from oilseed crushing and dried distillers' grain with solubles (DDGS) from ethanol production are only taken into account in the BU-model and not in the LEITAP version applied for this analysis. Although the results on primary energy, GHG emissions and BU cost projections include by-products, the production of by-products can also have potential impacts on other sectors and land requirements.
- The impact of large scale deployment of biomass on direct and indirect land use change was not assessed in this study, but could be significant, especially when larger regions with increased demand for biomass are studied. Studies, including LEITAP, show that biofuel production induces land use change resulting in significant amounts of carbon release [42]. These emissions could reduce the GHG mitigation potential or even result in negative reduction of GHG emissions.

Another limitation of this study is the focus on bio-based technologies. The EmployRES study [43] analyses the economic impact of Renewable Energy (RES) supporting policies for the EU27. For the Netherlands they found that strong support of RES technologies resulted in increased employment in knowledge-intensive generation technologies due to the related investments. Moderate RES-supporting policies result in employment via biofuels. The EmployRES study does not take bio-based production of chemicals into account, but it considers other renewable technologies such as wind and photovoltaics that could generate potential economic activities in the Netherlands.

Appendix Chapter 3

Table A 3-1 Fossil and bio-based feedstocks.

Feedstock	Fossil fuel prices and biomass cost (€/GJ)[a] Year 2010	2020	2030	Primary energy (fossil)[a] GJ_p/GJ	Fossil GHG emissions[a] kg. CO_2/GJ	References
Natural gas	6	6	6	1.10	3.33	[35]
Coal	2	2	2	1.04	10	
Gasoline[b]	13.9	13.9	13.9	1.14	12.5	
Diesel[b]	12.7	12.7	12.7	1.16	14.2	
Crude palm oil	6.89	5.85	5.71	0.08	11.02	[44, 45]
Jatropha oil	5.20	4.82	4.49	0.04	29.49	[35, 44]
Crude rapeseed oil	14.31	14.31	14.31	0.19	66.89	[44, 45]
Fat and oil residues (domestic)	7.49	7.49	7.49	0.00	0.20	[5, 35]
Sugar beet (EU)	6.82	6.82	6.82	0.09	21.82	[45, 46]
Wheat (EU)	8.55	8.55	8.55	0.16	36.87	[45, 46]
Wood (EU)	4.69	4.69	4.69	0.12	5.19	[35, 46]
Wood (tropical)	7.69	7.69	7.69	0.14	7.69	[35, 44]
Sugar cane (BR)	7.59	7.59	7.59	0.04	18.31	[45]
Wood residues (domestic)	2.53	2.53	2.53	0.01	0.49	[5, 47]
Agro. residues (domestic)	1.85	1.85	1.85	0.11	0.36	[5, 47]

a) Prices of fossil energy carrier and biomass production cost, energy requirements and GHG emissions to factory gate, including mining / cultivation and harvesting, pre-treatment and transport to the Netherlands. Transport based on (JEC 2007) [35]. Pre-treatment includes oil pressing (Dornburg et al. 2007) [44] and pelletization (Hamelinck et al. 2005) [66].

b) Based on crude oil = 75 USD_{2006}/bbl, $USD_{2006}/€_{2006}$ = 0.80, refining costs = 20 $\%_{mass}$ (Wielen et al. 2006) [69]. Note that the scenarios are also calculated with oil prices of 56 USD_{2006}/bbl and 112 USD_{2006}/bbl.

Table A 3-2 Technical and economic specifications of biomass conversion technologies: Electricity.

Technology	Year	Capex	Opex	Efficiency (lhv)	CoE[a]	Avoided[b] Fossil energy	GHG	References
		€/kWe	€/GJ		€/GJ[c]	GJp/GJe[c]	kg. CO_2/GJe[c]	
NGCC	2010	500	1.3		13.2			
	2020	450	1.3	60 %	12.6			[48]
	2030	450	1.2	63 %	12.1			
NGCC co-gasification (25 %)	2010	697	5.0	52 %	14.4 - 15.7	0.25 - 0.26	14 - 17	
	2020	617	5.0	56 %	13.4 - 14.6	0.31 - 0.31	17 - 19	[48-50]
	2030	592	5.0	60 %	12.7 - 13.7	0.32 - 0.32	18 - 20	
PC	2010	1182	8.7	46 %	11.7			
	2020	1100	8.1	49 %	11.0			[48]
	2030	1053	7.4	52 %	10.3			
PC co-firing (20 %)	2010	1207	9.2	46 %	12.5 - 13.4	0.40 - 0.45	43 - 45	
	2020	1125	8.7	49 %	11.7 - 12.6	0.37 - 0.42	40 - 42	[44, 48, 51]
	2030	1078	8.0	52 %	11.1 - 11.9	0.35 - 0.40	38 - 40	
MSW	2010	2700	1.4	29 %	17.3	3.99	160	
	2020	2700	1.4	29 %	17.3	3.99	160	[52, 53]
	2030	2700	1.4	29 %	17.3	3.99	160	
CHP (digestion)	2010	3700	58.0	15 %	28.9	2.00	166	
	2020	3700	58.0	15 %	28.9	2.00	166	[51, 54]
	2030	3700	58.0	15 %	28.9	2.00	166	

a) Discount rate: 10 %, lifetime: 20 years, load factors: NGCC (Co-gasification) and MSW 6000 h/yr, PC (Co-firing) 7000 h/yr, Co-digestion 7500 h/yr.

b) Avoided fossil primary energy and avoided GHG emissions relative to the life cycle fossil reference systems (cradle to factory gate).

c) The chain performance depends on the biomass feedstock used. The lower bound is for agricultural or woody residues whereas the upper bound is for SRC (willow) cultivated in Europe.

Table A 3-3 Technical and economic specifications of biomass conversion technologies: transport fuels.

Technology	Year	Capex	Opex	Efficiency (lhv)		CoF[a]	Avoided[b]		References
		€/kW$_f$	€/GJ	Fuel	Electricity	€/GJ	Fossil energy GJ$_p$/GJ$_f$[c]	GHG kg. CO_2/GJ$_f$[c]	
FAME (veg. oil)[d]	2010	154	1.02	101 %		5.7 - 14.7	0.8 - 0.9	26.2 - 42.9	[44, 55-57]
	2020	141	1.00	101 %		6.0 - 15.4	0.8 - 0.9	26.2 - 42.9	
	2030	136	1.00	101 %		6.5 - 16.2	0.8 - 0.9	26.2 - 42.9	
FAME (oil and fat residues)[d]	2010	232	1.11	101 %		8.3	0.9	92.9	[58]
	2020	211	1.09	101 %		9.0	0.9	92.9	
	2030	204	1.08	101 %		9.8	0.9	92.9	
EtOH from starch (wheat)	2010	515	0.45	52 %		13.6	0.2	22.2	[56, 59]
	2020	515	0.45	52 %		13.2	0.2	22.2	
	2030	515	0.45	52 %		13.1	0.2	22.2	
EtOH from sugar (sugar beet)	2010	597	1.29	45 %		9.5	0.3	29.4	[58, 60]
	2020	579	1.25	45 %		9.4	0.3	29.4	
	2030	548	1.18	45 %		9.2	0.3	29.4	
EtOH from sugar (sugar cane)	2010	508	2.29	43 %		9.2	1.2	71.0	[56, 61-63]
	2020	438	1.98	44 %		8.5	1.2	71.0	
	2030	378	1.70	45 %		7.8	1.2	71.0	
FT- diesel[a]	2010	1879	2.87	41 %	3 %	15.0 - 19.4	1.0 - 1.1	81.1 - 85.9	[64, 65]
	2020	1425	2.18	41 %	3 %	12.5 - 16.9	1.0 - 1.1	81.1 - 85.9	
	2030	1188	1.82	41 %	3 %	11.2 - 15.5	1.0 - 1.1	81.1 - 85.9	
EtOH from lign. biomass[a]	2010	2346	5.21	33 %	3 %	17.0 - 25.8	0.7 - 1.0	66.8 - 71.6	[66]
	2020	1580	2.74	36 %	12 %	11.2 - 11.4	0.8 - 1.0	66.8 - 71.6	
	2030	1074	1.34	44 %	3 %	7.4 - 13.9	0.8 - 1.0	66.8 - 71.6	

a) Discount rate: 10 %, lifetime: 20 years, load factors: NGCC (Co-gasification) and MSW 6000 h/yr, PC (Co-firing) 7000 h/yr, Co-digestion 7500 h/yr.

b) Avoided fossil primary energy and avoided GHG emissions relative to the life cycle fossil reference systems (cradle to factory gate).

c) The chain performance depends on the biomass feedstock used. The lower bound is for agricultural or woody residues whereas the upper bound is for SRC (willow) cultivated in Europe.

d) Note that the production cost of FAME increase in the future due to the reduced value of glycerine that is co-produced (Dornburg et al. 2007) [44].

Table A 3-4 Technical and economic specifications of biomass conversion technologies: Chemicals.

Technology	Year	Capex	Opex	Efficiency		Prod. costs[a]	Avoided[b]		References
					Electricity		Fossil energy	GHG[c]	
		€/t	€/t	t/t dm	(GJ/t)	€/t	GJ_p/t	t CO_2/t	
Ethylene from sugar cane ethanol	2010	123	17	0.61		803	58.3	3.73	[67]
	2020	123	17	0.61		750	58.3	3.73	
	2030	123	17	0.61		703	58.4	3.73	
Ethylene from crude oil (via napthta)	2010	405	51	1.00		679			[67-69]
	2020	405	51	1.00		679			
	2030	405	51	1.00		679			
Caprolactam (from fermentable sugars)	2010	390	460	0.39		1473	11.9	2.63	[56, 59, 70]
	2020	390	460	0.39		1473	11.9	2.63	
	2030	390	460	0.39		1473	11.9	2.63	
Caprolactam (phenol based)	2010	700	788			1488			[71]
	2020	700	788			1488			
	2030	700	788			1488			
Hydrogen (lignocellulosic biomass)	2010	1035	352	0.05	69	1193-2301	307-355	18.51-21.37	[72, 73]
	2020	648	221	0.05	69	615-1732	313-354	18.84-21.27	
	2030	583	199	0.06	68	565-1605	312-353	18.78-21.19	
Hydrogen (natural gas, SMR)	2010	135	360	0.34		737			[74]
	2020	118	356	0.34		717			
	2030	100	352	0.34		696			

a) Discount rate: 10 %, lifetime: 20 years, load factors: NGCC (Co-gasification) and MSW 6000 h/yr, PC (Co-firing) 7000 h/yr, Co-digestion 7500 h/yr.

b) Avoided fossil primary energy and avoided GHG emissions relative to the life cycle fossil reference systems (cradle to factory gate).

c) The chain performance depends on the biomass feedstock used. The lower bound is for agricultural or woody residues whereas the upper bound is for SRC (willow) cultivated in Europe.

Table A 3-5 Armington Elasticities in the Reg (Normal) and Glob (International - high) scenarios in LEITAP.

Sector		1st Level: Elasticity of substitution between domestic and aggregated imports		2nd Level: Elasticity of substitution amongst different importing origins	
		'Normal'	High levels in Scenario 'International - high'[1]	'Normal'	High levels in Scenario 'International - high'[1]
ESBD/ESBM		ESUBD	ESUBD	ESUBM	ESUBM
1 pdr	Paddy rice	3.63	5.4	5.95	8.85
2 wht	Wheat	4.45	6.6	8.9	13.4
3 grain	Cereal grains nec	1.3	1.95	2.6	3.9
4 oils	Oil seeds	2.45	3.75	4.9	7.35
5 sug	Sugar cane and beet, sugar	2.7	4.05	5.4	8.1
6 hort	Vegetables, fruit, nuts	1.85	2.85	3.7	5.55
7 wdcrp	Woody crops	3.09	4.65	6.17	9.3
8 othcr	Other crops	3.09	4.65	6.17	9.3
9 cattle	Cattle	3.29	4.95	7.44	11.1
10 oap	Animal products nec	2.69	4.05	7.08	10.6
11 milk	Raw milk	3.65	5.4	7.3	10.9
12 dairy	Diary products	3.65	5.55	7.3	10.9
13 sugar	Sugar	2.7	4.05	5.4	8.1
14 vol	Vegetable oils and fats	3.3	4.95	6.6	9.9
15 ofd	Food products nec	2	3	4	6
16 agro	Other agr-food products	1.17	1.8	2.33	3.45
17 frs	Forestry	2.5	3.75	5	7.5
18 c_oil	Oil	5.2	7.8	10.4	15.6
19 petro	Petroleum products	2.1	3.15	4.2	6.3
20 gas	Gas	10.9	16.4	16.3	24.5
21 coa	Coal	3.05	4.5	6.1	9.15
22 ely	Electricity	2.8	4.2	5.6	8.4
23 fchem	Fine Chemicals	3.54	5.25	7.26	10.9
24 othind	Other industries	3.54	5.25	7.26	10.9
25 ser	Services	1.91	2.85	3.8	5.7
Total	Total	80.5	121	157	236

1) All elasticities in the international scenarios (Glob) are 50 % relative to the normal (Reg.) scenario level for all products.

Table A 3-6 Gross final energy demand and non-energy use from fossil and renewable resources in the Netherlands in the scenarios (PJ/year).

Scenario / End-use	Year 2006	2010	2020	2030
RegLowTech				
Electricity[1]	433	493	510	551
Transport[2]	491	566	626	692
Of which road transport[1]	432	497	554	624
Non-energy use[3]	582	599	651	721
Of which chemicals[4]	455	469	510	565
Heat[5]	1123	1107	1045	946
Total	2629	2765	2833	2910
GlobLowTech				
Electricity[1]	433	476	484	517
Transport[2]	491	563	625	705
Of which road transport[1]	432	497	555	626
Non-energy use[3]	582	602	663	739
Of which chemicals[4]	455	471	520	579
Heat[5]	1123	1167	1157	1042
Total	2629	2807	2928	3003
RegHighTech				
Electricity[1]	433	486	504	553
Transport[2]	491	572	639	715
Of which road transport[1]	432	497	556	627
Non-energy use[3]	582	600	659	735
Of which chemicals[4]	455	470	516	576
Heat[5]	1123	1187	1196	1182
Total	2629	2846	2998	3185
GlobHighTech				
Electricity[1]	433	467	474	510
Transport[2]	491	572	653	743
Of which road transport[1]	432	497	557	633
Non-energy use[3]	582	603	666	748
Of which chemicals[4]	455	472	522	586
Heat[5]	1123	1205	1266	1353
Total	2629	2847	3060	3354
GlobHighTechAC				
Electricity[1]	433	467	482	549
Transport[2]	491	572	655	746
Of which road transport[1]	432	497	558	636
Non-energy use[3]	582	603	666	748
Of which chemicals[4]	455	472	522	586
Heat[5]	1123	1205	1266	1353
Total	2629	2847	3069	3396

1) Baseline (CBS Statline), 2010 - 2030 results based on LEITAP projections as described in Section 3.2.4.
2) Road transport based on LEITAP projections, other transport based on the WLO scenarios (Janssen et al. 2006) [10].
3) Non-energy use of energy carriers in industries and transport (mainly lubricants). Baseline (CBS Statline), 2010 - 2030 results based on LEITAP projections as described in Section 3.2.4.
4) Non-energy use in fertilizer production, organic base chemistry, other anorganic base industry, and chemical end products. Baseline (CBS Statline), 2010 - 2030 results based on LEITAP projections as described in Section 3.2.4.
5) Final heat demand, based on WLO projections (Janssen et al. 2006) [10].

References Chapter 3

[1] IPCC. Special Report on Renewable Energy Sources and Climate Change Mitigation - Final Release. Working Group III - Mitigation of Climate Change. 2011.

[2] IPCC. Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2007.

[3] Beurskens LWM, Hekkenberg M. Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States. Renewable Energy Projections As Published in the National Renewable Energy Action Plans of the European Member States 2011.

[4] Atanasiu B. The role of bioenergy in the National Renewable Energy Action Plans: a first identification of issues and uncertainties. 2010, November 2010. 22 p. . Biomass role in achieving the Climate Change & Renewables EU policy targets. Demand and Supply dynamics under the perspective of stakeholders . IEE 08 653 SI2. 529 241.

[5] Rabou LPLM, Deurwaarder EP, Elbersen HW, Scott EL. Biomass in the Dutch Energy Infrastructure in 2030. ECN and WUR. 2006.

[6] Brehmer B, Boom RM, Sanders J. Maximum fossil fuel feedstock replacement potential of petrochemicals via biorefineries. Chem Eng Res Design 2009; 87(9): 1103-19.

[7] Melillo JM, Reilly JM, Kicklighter DW, Gurgel AC, Cronin TW, Paltsev S, et al. Indirect emissions from biofuels: How important?. Science 2009; 326(5958): 1397-9.

[8] Beckman J, Jones CA, Sands R. A Global General Equilibrium Analysis of Biofuel Mandates and Greenhouse Gas Emissions. Am J Agric Econ 2011; 93(2): 334-41.

[9] Wicke B. Indirect land use change: review of existing models and strategies for mitigation. Biofuels 2012; 3(1): 87.

[10] Janssen L, Okker R and Schuur J. Welvaart en Leefomgeving [internet]. 2006.

[11] Hoefnagels R, Dornburg V, Faaij A, Banse M. Analysis of the Economic Impact of Large-Scale Deployment of Biomass Resources for Energy and Materials in the Netherlands. Creative Energy, Energy Transition. 2009.

[12] van den Broek M, Faaij A, Turkenburg W. Planning for an electricity sector with carbon capture and storage. Case of the Netherlands. International Journal of Greenhouse Gas Control 2008; 2(1): 105-29.

[13] Government of the Netherlands. National renewable energy action plan of the Netherlands - Directive 2009/28/EC. the Netherlands; 2011. 118 p.

[14] Neelis ML, Pouwelse JW. Towards consistent and reliable Dutch and international energy statistics for the chemical industry. Energy Policy 2008; 36(7): 2719-33.

[15] Tefera N. CEH Report : Caprolactam [internet]. SRI Consulting; 2006.

[16] Haveren Jv, Scott E, L., Sanders J. Bulk chemicals from biomass. Biofuels, Bioproducts and Biorefining 2008; 2(1): 41-57.

[17] Banse M, Van Meijl H, Tabeau A, Woltjer G. Will EU biofuel policies affect global agricultural markets?. Eur Rev Agric Econ 2008; 35(2): 117-41.

[18] Burniaux J-, Truong TP. GTAP-E: An Energy-Environmental Version of the GTAP Model. 2002.

[19] Hertel T. Global Trade Analysis. Modelling and Applications. Cambridge University Press. 1997.

[20] Kretschmer B, Peterson S. Integrating bioenergy into computable general equilibrium models -- A survey. Energy Econ 2010; 32(3): 673-86.

[21] Gitiaux X, Paltsev S, Reilly J, Rausch S. Biofuels, Climate Policy and the European Vehicle Fleet. Cambridge, US; Massachusetts Institute of Technology (MIT). 2009.

[22] Kretschmer B, Peterson S, Ignaciuk A. Integrating Biofuels into the DART Model. Kiel, Germany; Kiel Institute for the World Economy. 2008.

[23] Hertel TW, Tyner WE, Birur DK. The Global Impacts of Biofuel Mandates. The Energy Journal 2010; 31(1): 75-100.

[24] FO Licht. Licht Interactive Data 2007.

[25] Eickhout B, Notenboom J, Ros JPM, Van dB, Van Oorschot M, Van Vuuren DP, et al. Local and global consequences of the EU renewable directive for biofuels. Bilthoven, the Netherlands; PBL. 2008.

[26] van Meijl H, Van Rheenen T, Tabeau A, Eickhout B. The impact of different policy environments on agricultural land use in Europe. Agric , Ecosyst Environ 2006; 114(1): 21-38.

[27] Eickhout B, Van Meijl H, Tabeau A, Stehfest E. The impact of environmental and climate constraints on global food supply. Economic Analysis of Land Use in Global Climate Change Policy. Routledge, New York. 2009.

[28] de Wit M, Faaij A. European biomass resource potential and costs. Biomass Bioenerg 2010; 34(2): 188-202.

[29] Fischer G, Prieler S, van Velthuizen H, Lensink SM, Londo M, de Wit M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. Biomass Bioenergy 2010; 34(2): 159-72.

[30] Hoogwijk M, Faaij A, de Vries B, Turkenburg W. Exploration of regional and global cost-supply curves of biomass energy from short-rotation crops at abandoned cropland and rest land under four IPCC SRES land-use scenarios. Biomass Bioenergy 2009; 33(1): 26-43.

[31] Dornburg V, Van Vuuren D, Van De Ven G, Langeveld H, Meeusen M, Banse M, et al. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy and Environmental Science 2010; 3(3): 258-67.

[32] IEA. World Energy Outlook 2008. Paris; International Energy Agency (IEA). 2009.

[33] Sikkema R, Steiner M, Junginger M, Hiegl W, Hansen MT, Faaij A. The European wood pellet markets: current status and prospects for 2020. Biofuels, Bioproducts and Biorefining 2011; 5(3): 250-78.

[34] Woltjer G, Banse M, Meijl H, Tabeau A. Alternative Approaches to Extend GTAP to Biofuel Crops 2007.

[35] JEC. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre (JRC/IES). 2007.

[36] European Commission. Directive 2009/28/EC of the European Parliament and of the Council - on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Brussels, Belgium; European Commission. 2009. 62 p.

[37] Cocchi M, Nikolaisen L, Junginger M, Goh CS, Heinimö J, Bradley D, et al. Global Wood Pellet Industry Market and Trade Study. IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. 2011. 190 p.

[38] Banse M. Analysis of the Economic Impact of Large-Scale Deployment of Biomass Resources for Energy and Materials in the Netherlands-Appendix II Macro-Economic Scenarios 2009.

[39] Van Horssen A, Kuramochi T, Jozwicka M, Koornneef J, Van Harmelen T, Ramírez A. . The Impacts of CO2 Capture Technologies in Power Generation and Industry on Greenhouse Gases Emissions and Air Pollutants in the Netherlands 2009.

[40] Birur DK, Beach RH, Hertel TW, McCarl B. Global Implications of U.S. Biofuels Policies in an Integrated Partial and General Equilibrium Framework 2010.

[41] Taheripour F, Tyner W, Hertel T, Golub A, Birur D, Baldos U, et al. Economic and Environmental Consequences of US Corn Ethanol Production: A Comprehensive Analysis 2010.

[42] Edwards R, Mulligan D, Marelli L. Indirect Land Use Change from increased biofuels demand - Comparison of models and results for marginal biofuels production from different feedstocks. Ispra, Italy; European Commission Joint Research Centre (JRC). 2010.

[43] Ragwitz M, Schade W, Breitschopf B, Walz R, Helfrich N, Rathmann M, et al. EmployRES - The impact of renewable energy policy on economic growth and employment in the European Union. Karlsruhe; 2009.

[44] Dornburg V, Faaij A, Wicke B. . Supportive Study for the OECD on Alternative Developments in Bioenergy Production Across the World: Electricity, Heat and 2nd Generation Biofuels 2007.

[45] Smeets EMW, Bouwman LF, Stehfest E, van Vuuren DP, Posthuma A. Contribution of N2O to the greenhouse gas balance of first-generation biofuels. Global Change Biol 2009; 15(1): 1-23.

[46] de Wit M, Faaij A. European biomass resource potential and costs. Biomass Bioenergy 2010; 34(2): 188-202.

[47] Kip H, Lammers E, Godthelp M, Beeks T, Daalen Wv, Dongen Av, et al. Electriciteit uit biomassa - Platform duurzame electriciteitsvoorziening werkgroep transitiepad bioelectriciteit. 2007.

[48] van den Broek, Faaij A, Turkenburg W. Planning for an electricity sector with carbon capture and storage: Case of the Netherlands. International Journal of Greenhouse Gas Control 2008; 2(1): 105-29.

[49] Zwart RWR. Technical, Economic and Environmental Potential of Cofiring of Biomass and Waste in Natural Gas Fired Turbines and Combined Cycles. Petten, The Netherlands; ECN. 2003. ECN-RX--03-003.

[50] Feber MAPC, Gielen DJ. BIOMASS FOR GREENHOUSE GAS EMISSION REDUCTION - Task 7: Energy Technology Characterisation. Petten, The Netherlands; ECN. 2000. ECN-C--99-078.

[51] IEA. World Energy Outlook 2008. International Energy Agency (IEA); 2008.

[52] Van Tilburg X, Lensink SM, Londo HM, Cleijne JW, Pfeiffer EA, Mozaffarian M, et al. . Technisch-economische Parameters Van Duurzame Energieopties in 2009-2010 2008.

[53] Afvalbedrijven V. Energie uit Afval (Energy from Waste), in Dutch. 2007.

[54] Tilburg XV, Lensink SM, Mozaffarian M, Cleijne H, Pfeiffer EA. Techno-economical Parameters of Sustainable Electricity Options in 2008. Techno-economical Parameters of Sustainable Electricity Options in 2008 2007.

[55] Rafiq A. ICIS Pricing Glycerine Europe [internet]. ICIS Pricing; 2008.

[56] Hamelinck CN, Hoogwijk M. . Future Scenarios for First and Second Generation Biofuels 2007.

[57] Berghout NA. Technological Learning in the German Biodiesel Industry; an Experience Curve Approach to Quantify Reductions in Production Costs, Energy Use and Greenhouse Gas Emissions 2008.

[58] Deurwaarder EP, Lensink SM, Londo HM. BioTrans biofuel data - Appendix to 'Use of BioTrans in Refuel'; functional and technical description. Petten; ECN. 2007. 22 p.

[59] Elsayed MA, Matthews R, Mortimer MD. Carbon and Energy Balances for a Range of Biofuel Options. Sheffield; Sheffield Hallam University, Resources Research Unit. 2003.

[60] Hamelinck CN, Faaij APC. Outlook for advanced biofuels. Energy Policy 2006; 34(17): 3268-83.

[61] Damen K. Future prospects for biofuel production in Brazil;A chain analysis comparison of ethanol from sugarcane and methanol from eucalyptus in Sao Paulo state 2001.

[62] Smeets E, Junginger M, Faaij A. Supportive study for the OECD on alternative developments in biofuel production across the world. Utrecht; 2005. Universiteit Utrecht.

[63] van den Wall Bake JD, Junginger M, Faaij A, Poot T, Walter A. Explaining the experience curve: Cost reductions of Brazilian ethanol from sugarcane. Biomass Bioenergy 2009; 33(4): 644-58.

[64] Hamelinck CN, Faaij APC, den Uil H, Boerrigter H. Production of FT transportation fuels from biomass; technical options, process analysis and optimisation, and development potential. Energy 2004; 29(11): 1743-71.

[65] Hamelinck CN, Faaij APC. Outlook for advanced biofuels. Energ Policy 2006; 34(17): 3268-83.

[66] Hamelinck CN, Van Hooijdonk G, Faaij APC. Ethanol from lignocellulosic biomass: Techno-economic performance in short-, middle- and long-term. Biomass Bioenergy 2005; 28(4): 384-410.

[67] Patel M, Crank M, Dornburg V. The BREW report, Medium and long-term opportunities and risks of the biotechnological production of bulk chemicals from renewable resources the potential of white biotechnology. Utrecht; ISI/Utrecht University. 2006.

[68] Meesters KPH. Directions to a sustainable future - TNO-report. Groningen; TNO. 2006. KvL-A R 2006/016.

[69] Wielen LAMvd, Nossin PMM, Bont JAAd, al. e. Potential of Coproduction of Energy, Fuel and Chemicals from Biobased Renewable Resources. Delft; Delft University of technology. 2006.

[70] USDA. The Economic Feasibility of Ethanol Production from Sugar in the United States. 2006.

[71] Neelis M. Database Inventory of processes in the chemical and refinery industry [internet]. Utrecht University; 2006.

[72] Hamelinck CN, Faaij APC. Future prospects for production of methanol and hydrogen from biomass. J Power Sources 2002; 111(1): 1-22.

[73] Hamelinck CN, Faaij APC. Outlook for advanced biofuels. Energy Policy 2006; 34(17): 3268-83.

[74] Rutkowski MD. M2: Excel spreadsheet model H2 production from natural gas [internet]. NREL; 2008. Available at: http://www.hydrogen.energy.gov/h2a_prod_studies.html;.

Chapter 4

The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S.

Keywords: Wood pellets; Southeast US; Bioenergy; Transport pallets; Other removals; Pole peelings

Abstract: The global demand for wood pellets used for energy purposes is growing. Therefore, increased amounts of wood pellets are produced from primary forestry products, such as pulp wood. This analysis demonstrates that substantial amounts of alternative, low-value wood resources are available that could be processed into wood pellets. For three resources, test batches have been produced and tested to qualify for industrial pellet standards. These include: primary forestry residues from premerchantable thinning operations and land clearing activities, secondary forestry residues from pole mills and post-consumer wood wastes from discarded wooden transport pallets. The total dry wood potential of these resources in the southeast of the U.S. (Florida, Georgia, North Carolina, South Carolina), was estimated to be 1.9 Tg y^{-1} available at roadside (excluding transport cost) for 22 \$ Mg^{-1} (dry) increasing to over 5.1 Tg y^{-1} at 33 \$ Mg^{-1} (dry). In theory, 4.1 Tg y^{-1} pellets could be produced from the estimated potential. However, due to the geographic dispersed supply of these resources, the cost of feedstock supply at a pellet plant increases rapidly at larger plants. It is therefore not expected that the total potential can be processed into wood pellets at competitive costs to conventional wood pellets. The optimal size of a pellet plant is estimated between 55 Gg y^{-1} and 315 Gg y^{-1} pellets depending on the location and feedstock supply assumptions. At these locations and plant sizes, pellets could be produced at competitive costs between 82 \$ Mg^{-1} and 100 \$ Mg^{-1} pellets.

Submitted to *Biomass and Bioenergy*. Co-authors: Martin Junginger, André Faaij (Utrecht University)

4.1 Introduction

Concerns on energy supply security and climate change have increased the demand for biomass used for bioenergy purposes including liquid biofuels, such as ethanol and biodiesel, and solid biofuels, such as wood chips and wood pellets. Wood biomass is still mainly used traditionally, i.e. for local cooking and (low temperature) heating. However, policies targeted to renewable energy generation, have driven the demand for solid biomass for industrial uses including electricity generation in standalone or co-firing in coal power plants, combined heat and power and district heating, especially in the European Union (EU-27). In contrast to residential sectors, industrial uses of solid biofuels in the EU-27 are highly import dependent [1, 2]. Trade of solid biofuels and in particular wood densified into wood pellets, has therefore grown rapidly. In the EU-27, the import of wood pellets increased from 1.9 Tg (teragram) in 2009 to 4.6 Tg in 2012 [3] and this trend is likely to continue in the future. By 2020, the global demand for wood pellets is estimated to be between 45 Tg and 80 Tg with imports of wood pellets to the EU-27 in the range of 15 Tg to 30 Tg depending on policy developments, the deployment of bioenergy and the mobilization of domestic resources [2-4].

West Canada (British Columbia) and the southeast of the U.S., have become key exporting regions of wood pellets mainly driven by the demand in the EU-27. In the U.S. southeast of the U.S. (Florida, Georgia, North Carolina, South Carolina), over 3.6 Tg y^{-1} wood pellet production capacity is currently online (44% of the total capacity in the U.S.) and almost 3.0 Tg y^{-1} wood pellet production capacity is under construction or proposed [5, 6]. By-products from wood processing industries, such as saw dust, are still the primary source of wood pellet production. However, the sawmilling industry has retrenched due to the sharp decline in demand for solid wood timber products. The demand for solid wood timber products in the U.S. halved from 202 million m^3 in 2005 to 110 million m^3 in 2009 mainly a result of the economic crisis and its effect on the housing market [7]. This has resulted in an imbalance between supply and demand of secondary wood residues [8] and in combination with the decreased demand for primary wood sources, has increased the production of wood pellets from primary forestry products, for example pulp wood.

Several NGOs and other actors have criticized the uses of primary forestry products (mainly pulp grade wood) for energy purposes for ecological concerns and possible reduced or even negative greenhouse gas (GHG) mitigation performances. Furthermore, there are also wood sources available that are currently unused or used inefficiently, (e.g. in low temperature heating systems) and not used for the production of wood pellets because they do not comply with the high quality standards for wood pellet production or are too expensive to mobilize compared to conventional wood sources. Examples of these unconventional wood sources include forest biomass (both primary and secondary residues) and urban wood wastes. Urban wood waste is the collective term for the woody component of municipal solid waste (MSW) and construction and demolition (C&D) wood. In the U.S., over 72 Tg dry wood could to be available for bioenergy production for under 44 \$ Mg^{-1}, including primary forestry residues (46 %), other removal residues (15 %), secondary forestry residues from saw mills (9 %) and urban wood wastes (29 %), but excluding roundwood and pulp wood [9]. Part of this material could also become available for the production of wood pellets if the biomass material is properly collected and when adequate pre-processing techniques are used. Processing of these low-value wood resources by pelletization, results in a high value energy commodity that can be transported over long distances and used in efficient conversion plants. However, for many of these resources, the logistics and removing or avoiding contaminations, e.g. sand, are still a major challenge.

This chapter analyses the economic potential of wood pellet production from alternative wood sources in the "wood fiber basket" region in the southeast of U.S including the following states: Florida, Georgia, North Carolina and South Carolina. The emphasis of this study is on the current supply potential and cost of biomass, but also conservative medium term (2020) scenario projections are included. This study focuses on wood resources that are suitable for the production of wood pellets and are currently underutilized due to abundance of supply and lack of markets, used inefficiently, e.g. as boiler fuel, or not used and discarded as waste.

4.2 Methodology and data

4.2.1 Wood resources selection

This analysis includes three types of wood, as shown in Table 4-1, that have been selected from a candidate list of potential alternative wood fiber sources that have been collected in Georgia (U.S.) [10]. The supply, demand, logistics and composition (ash, moisture, possible contaminations) have been analyzed for each sample as summarized in Table A 4-1. The selected wood sources have favorable availability within the proximity of a pellet plant, low to moderate demand and are only utilized for low-value purposes, e.g. furnace fuel, or discarded as waste.

Wood chips from discarded wooden transport pallets have been selected because it is a relatively clean type of post-consumer residue (tertiary biomass) that can meet the quality specifications of the wood pellet plant if processed correctly. At the end of the life cycle, the majority of transport pallets are either collected by pallet recycling companies or collected at landfill areas. Pallet recycling companies already separate different qualities of pallets and remove possible contaminations (plastics, paper) to produce wood chips for mulch, fuel and animal bedding. Nails are removed from ground pallets using magnets. Currently, most pallet recycling companies reject pallets that cannot be repaired or recycled because there are only few markets for chipped pallet. Other sources of urban wood wastes (from limbs, power line clearings, residential wood waste, and construction debris) have also been tested and could potentially also be cleaned and processed to remove contaminations and reduce ash levels (13 % to 52 % in tested samples, Table A 4-1). These options have not been assessed in this analysis.

Wood residues from primary wood processing industries are the preferred source of wood fiber for wood pellet production because it does not require major resizing and it is relatively dry and clean. However, 98 % of these wood residues are already utilized in the U.S. [9]. Still, the demand for wood residues from pole production mills is identified to be low in Georgia [10]. Utility pole mills process pine trees into standard sizes by debarking, and sizing (cutting to length and circumferences). The by-products are a mixture of clean wood and bark and therefore difficult to use in existing markets [10]. Pole mill residues are mainly used in the pole mills or sold as furnace fuels [11, 12].

These forest residues are generated during precommercial thinnings, to improve the quality of the remaining stands, or timberland clearing for other land uses or replanting. The wood removed includes unmerchantable, poor shaped or undesired types of stems, small (hardwood) trees, limbs, barks and tops and is also referred to as 'other removals' [9, 13, 14]. Due to the nature of these forest management activities, other removals are a heterogeneous source of wood with potentially high ash contents (sand, bark, leaves) that are not always economically feasible to mobilize [9]. Nevertheless, the tested samples demonstrate that pellets could be produced with ash contents below 2 % (Table 4-1). These unmerchantable forest residues are currently left (and burned) in the forest or chipped and used as a furnace fuel, of which the fuel demand is not constant [10]. It is unknown how much is used and how much is left unused in the forest.

Table 4-1 Selected wood resources and properties [10].

Name		Description	Ash mass fraction (%)			Moisture mass fraction (%)[a]
1	Discarded pallets	Wood waste: chipped wooden transport pallets that cannot be recycled (hardwood chips)	0.9	-	1.5	23.3 (23.3-24.8)
2	Pole peelings	Sawmill residues: pole mill residues (ground/chipped softwood)	0.5	-	1.34	17.0 (15.7-18.9)
3	Unmerchantable forest residues	Forest residues: wood chips produced from land clearing and premerchantable harvest forest management activities (hardwood chips)	1.38	-	1.98	Hardwood: 42.9 (35.5-42.9) Softwood[b]: 50.0

a) Moisture content assumed in this analyses (transportation and drying) and the ranges found in test samples between brackets.
b) No test samples available for softwood. The moisture content for softwood in this analysis based on pine (whole tree) sample (Table A 4-1).

4.2.2 Resource assessment of selected wood sources

This analysis uses a spatially explicit approach to quantify the potential of wood fiber sources available for the production of wood pellets in the southeast of the U.S.. First, the technical potential is determined by the fraction of the theoretical potential that can be mobilized taking technical constraints, for example implied by collection techniques, into account as well as competition with different uses of the selected resources [15]. In this analysis, uses of wood fibers for materials, e.g. mulch or animal bedding, are considered unavailable for wood pellet production. Part of the wood resources assessed in this study is however already also used for bioenergy purposes, mainly as a low grade furnace fuel. At the same time, many low-grade wood sources are currently unused because of the availability of better alternatives [10]. It is assumed that, when new pellet markets develop, these wood fiber sources will be reallocated driven by the higher market value as a feedstock for pellet production compared to furnace fuels [16].

Secondly, the economic potential is determined from the technical potential based on the cost of the wood sources at the supply origin and the cost of logistics to get the wood sources from the forest or mill to the pellet production plant.

4.2.2.1 Unmerchantable forest residues

The unmerchantable forest residues in this analysis, are consistent with the definition of the forest biomass category 'other removals' [9]: "*Other removal residues are the unutilized wood volume from cut or otherwise killed growing stock, from cultural operations such as pre-commercial thinnings, or from timberland clearing. Does not include volume removed from inventory through reclassification of timberland to productive reserved forest land*." Data of other removals (in volume wood generated) are collected by the U.S. Department of Agriculture Forest Service in context of the Forest Inventory and Analysis (FIA) program and reported in the Timber Product Output (TPO) database. Data is available for every two years up to 2009 per wood class (hardwood and softwood), county, and land ownership (public or private) and growing and non-growing stock volumes removed[6] [17]. The main limitation of the TPO database is that it does not distinguish between other removals that are produced from land clearing activities and other removals from precommercial thinning operations. Although the production of other removals is not driven by demand markets, the inclusion of other removals from land clearing makes the carbon saving potential disputable when used for bioenergy [18].

Pre-commercial thinning operations, but especially land clearing activities vary in time and region. The data of the TPO shows that the amount of other removals generated have been fluctuating heavily in the selected region (Figure 4-1). Therefore, average removals in the period 1999 to 2009 were assumed to represent the current theoretical availability of other removal residues. Considering that other removals are difficult to recover, a recovery factor of 50 % was assumed similar to the updated Billion Ton study [9] to calculate the technical potential (Equation 4-1) [19]. The lowest and highest generation of other removals in the period 1999 to 2009 in the individual states are assumed to represent lower and upper bound ranges of other removals.

$$TCP_{ORR_{x,y}} = THP_{ORR_{x,y}} * AR \qquad \text{Eq. 4-1}$$

[6] Growing stock volume: "the volume of sound wood in growing stock trees at least 5.0 inches diameter at breast height from a 1-foot stump to a minimum 4.0 inch top diameter outside bark of the central stem". Non-growing stock sources: "the net volume removed from the nongrowing-stock portions of poletimber and sawtimber trees (stumps, tops, limbs, cull sections of the central stem) and from any portion of a rough, rotten, sapling, dead or nonforest tree" [17].

$TCP_{ORR\,x,y}$: technical potential of other removal residues in county x in year y, (Mg y^{-1})
$THP_{ORR\,x,y}$: theoretical potential of other removal residues in county x in year y, (Mg y^{-1})
AR: average recovery ratio of other removal residues

There is limited information available on the cost of harvest and collection and roadside prices of other removals [9, 20]. Similar to the updated Billion Ton Study [9], the following assumptions have been made to estimate the economic potential of other removals:

- 33 % of the technical potential is available at roadside for 22 \$ Mg^{-1} (dry)
- 67 % of the technical potential is available at roadside for 33 \$ Mg^{-1} (dry)

In comparison, Walsh [20] estimates break even cost of collection and chipping of other removals using the regional distribution of non-growing stock harvest costs. At 33 \$ Mg^{-1} or less, 36 % of total other removals were estimated to be available compared to 33 % in this analysis at similar cost levels and including a recovery factor of 50 %.

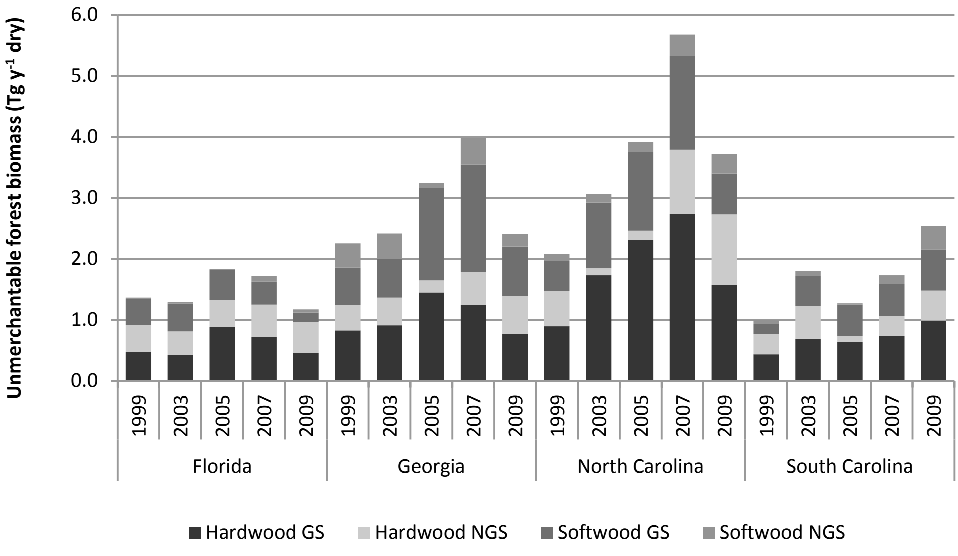

Figure 4-1 Unmerchantable forest biomass produced in the southeast of the U.S. 1999-2009 per state, wood type (hard wood, softwood) and source (GS: growing stock, NGS: non-growing stock) [17] in Tg y^{-1} dry wood (moisture content hardwood 43 %, softwood 50 %). Data for 2001 was not available for all states in the selected region.

4.2.2.2 Secondary residues: pole peelings

The amounts of by-products produced in pole mills and their current uses in the southeast of the U.S. are collected by the USDA-Forest Service by the Timber Product Output group. For reasons of confidentiality, these figures are reported collectively with the residues produced in 'other primary wood processing mills' in the TPO database. For this analysis, the amount of by-products from pole mills are therefore quantified based on the primary output of poles, posts and pilling mills that are reported at the county level in the TPO database and Equation 4-2 [19]. The residue factors in Table 4-2 are based on forest production conversion factors for pole mills in the U.S. which are available at the USDA Forest Service [11]. The ranges for wood residues are based on the global minimum and maximum conversion factors for pole, post and piling mills [21].

$$TCP_{res_{x,y}} = FP_{x,y} * RF_{bark,wood} - USR_{bark,wood\ x,y} \qquad \text{Eq. 4-2}$$

$TCP_{res\ x,y}$: technical potential of pole mill residues in county x and year y
$FP_{x,y}$: volume of pole production in county x in year y ($m^3\ y^{-1}$)
$RF_{bark,wood}$: residue factor for wood and bark per volume of the produced poles in county x in *year y* ($m^3\ y^{-1}$)

$USR_{x,y}$: volume of residues used for material production (e.g. wood chips, lump wood and bark consumed by board industry) or internally utilized by the sawmill as energy source, in county x in year y ($m^3\ y^{-1}$). It was assumed that all wood residues produced in pole mills could be reallocated to wood pellet production and all bark residues are used internally by the pole mills.

Table 4-2 Residue factors of poles, posts and piling mills from softwood [11, 21].

Residue	Unit	Residue factor
Bark[a]	m^3/m^3	0.28
Wood	m^3/m^3	0.20 (0.15 - 0.24)[b]

a) Average pole volume = 0.375 m^3 / pole, moisture mass fraction = 17 %, wood density = 0.589 Mg / m^3
b) Ranges between brackets are based on the lowest conversion factor (most efficient) for post, poles, pilings (1.10 for utility poles in Ireland [21]) and highest conversion factor (least efficient) for post, poles, pilings (1.75 for pilings in Slovakia [21]).

4.2.2.3 Tertiary biomass: discarded transport pallets

Pallets are flat structures that improve handling and stability of goods during transport, handling and storage. Pallets are constructed from different materials including metals and plastic, but the most common are wooden pallets and about 90 % of all pallets are made from wood, predominantly hardwood [22]. Pallets are either used in closed loop (pooled) and open loop (non-pooled) [22]. Non-pooled pallets change owner with the transported cargo and generally have a short lifetime whereas pooled pallets circulate in a closed system and are built to higher specifications with thicker and higher grade boards, better nails and are generally used multiple times, either with or without repair [23, 24]. In the U.S., between 2 to 4 billion wooden transport pallets are in use every day that are either new, re-used without repair or re-used after repair [25, 26].

At the end of life, pallets are either recycled, downcycled (i.e. used for lower grade purposes), or landfilled in MSW and C&D landfills [22, 27]. Recycled pallets are either re-used without repair, repaired or dismantled for repair material. Downcycled pallets are mainly ground and used for colored and uncolored landscape mulch, animal bedding and energy (furnace fuel). Although markets for landscape mulch are currently much better than energy markets, the use of ground pallets for wood pellet production could increase the market value of energy over the current use as a low-grade furnace fuel. In this analysis, we considered pallets that are used for material markets (mulch and animal bedding) to be unavailable for wood pellet production. The remaining fraction of downcycled pallets and pallets that are currently landfilled are assumed to be available for wood pellet production.

To estimate the potential of ground pallet material for pellet production, this analysis uses survey data of the wood container and pallet manufacturing industry in the U.S. (NAICS code 321920) as collected every five years by Virginia Tech. The most recent data available is from 2006 and based on the responds of 450 out of 2580 unique firms contacted. These firms represent 590 production facilities in the U.S. [28]. The results are extrapolated per region in the U.S. based on employment numbers. Figure 4-2 shows the flow diagram of GMA (Grocery, Manufacturers, Association), the most common type of pallet, and the 2006 survey data from Virginia Tech used to estimate the potential of discarded pallets. The values between brackets are for the south of the U.S..

In 2006, 441 million pallets have been produced from new wood consuming 11 million m^3 of hardwood and 6 million m^3 of softwood. These pallets are shipped to pallet customers, mainly product manufacturers that use these pallets to ship loads to wholesalers or distribution centers. Pallets are also directly sold to distribution centers for the purpose of creating mixed loads [24]. Most pallets remain in circulation and change owners several time before they are taken out of service. Wood pallets are collected by recycling companies if they need to be repaired, if they can be used for recycling or if they have no functional use [23]. Depending on the quality of the collected pallets, recyclers either pay for the collected pallets (1 to 2 $ per pallet) if they can be re-used without repair, collect them freely if they need to be repaired or request a tipping fee for the collection of pallets that need to be grinded or require high repairs [23]. Pallet grinding is considered a required activity to process unwanted material and most pallet recycling companies avoid receiving pallets they cannot recycle or reuse as much as possible [23]. In total, 460 million pallets were collected in 2006 by pallet recyclers/companies to re-use or remanufacture 321 million pallets from the recovered wood [28].

The most recent data for pallets disposed in landfills is from 1998 [27]. In that year, 178 million pallets were disposed in landfills of which 38 million were recovered and used for mulch (30 to 44 %), landfill cover (12 % to 16 %), fuel (15 %) or re-used as pallets (10 % to

22 %). The remaining fraction (66 % in C&D and 84 % in MSW landfills) was still landfilled in 1998. Many programs have been initiated to reduce landfilling of pallets. In North Carolina, the House Bill 1465 Act became active in 2009 which bans the disposal of wood pallets in MSW landfills [29]. Furthermore, landfills have started recovery operations and offer lower tipping fees for sorted loads to improve the recoverability of these pallets [27]. In this analysis, it is assumed that around 100 million pallets are still landfilled each year in the U.S. that could become available for the production of wood pellets.

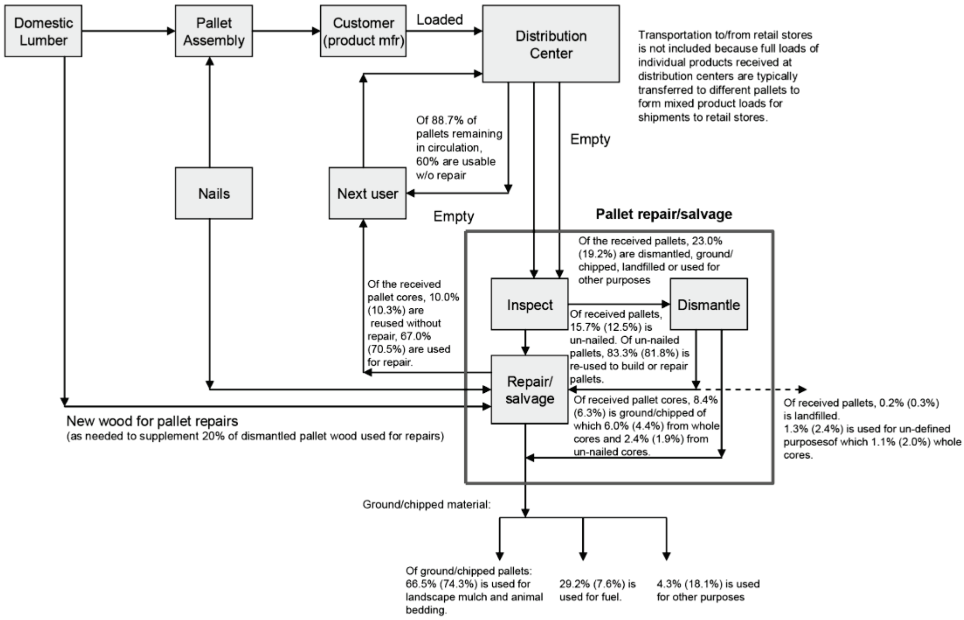

Figure 4-2 Flow diagram for GMA pallets, adapted from Franklin Associates [24] with data for all wooden pallets in the U.S. and for the south of the U.S. between brackets. Data from Bush and Araman [28].

4.2.3 Future potential of wood resources

Projections to the future are made to 2020 using existing, conservative future scenario projections. The future potential of unmerchantable forest residues is assumed to be similar to the growth of other removals in the updated Billion Ton study between 2012 and 2020 [9] of 0.2 % (Florida) to 0.3 % (Georgia, North Carolina, and South Carolina). The projections in the updated Bullion Ton study are made using RPA timberland projections and, similar to the updated Billion Ton study, exclude the potential of other removals from timberland clearings which is projected to decline with 2.4 million ha to 2030 [9].

The potential of pole mill residues depends on the future production of utility poles in the southeast of the U.S. and emerging markets for pole mill residues. The market for utility poles can increase shortly after natural disasters, but could also decline, e.g. as a result of undergrounding of transmission cables. Because no market outlooks are available for pole industries, future projections are based on the conservative growth rate of softwood sawtimber in the U.S. for the Constant Demand, Low GDP scenario of the Southern Forest Resource Project to 2020 [30]. For similar reasons, the same scenario was also used for the future outlook of wood pallet production and the related potential of discarded pallets. Because pallet production is the largest consumer of hardwood lumber and consumes 90 % of all lumber and 70 % of all structural panels produced for packaging and shipping [7], the growth rate of hardwood lumber to 2020 was used as a proxy for wood pallet production.

4.2.4 Feedstock supply and pellet production

4.2.4.1 Transport and handling

The cost of biomass transport from the supply origin to the pellet plant includes fixed handling cost (loading and unloading) and variable transportation cost. These costs can add substantially to the total feedstock cost delivered at the pellet mill depending on the hauling distance, the moisture content and the bulk density of the feedstock. A Geographic Information Systems (GIS) based tool is used running in the Network Analyst extension of ESRI's ArcGIS® 10.1 with street map vector data for North America [31] to estimate the cost of feedstock supply. Similar to Staudhammer et al. [32], the routes are optimized for shortest travel time. Furthermore, the following assumptions are made:

- Variable transport cost (per truck): 0.031 $ km^{-1}
- Fixed handling cost (loading/unloading): 2.00 $ Mg^{-1} (ar) (ar: as received)
- Empty returns: yes
- Speed: 75 % of the road specific allowed speed
- Bulk capacity (per truck): 18 Mg (ar)
- Fuel economy (diesel): 0.39 L km^{-1}
- Fuel cost (diesel): 0.93 $ L^{-1}

4.2.4.2 Pellet production

The wood pellet production process covers all operations required to convert raw biomass feedstock into industrial wood pellets, including storage, drying, grinding and densification. The cost of pelletization can vary substantially between locations [33] and the type of process used [34]. The capital requirements in this analysis are based on studies for North America [35]. The final energy requirements (electricity) are mainly based on European studies [33, 36] due to lack of transparency and data in studies for North America.

Most of the equipment used in a pellet production plant is difficult to scale up and require multiple parallel systems. For example, most pellet mills include several pellet mills, cyclones and grinders. Nevertheless, a scale factor of 0.7 is assumed in this analysis based on Pirraglia et al. [35], to calculate the capital invest for the required plant size using the power law formula (Eq. 4-4). Capital investments are annualized using Eq. 4-5 and a discount rate of 6 % [35]. The lifetime is equipment specific ranging from 10 years for the hammer mills to 20 years for office buildings [35]. The specific capital costs of larger pellet plants are lower due to economies of scale. However, these pellet plants require a larger sourcing area for the supply of wood materials and therefore imply higher hauling cost compared to smaller pellet plants. Detailed cost structures are provided in Table A 4-2.

$$Inv = Inv_{ref} * (P / P_{ref})^{0.7} \qquad \text{Eq. 4-4}$$

$$CRF = \frac{i}{1-(1+i)^{-L}} \qquad \text{Eq. 4-5}$$

Inv = capital investment of the pellet plant
Inv_{ref} = capital investment of the reference pellet plant
P_{ref} = size of the reference pellet plant (Mg pellets y^{-1})
P = size of the pellet plant (Mg pellets y^{-1})
CRF = Capital Recovery Factor
L = utilization period (years)
i = interest rate

4.2.4.3 Cost-supply curves and total cost

The geographic supply of unmerchantable forest residues, pole mill residues and discarded pallets, are geographically scattered. There are only a limited number of pole mills and pallet recycling companies in the southeast of the U.S. and unmerchantable forest residues are being generated at relatively small land areas that are geographically scattered throughout the region (Figure 4-3). In the selected four states, 11 pellet production plants have been identified that are currently operational (5 plants), under construction (1 plant) or proposed (5 plants) with pellet production capacities ranging from 35 Gg y^{-1} to 825 Gg y^{-1} [6]. These locations are assumed to represent the candidate locations to process the selected feedstocks. The specific designs or capacities of these pellet plants are not considered in this analysis. For example, the infrastructure of some of these pellet plants is designed to process dedicated feedstocks such as pulpwood and might not be able to process the selected wood sources in this study.

4.3 Results

4.3.1 Potential of wood resources

The combined dry wood potential of the selected wood sources in this analysis add up to 1.9 Tg y^{-1} available at roadside or mill gate for 22 \$ Mg^{-1} (dry) to over 5.1 Tg y^{-1} when other residues available for 33 \$ Mg^{-1} (dry) or less are included (Table 4-3). In theory, the estimated potential of the selected resources in the U.S. is sufficient to produce 4.1 Tg y^{-1} wood pellets (ar, moisture mass fraction: 7%) taking into account the dry matter losses from feedstock drying and pelletization. In comparison, the total production capacity in the U.S. that is currently operating, proposed or under construction is 10 Tg y^{-1} wood pellets, of which 66 % of this capacity is located in southeast of the U.S. [5].

The highest potentials are available in Georgia and North Carolina where most pallet recycling companies and pole production mills are located (Georgia, Figure 4-3) and the largest amounts of unmerchantable forest residues are generated (North Carolina, Figure 4-1). However, variations in the production of unmerchantable forest could increase or decrease the potential substantially. For example, if in Georgia relatively low amounts of unmerchantable forest residues are generated, such as in 1999, the supply potential of unmerchantable forest residues available at roadside for 22 \$ Mg^{-1} (dry) would reduce the total potential of dry wood in Georgia with 60 %. Note also that pole mill residues and discarded pallets have favorable moisture contents over unmerchantable forest residues (Table 4-1). Hauling cost and dry matter losses from feedstock drying are therefore higher for unmerchantable forest residues as discussed in Section 4.3.2.

Table 4-3 Potential of other removals, pole mill residues, chipped pallets estimated to be available for wood pellet production in the southeast of the U.S. at 22 \$ Mg^{-1} (dry) and the cumulative potential available at 33 \$ Mg^{-1} (dry).

	2012				2020			
	22 \$ Mg^{-1} (dry)		33 \$ Mg^{-1} (dry)		22 \$ Mg^{-1} (dry)		33 \$ Mg^{-1} (dry)	
	Dry wood potential and lower and upper ranges between brackets (Gg y^{-1})							
Unmerchantable forest residues								
Florida	246	(104 - 423)	739	(312 - 1 269)	247	(104 - 424)	740	(313 - 1 271)
Georgia	477	(206 - 848)	1 430	(617 - 2 544)	478	(206 - 851)	1 434	(619 - 2 552)
North Carolina	615	(239 - 1 101)	1 846	(718 - 3 303)	617	(240 - 1 104)	1 851	(720 - 3 312)
South Carolina	278	(98 - 497)	834	(295 - 1 492)	279	(99 - 499)	836	(296 - 1 496)
Total	**1 616**	**(648 - 2 869)**	**4 848**	**(1 943 - 8 607)**	**1 620**	**(649 - 2 877)**	**4 861**	**(1 948 - 8 631)**
Pole mill residues								
Florida	13	(10 - 15)	13	(10 - 15)	14	(10 - 16)	14	(10 - 16)
Georgia	57	(42 - 67)	57	(42 - 67)	59	(43 - 69)	59	(43 - 69)
North Carolina	5	(4 - 6)	5	(4 - 6)	5	(4 - 6)	5	(4 - 6)
South Carolina	14	(10 - 16)	14	(10 - 16)	14	(11 - 17)	14	(11 - 17)
Total	**89**	**(66 - 104)**	**89**	**(66 - 104)**	**92**	**(68 - 108)**	**92**	**(68 - 108)**
Discarded pallets								
Florida	43	(7 - 61)	43	(7 - 61)	48	(8 - 68)	48	(8 - 68)
Georgia	78	(12 - 111)	78	(12 - 111)	87	(14 - 124)	87	(14 - 124)
North Carolina	53	(8 - 75)	53	(8 - 75)	59	(9 - 84)	59	(9 - 84)
South Carolina	15	(2 - 21)	15	(2 - 21)	17	(3 - 24)	17	(3 - 24)
Total	**189**	**(30 - 269)**	**189**	**(30 - 269)**	**210**	**(33 - 300)**	**210**	**(33 - 300)**
All feedstocks								
Florida	302	(120 - 499)	795	(328 - 1 345)	308	(122 - 508)	801	(330 - 1 355)
Georgia	612	(260 - 1 026)	1 565	(671 - 2 723)	624	(264 - 1 044)	1 580	(676 - 2 746)
North Carolina	673	(252 - 1 182)	1 904	(730 - 3 384)	681	(253 - 1 194)	1 915	(734 - 3 402)
South Carolina	307	(111 - 535)	863	(308 - 1 529)	310	(112 - 539)	867	(309 - 1 536)
Total	**1 894**	**(743 - 3 243)**	**5 126**	**(2 038 - 8 981)**	**1 923**	**(751 - 3 285)**	**5 164**	**(2 049 - 9 039)**

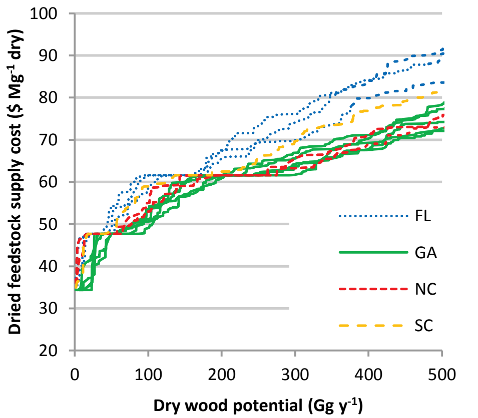

Figure 4-3 Cost-supply curves of all selected wood of all states delivered and dried at each pellet plant locations in each state in 2012 (US$$_{2012}$).

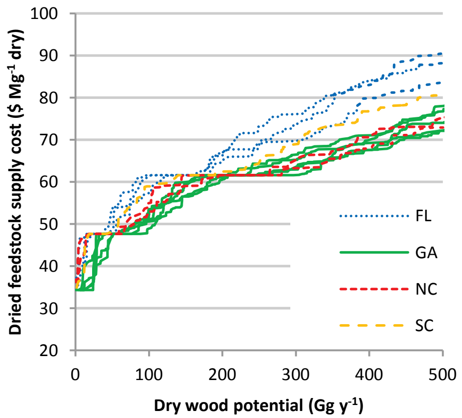

Figure 4-4 Cost-supply curves of all selected wood of all states delivered and dried at each pellet plant locations in each state in 2020 (US$$_{2012}$.

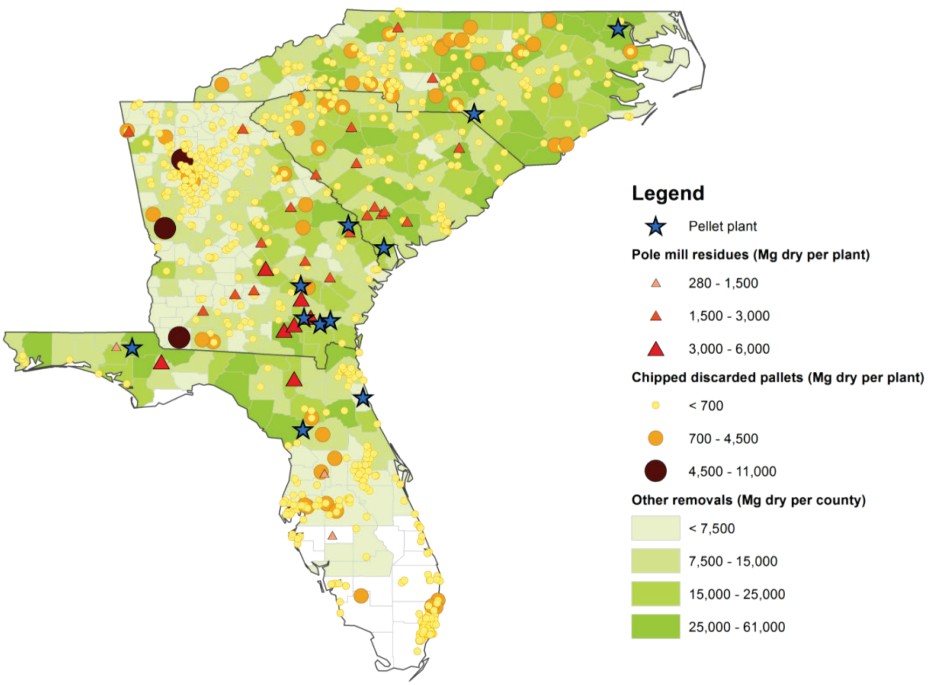

Figure 4-5 The geographic potential (Mg y^{-1} (dry)) of pole mill residues per plant, grind pallets per pallet company and unmerchantable forest residues per county in Florida, Georgia, North Carolina and South Carolina in 2012. Locations of pallet companies [37], administrative boundaries: ESRI data and maps [31].

4.3.2 Wood pellet production

Capital and O&M cost of the pellet production plant decrease for larger plant sizes due to economies of scale. The optimal size of the pellet production plant depends on the geographic supply potential in the wood supply area of the pellet plant. Larger pellet plants require a larger sourcing area to meet the wood fiber demand resulting in longer hauling distances and implied logistic cost. Figure 4-4 (2012) and Figure 4-5 (2020) show the total economic potential of feedstock delivered at each individual pellet production plant in the selected states. Dry matter losses and implied costs for drying to a moisture mass content of 7 % are also included. The scale of the supply curves are limited to 500 Gg y^{-1} dry feedstock, equivalent to pellet production capacities of 404 Gg y^{-1} to 423 Gg y^{-1} wood pellets. At these supply ranges, the cost of dried feedstock increase from 34 $ $Mg^{-}1$ to 36 $ Mg^{-1} at the start of the cost-supply curves to 72 $ Mg^{-1} in Georgia and up to 91 $ Mg^{-1} (dry) in Florida. The future, conservative projections of feedstock potentials hardly affect the cost-supply curves to 2020 (Figure 4-5).

The average capacity of pellet plants in the selected states that are operational, under construction or proposed, is about 300 Gg y^{-1} pellets (ar). Most new pellet plants are designed for primary sources of (pulp) wood with production capacities up to 825 Gg pellets y^{-1} (ar) (Georgia). For the low value resources in this analysis, small pellet production plants are considered cost effective over large pellet plants. The cost of feedstock, including drying and total pellet production cost for pellet plants with production capacities between 40 Gg y^{-1} and 160 Gg y^{-1} (ar) are therefore depicted Figure 4-6. The colored bars show the cost ranges from different plant locations in each state. The error bars show the effect of uncertainty ranges in feedstock supply (Table 4-3). Under the main supply estimations, pellet production cost are estimated to be 88 $ Mg^{-1} pellets (ar) in Georgia to 99 $ Mg^{-1} pellets (ar) in Florida. Lower and upper bounds in the total supply potentials result in cost ranges of 85 $ Mg^{-1} to 108 $ Mg^{-1} pellets (ar).

Based on the cost-supply curves for each location and supply assumptions and economies of scale of the pellet plant, the optimal size and location has been calculated for each state as depicted in Figure 4-7. The optimal size of the pellet plant and the related pellet production cost can vary strongly depending on the location of the pellet plant and the feedstock supply potential. The optimal pellet production capacity could be as low as 55 Gg y^{-1} if only pole mill residues and discarded pallets are available (d) to over 315 Gg y^{-1} for the upper bound supply potential in South Carolina (c). For the main supply scenarios in 2012 (a) and 2020 (f), Georgia has the most optimal location (lowest cost) for pellet production from the selected wood sources. In Georgia, pellets could be produced for 82 $ Mg^{-1} at a pellet plant of 120 Gg to 125 Gg y^{-1} pellet production capacity.

In comparison, FOB (Free on Board) export spot prices of wood pellets in the southeast of the U.S. fluctuated from 140 US$ Mg^{-1} to 155 US$ Mg^{-1} in 2012 [38]. Note however that the cost estimates in this analysis do exclude the cost of handling and transport between the pellet plant and the ocean export terminal and the cost of loading into a bulk ocean carrier for export.

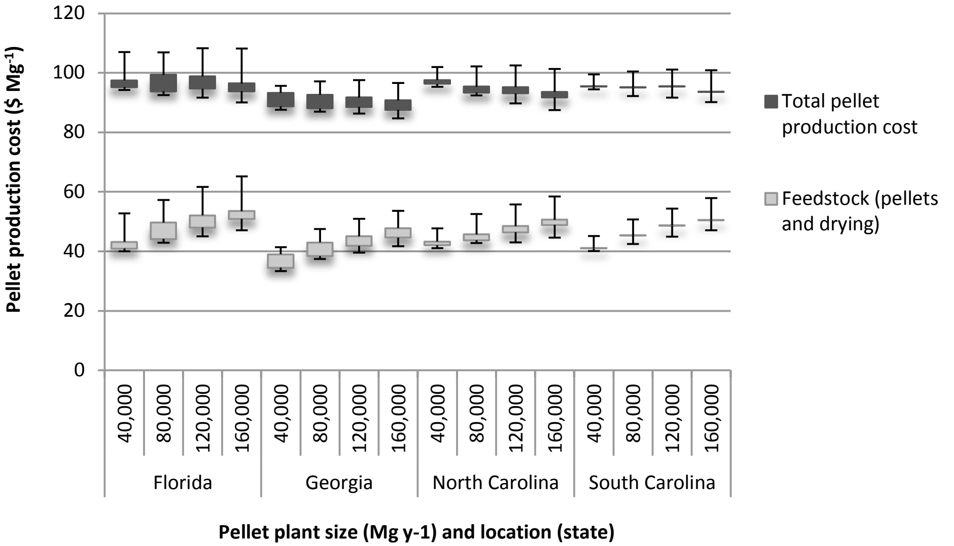

Figure 4-6 Feedstock supply cost (fuel for drying and feedstock for pellets) and total cost of pellet production. The result series show the cost differences between the different locations of pellet plants in each state except for South Carolina, with only one pellet plant location defined (Figure 4-5). The error bars show the impact of the lower and upper bounds of the feedstock potentials on the wood pellet production cost.

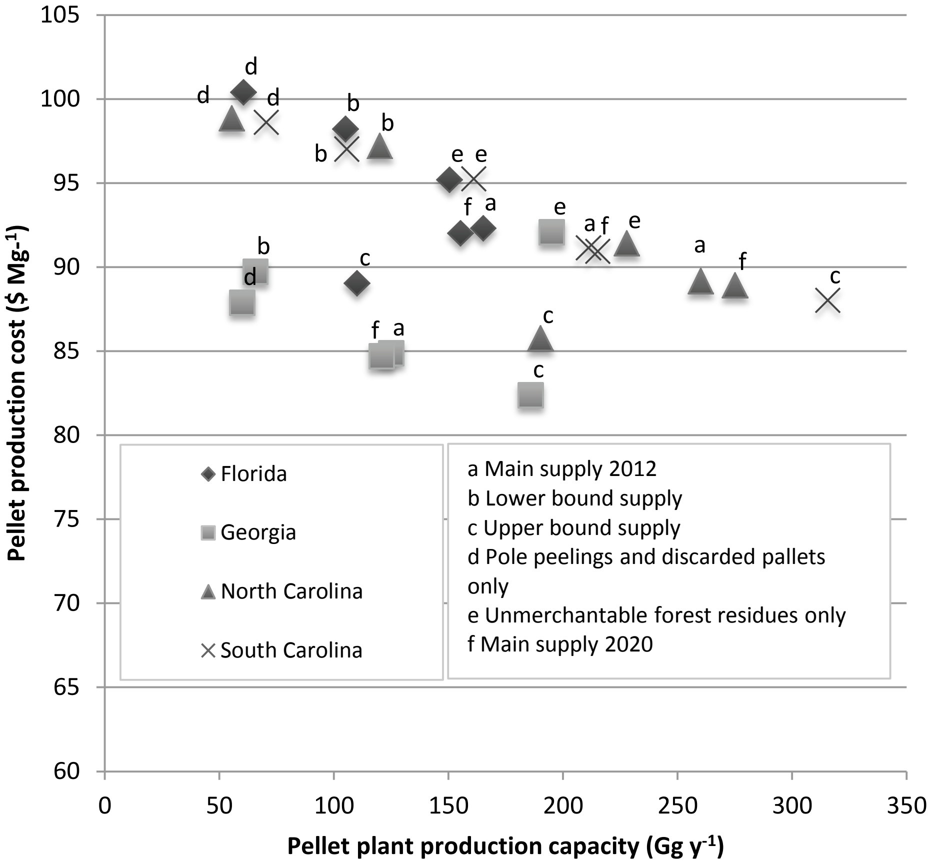

Figure 4-7 Pellet production capacity and cost for optimal plant sizes per state in the southeast of the U.S., scale factor = 0.7, in US$$_{2012}$.

4.4 Discussion

4.4.1 Unmerchantable forest residues

Statistical data of other removals in the U.S. are collected by the USDA Forest Service and reported in the TPO database. There are two main uncertainties in using this database to estimate the potential of other removals available for wood pellet production. First, hardly any research has been conducted on the economic potential and logistics to collect these resources in an economic and ecological sustainable way to produce wood pellets [20]. The technical recovery factor and economic potentials assumed in this study are based on expert estimations [9], but not supported by empirical data from commercial operations or field studies. Secondly, the TPO database does not distinct between other removals generated from precommercial thinning operations and land clearing activities. Precommercial thinnings are conducted to improve the quality of the living stock and could potentially increase the carbon value of managed forests. Land clearing activities, a common practice in the southeast of the U.S., could release substantial amounts of carbon stored in the growing and nongrowing-stock of the trees removed resulting in a net loss of carbon if the land is not replanted with trees. Although recommended by SFI Fiber Sourcing, replantation (reforestation) after land clearing is not obligatory and it is also not legally required by Best Management Practices or Best Harvesting Guidelines in the southeast of the U.S. [39]. For this reason, the Union of Concerned Scientists (UCS) considers other removals not to be a sustainable source of bioenergy [18]. Note however that despite local land clearing activities, on a macro-level, the total forest area remains stable [39].

The potential of unmerchantable forest residues in this analysis is calculated with similar assumptions to the updated Billion Ton study for other removals [9]. However, the potential of other removals available for bioenergy in the U.S. in the updated Billion Ton study is based on other removals in 2003, when relatively low amounts of other removals were generated compared to 2007 (Figure 4-1). The potential of other removals is therefore significantly lower (3.3 Tg dry wood in the southeast of the U.S.) compared to the 4.8 Tg dry wood estimated in this analysis. Note also that the fluctuations in other removals do not necessary reflect the minimum and maximum potentials of other removals and fluctuations could be larger if longer time periods would be considered.

4.4.2 Pole mill residues

Although pole, posts and piling mills in the U.S. do report the amount of wood residues produced to the USDA-Forest Service, such information is confidential. The amounts of wood residues produced in pole processing mills in the southeast of the U.S. are therefore based on a statistical approach using the total output of wood products produced in post, pole and piling mills per county as reported in the TPO database in combination with the average residue factors for wood and bark of these industries. This method does not distinct between the production of utility poles versus other types of posts, poles and pilings because they are reported in a single category in the TPO database. Furthermore, residue factors are provided per number of poles produced whereas the TPO database only reports the total mass of post, poles and pilings produced in these mills. This creates additional uncertainties in the total potential of pole mill residues. However, compared to the global residue factors reported by the FAO [21], the residue factors calculated in this analysis appear to be plausible.

This analysis assumes that pole mill residues have no competitive markets other than internal use based on a local market analysis in Georgia [10]. Such markets might exist in other regions in the southeast of the U.S. and would reduce the availability of these residues for wood pellet production. These effects would be small because pole mill residues do not add substantially to the total supply potential in this analysis (Table 4-3).

4.4.3 Discarded transport pallets

Virginia Tech has a Pallet and Container Industry Production and Recycling Research program that surveys all wooden container and pallet manufacturing industries (NAICS code 32192) in the U.S. [28]. This analysis uses the most recent data from the research program (2006) to estimate the amount of discarded wooden pallets available for the production of wood pellets per state. For the geographic potential, the potential in each state has been allocated to companies with NAICS code 32192 based on the number of employees of each company relative to the total employment in the wooden container and pallet manufacturing industries. This implies that the calculated potential of chipped pallets is highest at larger companies with a high number of employees, regardless if they recycle wooden pallets. In reality, only 55 % of these companies are involved in recovery, remanufacturing and repair of wooden pallets [28]. However, the locations of these specific companies are unknown. Furthermore, wooden pallets are also collected at landfill areas where they are often recovered from other types of urban wood wastes [27]. These locations are not considered as a potential location of wooden pallet materials in estimating the geographic supply in this analysis. Rather, it is assumed that these pallets will be collected by pallet recycling companies if the market for chipped pallet materials will grow.

4.4.4 Certification

To guarantee the sustainability of biomass, several sustainability standards, criteria and certification schemes have been developed [40]. The most widely used voluntary schemes are Green Gold Label (GGL), Laborelec Label and the Drax Power Sustainability principles [41]. Although EU wide mandatory sustainability criteria for solid biomass used for electricity and heat generation are still under discussion, some EU member states, including Belgium and the United Kingdom, already implemented sustainability requirements in national policy schemes. In the Netherlands, sustainability criteria are still under development, but also in the Netherlands, almost all wood pellets imported from the U.S. are certified as required by end-users [41]. Because these countries are the main importing countries of wood pellets from North America [1], hardly any market exists if the produced pellets cannot be certified.

Sikkema et al. [42] assessed the suitability of existing certification systems for the selected resources in this analysis and identified two suitable systems: GGL and NTA 8080. Unmerchantable forest residues and pole mill residues are similar to wood categories that are already widely used for the production of certified wood pellets and could be certified using existing certification schemes. In contrast, no certified wood pellets have been produced from post-consumer wood waste sources yet. Because post-consumer wood wastes are not covered in GGL [42], additional lab tests are required to guarantee that clean wood is being used for the pellets produced from discarded transport pallets. NTA 8080 recognizes clean post-consumer wood wastes in the classification list of biomass sources for bioenergy purposes: NTA 8003. As long as category A wood is being used (clean unpainted wood), the pellets could be certified with NTA 8080. Until post-consumer wood sources are covered in GGL, NTA 8080 is therefore the preferred certification system [39].

If used for electricity generation in Europe, greenhouse gas reductions of over 85 % could be achieved which is well above the minimum threshold of 60 % as required in the UK [42] and recommended by the EU [43]. Pellets produced from post-consumer wood resources may also be subject to import/export legislations by the Competent Authorities of the Shipment Regulation. Up to now however, category A (clean wood) is exempted from this regulation [39].

4.5 Technical barriers

Unmerchantable forest residues are often pushed up and piled before chipping [9] leading to possible contaminations with soil and sand and pole peelings have high bark contents [10]. These contaminations could reduce pellet dye life resulting in high repair and maintenance. Test batches produced from unmerchantable forest residues and pole peelings demonstrate that it is possible to produce qualified pellets [42]. Impurities in discarded pallets should be avoided before chipping. Nails can and are removed from the chipped pallet stream using magnets, but laminated timber, sometimes used to repair pallets, could result in dye clogging. Furthermore, glued laminated wood or painted wood falls under category B wood waste implying legislative and certification barriers if exported or imported [39].

4.6 Conclusion

This analysis assessed the potential of alternative, low-value wood resources available for wood pellet production that are currently under or unutilized in the southeast of the U.S. (Florida, Georgia, North Carolina, and South Carolina). A selection of potential resources was made based on criteria of suitability for wood pellet production, demand (unused, used for low-value purposes such as furnace fuel) and potential availability. The selected wood sources include: unmerchantable forest residues, pole mill residues and discarded wooden transport pallets.

At 22 $ Mg(dry) (excluding transport to a pellet plant), the total dry wood potential of the selected resources is estimated to be 1.9 Tg y^{-1} and increasing to 5.1 Tg y^{-1} at 33 $ Mg^{-1} (dry) or less. This could be processed into 4.1 Tg y^{-1} wood pellets taking into account the dry matter losses from feedstock drying and pelletization. These resources could therefore contribute substantially to the domestic supply or expected imports of wood pellets to the European Union (15 Tg to 30 Tg wood pellets in 2020).

The supply of these wood fiber sources is geographically dispersed. There are only few pole mills and pallet recycling companies in proximity to pellet plant locations and, although the production of unmerchantable forest residues is common in the southeast of the U.S., both the quantity and locations of production from often small areas, do change substantially over years. Based on the geographic supply potential and existing locations of pellet plants and the total cost of feedstock procurement and supply to these pellet plant locations, the least cost location of pellet production is estimated to be in Georgia. At an optimal pellet production capacity of 125 Gg y^{-1}, pellets could be produced for 85 \$ Mg^{-1} compared to 89 \$ Mg^{-1} in North Carolina and 92 \$ Mg^{-1} in Florida. The optimal size and cost of pellet production are sensitive to the estimated supply of resources. More conservative supply estimates could reduce the optimal size of the pellet plant in Georgia with almost 50 % and increase pellet production cost to 90 \$ Mg^{-1}. Furthermore, these cost estimates assume that all wood resources are available at each pellet plant location. When pellet plants are located in the same sourcing areas, competitive use could increase the cost of feedstock supply to the individual pellet plants.

These cost estimates do exclude the logistic cost of pellet transport, storage and handling between the pellet plant, the export shipping terminal and loading to a bulk ocean carrier. Nevertheless, it is expected that pellets from these wood resources can be produced at competitive costs compared to conventional pellets in the southeast of the U.S. with export FOB spot prices of 140 to 155 \$ Mg in 2012 and could therefore be an economically attractive case for export to Europe.

This analysis only assumes three resources to be available. In reality, multiple wood resources are available that are underutilized or discarded as waste. These wood sources could be mixed with conventional sources of wood pellet production, such as sawdust or even pulpwood for fuel diversification. Discarded pallets and other types of post-consumer waste wood have the lowest market value, but the potential is limited and for some post-consumer wood sources, advanced cleaning methods are required. The potential of unmerchantable forest residues in the southeast of the U.S. is large. However, both the economic potential, i.e. the potential that can be mobilized at competitive costs, and sustainable potential, i.e. the potential that can be removed under sustainability restrictions, are uncertain. More research is therefore required to quantify the economic and sustainable potential of these wood resources.

Appendix Chapter 4

Table A 4-1 Wood samples of candidate wood fiber sources for wood pellet production, collected in Georgia (U.S.) [10].

Description	Criteria		Supply	Demand	Moisture mass fraction: MC (%); Ash mass fraction: Ash (%)			
Wood chips produced from land clearing and premerchantable harvest forest management activities (hardwood chips)	Sustainability: Contaminations: Logistics:	+ Negligible[a] +	High	Moderate	MC Ash	35.5 1.4	- -	42.9 2.0
Pine, whole tree (softwood chips)	Sustainability: Contaminations: Logistics:	- [b] Negligible -/0 [c]	High	Moderate	MC Ash	49.8 1.0	- -	50.0 1.1
Pole mill residues (ground/chipped softwood)	Sustainability: Contaminations: Logistics:	+ Negligible + [d]	Low	Low	MC Ash	15.7 0.5	- -	18.9 1.3
Pine wood residues from animal bedding production (fines, dust, shavings)	Sustainability: Contaminations: Logistics:	+ Negligible + [d]	Moderate	Low	MC Ash	7.0 0.5	- -	9.5 2.1
Bald cypress, sawmill residues (chips and sawdust)	Sustainability: Contaminations: Logistics:	+ Negligible + [d]	Moderate	Seasonal[e]	MC Ash	46.9 0.4	- -	57.3 0.5
Chipped wooden transport pallets that cannot be recycled (hardwood chips)	Sustainability: Contaminations: Logistics:	+ Negligible[f] -	High	Low	MC Ash	23.3 0.9	- -	24.8 1.5
Ground wood wastes from limbs, power line clearings, residential wood waste, construction debris (mixed softwood & hardwood)	Sustainability: Contaminations: Logistics:	+ High[g] +	High	Moderate	MC Ash	28.1 12.6	- -	32.4 52.1

a) Potentially contaminated with bark, sand and soil leading to higher ash contents than clean wood.
b) The use of whole trees for energy purposes is considered less sustainable than wood residues and wood wastes.
c) High moisture content increases logistic costs
d) There are only few pole mills / animal bedding plants located within proximity of a potential pellet plant location.
e) Available outside the mulch season (spring - early summer)
f) Nails are removed from ground pallets using double magnets. Paper and plastic are removed with manual selection.
g) Urban wood wastes are potentially contaminated with plastic and ferrous metals. There are options to remove most of these contaminations to develop a 'clean' wood stream.

Table A 4-2 Pellet production cost and feedstock composition for optimal plant sizes and locations per supply scenario and state in the southeast of the U.S.. Pellet plant data from [33, 35, 44].

		Main supply 2012 (a)				Lower bound supply 2012 (b)				Upper bound supply 2012 (c)			
Location		FL	GA	NC	SC	FL	GA	NC	SC	FL	GA	NC	SC
Selected size	Mg_{ar} pellets y^{-1}	165 103	125 039	260 083	211 008	105 015	65 858	120 004	105 595	110 126	185 900	190 085	315 546
	Mg_{dry} pellets y^{-1}	153 257	116 068	241 423	195 868	97 480	61 133	111 394	98 019	102 224	172 562	176 447	292 905
Wood demand[a]	Mg_{dry} wood y^{-1}	197 457	141 209	313 830	246 987	124 559	72 586	146 069	120 119	131 242	214 224	224 249	375 402
Average moisture content	Mass fraction	41 %	34 %	42 %	38 %	39 %	31 %	42 %	34 %	40 %	36 %	39 %	40 %
Raw material input shares													
Other removals, at 22 $ Mg_{dry}^{-1}	Mass fraction	40 %	58 %	48 %	40 %	32 %	48 %	50 %	34 %	79 %	66 %	73 %	44 %
Other removals, at 33 $ Mg_{dry}^{-1}	Mass fraction	41 %	0 %	36 %	33 %	46 %	0 %	38 %	27 %	0 %	0 %	0 %	35 %
Pole peelings	Mass fraction	12 %	34 %	3 %	23 %	19 %	49 %	6 %	36 %	8 %	26 %	2 %	17 %
Chipped discarded pallets	Mass fraction	8 %	8 %	14 %	4 %	3 %	2 %	6 %	2 %	13 %	7 %	25 %	4 %
Raw material cost pellets	$ Mg^{-1} pellets	42.9	36.2	42.7	44.2	45.0	35.7	44.2	45.3	37.4	36.3	38.8	43.4
Raw material cost drying	$ Mg^{-1} pellets	9.1	6.1	9.6	8.5	9.1	5.3	10.2	7.6	8.0	6.7	7.8	9.0
Capital cost[a]	$ Mg^{-1} pellets	15.4	16.8	13.5	14.3	17.7	20.4	17.0	17.7	17.4	14.9	14.8	12.7
Insurance	$ Mg^{-1} pellets	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Consumables and replacement parts[b]	$ Mg^{-1} pellets	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
O&M[c]	$ Mg^{-1} pellets	6.0	6.5	5.3	5.6	6.9	8.0	6.6	6.9	6.8	5.8	5.8	5.0
Labor[d]	$ Mg^{-1} pellets	4.8	5.3	4.2	4.5	5.6	6.4	5.3	5.6	5.5	4.7	4.6	4.0
Electricity[e]	$ Mg^{-1} pellets	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Total pellet production cost	$ Mg^{-1} pellets	**92.3**	**84.9**	**89.2**	**91.1**	**98.2**	**89.7**	**97.2**	**97.0**	**89.0**	**82.4**	**85.8**	**88.0**

Table A 4-2 (continued) Pellet production cost and feedstock composition for optimal plant sizes and locations per supply scenario and state in the southeast of the U.S.. Pellet plant data from [33, 35, 44].

		Pole peelings and discarded pallets only 2012 (d)				Unmerchantable forest residues only 2012 (e)				Main supply 2020 (f)			
		FL	GA	NC	SC	FL	GA	NC	SC	FL	GA	NC	SC
Selected size	Mg_{ar} pellets y^{-1}	60 494	60 079	55 286	70 402	150 410	195 164	227 780	161 008	155 145	120 804	275 076	215 071
	Mg_{dry} pellets y^{-1}	56 154	55 768	51 319	65 351	139 618	181 161	211 437	149 455	144 013	112 137	255 339	199 639
Wood demand[a]	Mg_{dry} wood y^{-1}	60 609	59 694	56 016	69 954	188 741	244 900	285 828	202 039	181 570	135 383	331 397	251 160
Average moisture content	Mass fraction	20 %	18 %	22 %	18 %	46 %	46 %	46 %	46 %	38 %	33 %	42 %	38 %
Raw material input shares													
Other removals, at 22 $ Mg_{dry}^{-1}	Mass fraction	0 %	0 %	0 %	0 %	42 %	56 %	53 %	52 %	38 %	54 %	49 %	39 %
Other removals, at 33 $ Mg_{dry}^{-1}	Mass fraction	0 %	0 %	0 %	0 %	58 %	44 %	47 %	48 %	33 %	0 %	34 %	33 %
Pole peelings	Mass fraction	54 %	81 %	17 %	81 %	0 %	0 %	0 %	0 %	14 %	37 %	3 %	23 %
Chipped discarded pallets	Mass fraction	46 %	19 %	83 %	19 %	0 %	0 %	0 %	0 %	15 %	9 %	15 %	5 %
Raw material cost pellets	$ Mg^{-1} pellets	47.4	35.9	44.6	47.5	43.0	42.1	42.4	43.4	42.9	36.0	42.9	44.2
Raw material cost drying	$ Mg^{-1} pellets	3.4	2.4	3.7	3.1	11.2	11.0	11.0	11.3	8.4	5.8	9.5	8.4
Capital cost[a]	$ Mg^{-1} pellets	20.9	20.9	21.4	20.0	15.9	14.7	14.1	15.6	15.7	17.0	13.2	14.2
Insurance	$ Mg^{-1} pellets	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Consumables and replacement parts[b]	$ Mg^{-1} pellets	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5	4.5
O&M[c]	$ Mg^{-1} pellets	8.2	8.2	8.4	7.8	6.2	5.7	5.5	6.1	6.1	6.6	5.2	5.6
Labor[d]	$ Mg^{-1} pellets	6.6	6.6	6.7	6.3	5.0	4.6	4.4	4.9	4.9	5.3	4.2	4.5
Electricity[e]	$ Mg^{-1} pellets	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Total pellet production cost	$ Mg^{-1} pellets	**100.4**	**87.9**	**98.9**	**98.6**	**95.2**	**92.1**	**91.4**	**95.3**	**92.0**	**84.7**	**88.9**	**90.9**

a) Total equipment cost, storage and warehouse cost (7.8 % of building & office space capital cost), indirect cost (24 % of equipment, storage and warehouse capital cost) and contingency (10 % of total capital cost). Reference plant: 75,000 Mg pellets y-1, scale factor: 0.7. b) Replacement parts and consumables (dies and rollers and spare parts for the hammer mill). c) Service and maintenance cost pellet and hammer mill 10 % of capital pellet and hammer mills. Service and maintenance cost other 2 % of remaining capital investments [44]. d) Labor cost: 20 $ h^{-1}. e) Electricity use: 148 kWh Mg^{-1} pellets, electricity price: 54.8 $ MWh^{-1}.

References Chapter 4

[1] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. Renew Sust Energ Rev 2012; 16(5): 3176-99.

[2] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, et al. Wood pellet market and trade: a global perspective. Biofuel Bioprod Bior 2013; 7(1): 24-42.

[3] Lamers P, Marchal D, Heinimö J, Steierer F. Chapter 3: Global Woody Biomass Trade for Energy. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[4] Cocchi M, Nikolaisen L, Junginger M, Goh CS, Heinimö J, Bradley D, et al. Global Wood Pellet Industry Market and Trade Study. IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. 2011. 190 p.

[5] SELC. Biomass Energy in the South - MAPS [internet]. 2013. [cited 2013 July]. Available at: http://www.southernenvironment.org/cases/biomass_energy_in_the_south/maps/.

[6] BBI International. Biomass Magazine - Pellet Plants - USA [internet]. Grand Forks, ND: BBI International; 2013. [cited 2013 January]. Available at: http://www.biomassmagazine.com/plants/listplants/pellet/US.

[7] McKeever DB, Howard JL. Solid Wood Timber Products Consumption in Major End Uses in the United States, 1950 - 2009 - A Technical Document Supporting the Forest Service 2010 RPA Assessment. United States Department of Agriculture Forest Service. 2011.

[8] Hess JR, Jacobson JJ, Cafferty K, Vandersloot T. International Energy Agency (IEA) Task 40 Sustainable International Bioenergy Trade: Securing Supply and Demand Country Report 2010 - United States. Idaho Falls, ID; Idaho National Laboratory, Kansas State University. 2010.

[9] Perlack RD, Stokes BJ, (Lead Authors). U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. Oak Ridge, TN; Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy under contract DE-AC05-00OR22725. 2011, August. 227 p. . ORNL/TM-2012/224.

[10] Meyers S. Identifying sources of woody biomass for the purpose of pelletizing. Fram Renewable Fuels, LLC. 2011.

[11] Bentley J. Background data for the Timber Product Output (TPO) database: mill residue factors. Knoxville, TN; USDA Forest Service, SRS-FIA. 2012, February.

[12] Johnson TG, Bentley JW, Howell M. The South's timber industry - an assessment of timber product output and use, 2007. Asheville, NC; U.S. Forest Service. 2009.

[13] White EM. Woody Biomass for Bioenergy and Biofuels in the United States - A Briefing Paper. USDA Forest Service Pacific Northwest Research Station. 2010. PNW-GTR-825.

[14] Smith WB, Miles PD, Perry CH, Pugh SA. Forest Resources of the United states - A Technical Document Supporting the Forest Service 2010 RPA Assessment. USDA Forest Service. 2009. WO-78.

[15] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials-Methodological lessons from review of state of the art bioenergy potential assessments. Renew Sust Energ Rev 2012; 16(9): 6598-630.

[16] Conner RC, Adams TO, Johnson TG. Assessing the Potential for Biomass Energy Development in South Carolina. Asheville; United States Department of Agriculture Forest Service - Southern Research Station. 2009.

[17] USDA Forest Service. SRS TPO reports [internet]. U.S. Department of Agriculture Forest Service - Southern Research Station,; 2011.

[18] UCS. The Promise of biomass Clean Power and Fuel - If Handled Right. Union of Concerned Scientists (UCS). 2012.

[19] Vis MW, Berg Dvd. Harmonization of biomass resource assessments - Volume I: Best Practices and Methods Handbook. 1st ed. Biomass Energy Europe (BEE). 2010.

[20] Walsh M. Bioweb - Other removals [internet]. Sun Grant Initiative and the University of Tennessee; 2008. [cited 2013 July]. Available at: http://bioweb.sungrant.org/Technical/Biomass+Resources/Forest+Resources/Other+Removals/Default.htm.

[21] UN. Forest Product Conversion Factors for the Unece Region - Geneva Timber and Forest Discussion Paper 49. Geneva, Switzerland; United Nations - United Nations Economic Commission for Europe (UNECE) / Food and Agriculture Organization of the United Nations (FAO). 2010. ECE/TIM/DP/49.

[22] Mazeika Bilbao A, Carrano AL, Hewitt M, Thorn BK. On the environmental impacts of pallet management operations. Management Research Review 2011; 34(11): 1222-36.

[23] Araman P. Additional background information to the Updated Pallet and Container Industry Production And Recycling Research report (2008). Blacksburg, Virginia; Virginia Tech - Department of Wood Science and Forest Products. 2012.

[24] Franklin Associates. Life Cycle Inventory of Wood Pallet Systems - Final Summary Report. Prairie Village, Kansas; Franklin Associates - A Division of ERG. 2007.

[25] Buehlmann U, Bumgardner M, Fluharty T. Ban on landfilling of wooden pallets in North Carolina: an assessment of recycling and industry capacity. J Clean Prod 2008; 17: 271-275.

[26] Buehlmann U, Araman P, Bush R. Pallet re-use and recycling saves high value material from landfills. Engagement Matters 2010; 2(1): 8,10.

[27] Bush RJ, Corr DT, Araman PA. Fewer Pallets Reaching Landfills, More Are Processed for Recovery. Pallet Enterprise - Pallet and sawmill magazine 2001; May: 18-21.

[28] Bush RJ, Araman PA. Updated Pallet and Container Industry Production And Recycling Research. Blacksburg, Virginia; Virginia Tech - Department of Wood Science and Forest Products. 2008.

[29] NCDENR. Wooden Pallets [internet]. Raleigh, NC: N.C. Division of Environmental Assistance and Outreach; 2012. [cited 2012 August]. Available at: http://portal.ncdenr.org/web/deao/recycling/wp.

[30] Wear DN, Greis JG. Southern Forest Future Project: Summary Report. Asheville, NC; USDA-Forest Service, Southern Research Station. 2011. 54 p. . Gen. Tech. Rep. SRS-GTR-168.

[31] ESRI. Data and Maps for ESRI ArcGIS - North America Detailed Streets [DVD] 2010.

[32] Staudhammer C, Hermansen LA, Carter D, Macie E. Wood to energy: using southern interface fuels for bioenergy. USDA Forestry Service - Southern Research Station. 2011. 89 p.

[33] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass Bioenerg 2004; 27(6): 671-693.

[34] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008; 33(8): 1206-23.

[35] Pirraglia A, Gonzalez R, Saloni D. Techno-economical analysis of wood pellets production for U.S. manufacturers. BioResources 2010; 5(4): 2374-2390.

[36] Obernberger I, Thek G. The Pellet Handbook - The production and thermal utilisation of biomass pellets. London, Washington DC: Earthscan; 2010.

[37] Steppleton C. U.S. Wood-Using Mill Locations - Southern mills [internet]. Asheville, NC: USDA Forest Service Southern Research Station; 2005 (2009 by email request). [cited 2012 February]. Available at: http://www.srs.fs.usda.gov/econ/data/mills/.

[38] Argus. Argus Biomass Markets - Weekly Biomass Markets, News and Analysis 2012; May 2012, July 2012, October 2012, November 2012.

[39] van Dam J, Ugarte S, Spijkers S, Sikkema R, Schipper E. Inbio - B project: The Use of Post-Consumer Waste Wood for Energy Pellets in Europe. SQ Consult, Control Union. 2013.

[40] van Dam J, Junginger M, Faaij APC. From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. Renewable and Sustainable Energy Reviews 2011; 14(9): 2445-2472.

[41] Goh CS, Junginger M, Joudry J, Chum H, Pelkmans L, Smith CT, et al. Impacts of sustainability certification on bioenergy markets and trade - Strategic Inter-Task Study: Monitoring Sustainability Certification of Bioenergy. IEA Bioenergy. 2013, February. 61 p.

[42] Sikkema R, Meyers S, Schipper E. Sustainable import of pellets from the United States (Inbio A project). Zwolle, the Netherlands; Control Union. 2012. 28 p.

[43] European Commission. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling - Report from the Commission to the Council and European Parliament. Brussels, Belgium; 2010, February. COM(2010)11 final.

[44] Mani S, Sokhansanj S, Tagore S, Turhollow AF. Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant - Part 2: Cost of heat and power generation systems. Biomass Bioenerg 2010; 34(3): 356-364.

Chapter 5

International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union

Keywords: Biomass trade; RES policy; Bioenergy; Solid biofuel; GIS

Abstract: This article describes the development of a geographic information systems (GIS) based biomass transport analysis tool BIT-UU used in combination with the European renewable energy model Green-X. BIT-UU calculates cost and GHG emissions from, lowest cost routes, using intermodal transport (by road, rail, inland waterways and sea) between origins of supply and demand destinations. With the developed biomass trade module in Green-X, the role of bioenergy can be evaluated in the larger context of renewable energy deployment. The modeling framework takes into account the current and future energy policies at EU and country levels, competition with alternative sources of renewable energy (e.g. photovoltaic, wind) and sectors (electricity, heat, transport fuels) as well as competition between EU member states for the same biomass resources. Scenario projections to 2020 are used to demonstrate the developed modeling framework. According to these scenarios, biomass from domestic sources remains the most important source of bioenergy (91 % to 93 % in 2020). However, the role of traded solid biomass will become increasingly important. With a business as usual scenario, assuming continuation of current renewable energy policies to 2020, the binding renewable energy targets will not be achieved, but trade of solid biomass will still increase up to 451 PJ in 2020. In the scenario that meets the conditions to achieve the 20 % renewable energy target in 2020, traded solid biomass is projected to increase to 440 PJ if sustainability criteria are applied (minimum GHG saving) and 506 PJ without sustainability regulations. Because imports of solid biomass from outside the EU are projected to become larger than intra-EU trade in the scenarios, the scenarios show the importance of improving the representation of extra-EU biomass sources and trade in the modeling framework.

Submitted to: *Applied Energy*. Co-authors: Gustav Resch (Vienna University of Technology), Martin Junginger (Utrecht University), André Faaij (Utrecht University).

5.1 Introduction

The substitution of fossil energy carriers by renewable sources of energy has become one of the key challenges to mitigate greenhouse gas (GHG) emissions and to improve energy supply security by diversification and reducing dependencies on imported fossil energy carriers. Especially in the European Union (EU), where member states have agreed on binding targets for renewable energy generation, as laid down in the renewable energy directive (RED) 2009/EC/28 [1]. These country specific targets are aimed to increase the share of renewable energy in total gross final energy consumption in the EU to 20 % in 2020. The trajectories of how EU member states project to achieve these binding targets have been published in the National Renewable Action Plans (NREAPs) in 2011. The NREAPs include detailed information per sector (transport, electricity, heat), renewable energy type (e.g. wind, photovoltaic, biomass), capacities deployed and total renewable energy generated as well as current and future policy plans to achieve these targets. Bioenergy is expected to remain the largest source of renewable energy to 2020 with over 54 % of renewable energy in 2020 projected to be generated from biomass resources [2] providing almost 12 % of gross final energy consumption in the EU [3]. Therefore, bioenergy generation has to increase with 44% between 2010 and 2020 with 90 % growth in bio-based electricity, 22 % in production of heat from biomass and 129 % in biofuels [2].

Residential uses of solid biomass, are mainly based on domestic biomass resources. However, industrial sectors (i.e. for centralized heat, combined heat and power (CHP) or electricity generation in co-firing or dedicated electricity plants) where the largest growth is anticipated, have become increasingly dependent on imported biomass, in particular wood pellets [4-6]. Imports of wood pellets in the EU increased from 1.9 Tg in 2009 to 4.6 Tg in 2012 and are foreseen to increase to 15 Tg to 30 Tg in 2020 depending on economic factors, policies and the availability of domestic biomass resources [4-6]. Although many EU member states consider increasing imports of biomass, so far few EU member states have quantified the expected amounts of imported biomass. Likewise few countries have indicated possible countries to import from in their national renewable action plans (NREAPs) [7]. However, there is little information about the role of imported biomass. This can be explained by uncertainties in the volumes available, costs, the impact of sustainability criteria, the demand in competing importing regions and the competition with other renewable energy technologies. Bioenergy is a renewable, but not infinite source of energy and with the increasing demand and international trade of bioenergy, safeguarding the production and use of biomass in a sustainable way has become increasingly important [8]. Imports of biomass from third countries or from other EU member states, could improve the cost-effectiveness of renewable energy generation as well as supply security. On the other hand, it could as well shift import dependencies from fossil resources towards bioenergy [9].

To assess the potential role of biomass at the EU level an integral analysis is required that encompasses the complexities of international biomass supply and biomass demand markets that are not provided in the NREAPs. These include consequences of policy choices and the application of policy instruments. The dynamic characteristics of the future biomass supply potentials and costs, international competition for resources with food, feed and fiber markets and developments in agriculture and bioenergy conversion systems as well as developments in other renewable energy systems, e.g. wind or photovoltaic are key variables to be included. At the EU level, the roadmaps of renewable energy deployment and policy plans in the NREAPs have been evaluated [10-13] as well as the role of bioenergy in the EU to 2020 and beyond [2, 3]. Although bioenergy is covered in many energy modeling studies, only few studies assess bioenergy trade flows triggered by possible fluctuations in domestic supply and demand of bioenergy sources [14]. So far, the most comprehensive evaluation of bioenergy in the EU with biomass trade is provided in van Stralen et al. [2]. Van Stralen et al. [2] used the biomass potentials available from the Biomass Futures project [15] and the RESolve models to assess the feasibility of bioenergy in the NREAPs and possible biomass trade. Biomass trade in RESolve is based on distances between countries in Europe and the related fixed handling and variable transport costs of road, rail or short sea shipping. Biomass supply from outside Europe is aggregated in a single supply node [16].

Transport is a crucial component of the biomass supply chain and can add substantially to the total cost and GHG performances depending on the geographic locations of supply and demand as well as available transport networks [17], e.g. sea ports or inland waterways in land locked regions. For example, logistic cost can make up 40 % to 60 % of total ethanol production cost [18]. However, energy system models used in these studies tend to generalize the representation of costs, energy requirements and GHG emissions of logistic operations [19] and lack infrastructure specifications and geo-spatial features [17]. Another key aspect that needs to be covered is the evaluation of bioenergy in context of the dynamic development of other renewable energy sources as well as optimal uses of biomass uses from a policy support perspective. For example, cooperation between EU member states using harmonization mechanisms (renewable energy certificate trading) and virtual exchange of renewable energy might reduce the costs of renewable energy generation [20]. In other cases, it might be more effective to trade biomass between EU member states or import biomass from third countries. These effects can be modeled with the Green-X model. Green-X is a partial equilibrium model of the (renewable) energy sector that covers a detailed characterization of renewable energy technologies, their potentials and as well as renewable energy policy descriptions at member state level using country profiles [21]. However, in previous studies, the Green-X model did not allow for trade of biomass between EU member states and included a simplified representation of imports from third countries. Given the large contribution of biomass in renewable energy supply, this was an important limitation.

The main objective of this article to describe the structure, methodology and related data requirements of a geographic explicit modeling framework to assess supply, demand and trade of solid biomass in the EU27. Secondly, scenarios of renewable energy support policies and GHG sustainability criteria are analyzed with Green-X and compared with the NREAPs to demonstrate the modeling approach and show possible implications of bioenergy trade. The focus of the analysis is on the impacts of renewable energy support policy assumptions on the deployment of renewable energy (electricity, heat, transport) in the EU27 to 2020.

5.2 Methodology

This article demonstrates the extension of the European renewable energy model Green-X with an international biomass trade module. The cost and GHG emissions from logistic operations to move biomass from the sources of biomass supply to end use destinations, including handling, storage, pre-processing and transport have been calculated using the Geographic Information Systems (GIS) based Biomass Intermodal Transportation (BIT-UU) model developed for this purpose[7] [22-24]. The BIT-UU model enables lowest cost route calculations using actual transport networks of road, rail, inland waterways and sea and options to transfer biomass between different modes of transport and the related GHG emissions. GIS based biomass logistics are applied in a wide range of studies, e.g. to optimize the locations of biorefineries [25, 26] or to calculate the logistic costs of individual intercontinental shipping routes [24]. However, such a geographic explicit representation of biomass transport has not been applied yet in combination with a (renewable) energy model, such as demonstrated with Green-X in this article. Consequently, the biomass trade module in Green-X model combined with the BIT-UU model, enables the evaluation of renewable energy scenarios taking biomass trade as well as sector, commodity and country specific sustainability criteria into account including the GHG emissions of biomass logistics specific to the specific biomass trade routes. Since this article aims for an analysis of trade aspects, the subsequent assessment focusses on the use of solid biomass for energy purposes.

5.2.1 Characterization of Green-X

Green-X is a dynamic toolbox originally developed to analyze how cost-effective deployment of renewable electricity and CHP in Europe can be organized [27], but the current version also covers heat and transport sectors for the EU27 and possible extension to other countries, e.g. Croatia, Norway and Turkey. With Green-X, future deployment of renewable energy can be evaluated with current energy policy instruments (e.g. quota obligations, feed-in tariffs, tax incentives, investment incentives and emission trading). Future scenarios can be manipulated, e.g. to meet the binding RES targets to 2020 in a cost efficient way [27, 28]. Green-X calculates the deployment of renewable energy at country and technology level and associated capital expenditures, consumer expenditures and fossil fuel and GHG avoidance compared to the reference scenarios on a yearly basis up to 2030. In-depth assessments with Green-X are possible until 2020.

[7] Both the international solid biomass trade module and the BIT-UU model were developed within the Re-Shaping project [22], a projected supported by the “Intelligent Energy Europe” program of the European Commission, Executive Agency for Competitiveness and Innovation, and co-funding received through IEA Bioenergy Task 40 [23].

Green-X includes detailed representations of renewable energy policies which have been updated to 2011 based on the renewable energy country profiles in Teckenburg et al. [21]. The impact of possible combinations and interaction of policy instruments can be evaluated taking into account the dynamics of technological learning and technology diffusion, final energy demand and energy prices. Technology diffusion, following S shaped curves, can be altered by the parameterized mitigation of non-economic barriers. Technological learning and the technology diffusion characteristics as applied in Green-X are discussed in detail in Hoefnagels et al. [29].

Projections of the conventional (fossil) energy generation mix, the final and primary energy demand and related CO_2 intensities by sector and fossil fuel prices are exogenously applied to the Green-X model. For reasons of consistency with EU energy assessment studies and outlooks, the PRIMES[8] Baseline [30] and PRIMES High Renewables scenario projections have been used (Table 5-4). The PRIMES High Renewables scenario is, amongst others, used in the Energy Roadmap 2050 [31]. Input parameters specific to renewable energy systems (RES) are based on Green-X. Biomass trade parameters are specified in this analysis.

5.2.2 Model set-up for biomass trade specifications

To address for biomass trade endogenously in the Green-X modeling framework, two components have been added. An intra-European biomass trade module was added to allow each individual member state to compete for the biomass resource potentials available in the EU27 (Figure 5-5). Secondly, biomass sustainability restrictions can be applied to evaluate the impact of sustainability criteria. These include threshold values for minimum GHG savings. The GHG saving potential depends on the source of biomass, the supply chain and end conversion type. The GHG saving performance of CHP plants is often better than stand-alone electricity generation. It is therefore possible that biomass can meet the restrictions applied if used for CHP, but not for standalone electricity as calculated endogenously in Green-X. Furthermore, small scale generation of heat and electricity (< 1 MW) can be exempted from these criteria in the Green-X model. Figure 5-1 shows the model set-up of the extended Green-X model with intra-European solid biomass trade and with sustainability criteria.

Green-X is comprised of a series of input databases and scenario information and framework conditions linked to the Green-X calculation tool (see Figure 5-1, arrow (a)). The Green-X biomass database includes the potentials and cost of biomass supply at country level in Europe as well as possible wood pellet supply via third country imports. The biomass trade module developed in this study uses the same biomass database, but for each tradable commodity (excluding mainly gaseous biomass), time period and possible route of intra-European biomass trade, the biomass trade module adds the cost

[8] PRIMES is an agent based, price driven energy system model 35 countries in Europe and widely used in European energy assessment and outlook studies by the European Commission [30].

and GHG emissions implied by the logistic operations required (b). Green-X calculates the combined cost and revenues for each possible bioenergy resource and conversion system combinations allowed within the policy framework conditions. These scenario conditions change over time and include for example support incentives for heat and electricity generation and non-economic barriers that hamper the deployment of renewable energy technologies. For non-EU resources of biomass, the supply potentials are split by country of origin, reflecting differences in feasible import volumes, costs and specific GHG emissions that are associated with land use change, harvesting and transport to the EU. The extended Green-X model can model competition on biomass supply and demand at the country level as well as competition between EU member states affected by country and sector/technology specific support incentives for heat and electricity generation and competing renewable energy technologies (c).

The additional costs and GHG emissions associated with biomass trade are specific per biomass commodity and specific between countries. The cost and GHG emissions of logistic operations required are calculated with the GIS based BIT-UU model. BIT-UU is an analysis toolset developed with ESRI's ArcGIS Network Analyst extension [32] using geographic databases (f) combined with spreadsheet based input assumptions (e). The BIT-UU model uses the OD cost matrix analysis tool of ESRI's ArcGIS Network Analyst extension [32] to calculate the least cost path along the intermodal transport networks available in the BIT-UU model for all possible origins of biomass supply to all destinations of biomass demand (g) and added to the domestic biomass supply input data (d).

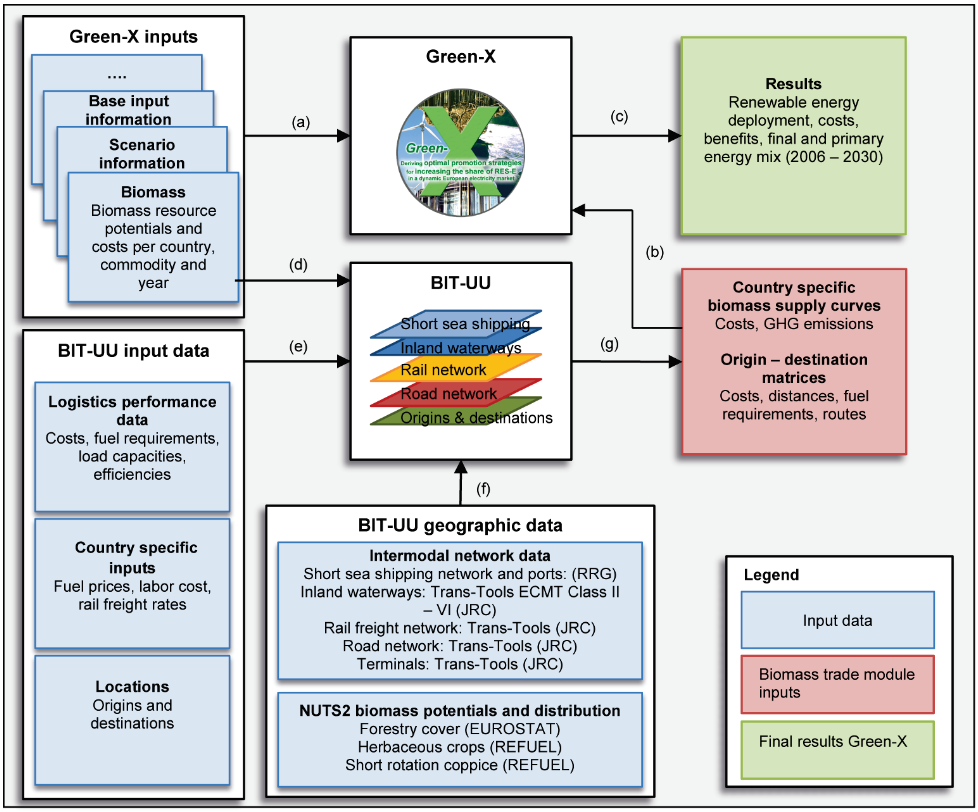

Figure 5-1 Overview of the modelling approach, components and data inputs for solid biomass trade in Green-X

5.2.3 Biomass logistics

5.2.3.1 Feedstock supply chains

The operations required to move biomass from the field or forest to end users depend on the type of biomass, e.g. herbaceous or woody biomass, the origin of supply, e.g. saw dust available at sawmills or straw available at field sides and distance to the end user. Figure 5-2 shows the biomass supply chains considered in this analysis. Herbaceous biomass sources (straw, switchgrass, miscanthus) are baled at field side and transported by truck to end users if used domestically (see Figure 5-2, arrow (a)). If herbaceous biomass is exported internationally, bales are transported to a central gathering point (CGP) and pelletized before long distance transportation (c). Forestry biomass is chipped in the forest and transported by truck to end users, if used domestically, or transported to a CGP and either transported as chips (b) or pelletized before long distance transportation if exported to other countries (c). The cost and GHG emissions of the logistic operations between field side and the CGP and domestic end users are calculated with an Excel tool. Long distance, international transportation is calculated with the BIT-UU model, described in Section 2.3.4.

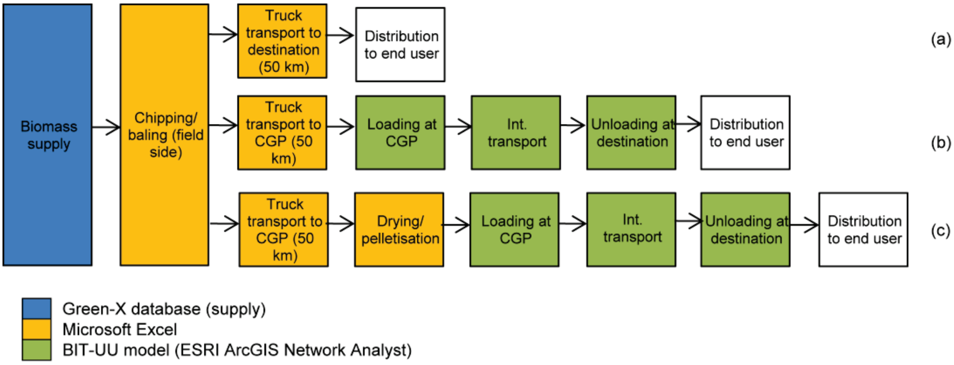

Figure 5-2 Lignocellulosic biomass feedstock supply chains.

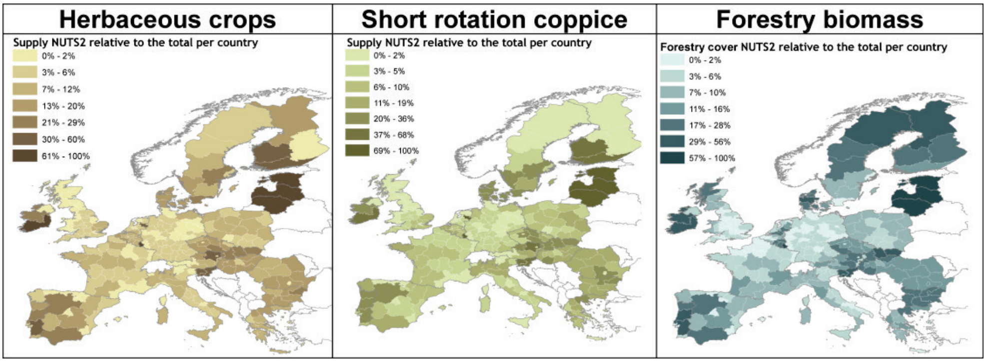

Figure 5-3 Geographic distribution of biomass supply. Supply fractions per NUTS2 region are calculated relative to the total supply at the country level of herbaceous crops and short rotation coppice from the REFUEL project and forestry cover per country in Europe from EUROSTAT [33, 34].

5.2.3.2 Biomass supply locations

Green-X includes a detailed, country specific database of actual production potentials of biomass for bioenergy to 2030, also referred to as 'implementation-economic biomass potential' [35, 36] as discussed in Section 3.2. The biomass supply and cost in Green-X are specified for each country, year and crop type as explained in detail in Hoefnagels et al. [29].[9] The future cost of the different biomass feedstock categories as used in the model

[9] To summarize briefly, the market assessment was based on the processing of statistical information on agriculture and forestry (for instance, FAOSTAT, Eurostat), complemented by other related information, as applicable from the National Renewable Energy Action Plans, as well as previous / on-going assessments in this

reflect correlations between developments in crude oil prices and feedstock-specific production costs. The effects of technological learning[10] in harvesting and transport, scale and possible imbalances in supply and demand could affect biomass feedstock prices substantially, but are not taken into account. Because biomass in Green-X is specified to the country level, the database is combined with the geographic biomass potentials at the NUTS2 level of dedicated energy crops (both herbaceous and short rotation coppice) from the REFUEL project[11] for the middle scenarios [34, 37, 38] to estimate the distributed supply within each country. For forestry products and residues, the fraction of forest cover at the NUTS2 level relative to the forest cover per country is used to estimate the geographic distribution using EUROSTAT data [33]. The geographic distribution per biomass type is shown in Figure 5-3.

5.2.3.3 Biomass pre-processing

The techno-economic performance parameters of biomass pretreatment (chipping, pelletization) are depicted in Table 5-1. The energy requirements and related GHG emissions for pretreatment are derived from the reports of the JRC [39] for willow crops and the European Commission [40]. Chipping cost are based on Hamelinck et al. [41]. The cost for pelletization are based on Thek and Obernberger [42], but corrected for inflation (Eurozone 1 $€_{2002}$ = 1.09 $€_{2006}$).

---

topical area. A non-exhaustive list of studies on potentials and costs for biomass considered for this analysis includes the EU FP7 project "Biomass Energy Europe" (for European potentials), the own analysis conducted within the RE-Shaping project as well as the corresponding global assessment as undertaken within IEA Bioenergy Task 40 on bioenergy trade. Moreover, previous studies conducted at the European level (for instance, the REFUEL project) provided useful insights.

[10] Note that technological learning, related to the conversion technology, is appropriately taken into account in the overall modelling framework.

[11] The Intelligent Energy Europe (IEE) project REFUEL (Renewable Fuels for Europe) was conducted under contract number EISAS/EIE/05/042/2005 between 2006 and 2008 and coordinated by ECN. The main goal of the project was to develop a realistic roadmap for biofuels in Europe up to 2030. The project included a detailed assessment of biomass supply potentials and cost for different scenarios in the EU27+ region [34, 37, 38].

Table 5-1 Cost and energy requirements of biomass pre-treatment

Parameter	Unit (output)	Wood chips	Wood pellets	Pellets (wood proc. Residues)[a]
Scale	Mg/h	10	10	10
Load factor		90	0.91	0.91
Capital	M€	0.2	1.06	0.62
	€/Mg[b]	0.2	13.7	8.07
O&M	€/Mg	0.4	6.2	0
Electricity	MJ/Mg		1260	720
Diesel	MJ/Mg	50	36	36
Heat	MJ/Mg		4235	847
Total cost[c]				
2010	€/Mg	1.7 - 2.2	51 - 53.9	42.8 - 45.9
2020	€/Mg	2 - 2.5	53 - 56.3	44.8 - 48.3

a) Reduced energy requirements and capital due to the physical properties of the feedstock (mainly sawdust).
b) Discount rate = 7 %.
c) The production cost differ per country due to variable energy prices

5.2.3.4 International transportation

The BIT-UU runs in ESRI’s ArcGIS Network Analyst extension an calculates the lowest cost routes between origins and destinations using an intermodal transportation network. Transport network layers (networks) in the BIT-UU model are derived from TRANS-TOOLS ("TOOLS for TRansport Forecasting ANd Scenario testing"), a decision support model for transport impact analyses [43]. TRANS-TOOLS includes major roads, rail (freight) and 6 classes of inland waterways (IWW) in Europe. Short sea shipping (SSS) has been added to the BIT-UU model using the short sea shipping network data from RRG [44]. The network model uses 4 different types of network data for each mode of transport (road, rail, IWW, SSS):

- Transport network links
- Transport network nodes
- Terminal connectors
- Terminal nodes

Network links represent existing transport networks (e.g. roads or rail lines) and attribute fields (the specifications that can be added to each individual link in the network dataset, e.g. distance, maximum allowed speed, tolls [45]) used to calculate the variable cost and GHG emissions per mode of transport. Transport network nodes are access/egress locations at network link locations, e.g. highway entrees or rail and inland waterway terminals. Figure 5-4 demonstrates how different transport network link layers are connected via terminal nodes and terminal connectors. Terminal connectors connect transport network nodes with transfer terminals where biomass can be transloaded between different transport modalities, e.g. from truck to ship. The terminal connectors include attribute fields to calculate the cost and GHG emissions of loading and unloading of biomass. Terminal nodes represent intermodal facilities where biomass can be transloaded between different modes of transport. Terminal nodes are assumed to be located in the geographic centers of NUTS3 regions because the actual locations of the intermodal terminals are not included in the TRANS-TOOLS database.

The intermodal transport route, depicted in Figure 5-4, shows biomass transport by truck to an intermodal terminal facility where it is transferred to a ship, that has relatively low variable transport cost compared to a truck. Finally, biomass is transferred back to a truck to reach the destination. At longer overland transport distances (> 100 km), such an intermodal transport route is often cost effective over unimodal transport (single transportation mode), despite the additional fixed cost to transfer biomass between different modes of transport [17, 41].

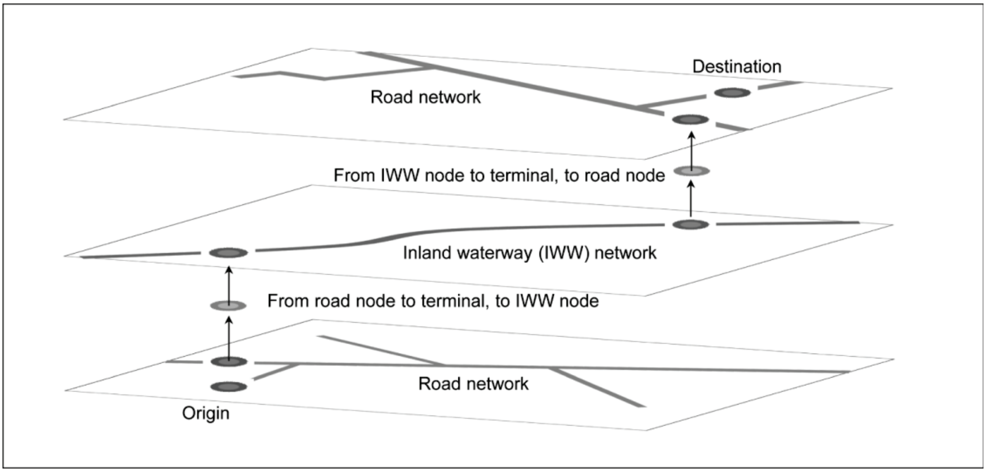

Figure 5-4 Intermodal transport network concept in the BIT-UU model, adapted from [46].

5.2.3.5 Transport input parameters

The cost and performance assumed for biomass transport per type of transport mode and transloading between each mode transport in the BIT-UU model are depicted in Table 5-2. Labor cost, based on hourly cost in Europe [47], excise duties and value added tax (VAT), based on transport statistics [48], are country specific as covered in in Hoefnagels et al. [22]. The total specific cost of transport are in turn different in each country. Furthermore, the allowed speed, which varies per road type and toll cost impact the total cost of transport. For inland navigation (IWW), four ship types are included that depend on the size of the waterway following the ECMT (European Conference of Ministers of Transport) classification [49].

Table 5-2 Performance parameters of transport parameters included (based on NEA [50], TML 2005 [51], Smeets et al.[52])

Network	Unit		Rail	Inland waterways per CEMT class				
				Cl II	Cl III	Cl IV	Cl V	Cl VI
Transport mode		Truck (EU)	Hopper cars (EU)	Small, dry bulk	Middle, dry bulk	Large dry bulk	Large dry bulk 2	Large dry bulk push tug
Labor (FTEs)	Person h^{-1}	1		1.3	1.4	2.6	2.6	3.8
Time cost	€ h^{-1}	18.4		10.3	21.9	72.2	106.7	214.2
Variable cost	€ km^{-1}	0.30		0	0	0.74	0.93	17.84
Rail freight rates	€ Mg^{-1} km^{-1}		0.03-0.15					
Fuel type		Diesel	Diesel	MDO	MDO	MDO	MDO	MDO
Fuel consumption full	MJ km^{-1}	13	207	220	314	470	470	717
Fuel consumption empty	MJ km^{-1}	8	207	177	272	425	425	661
Maximum load weight	Mg	27	1,820	550	950	2,500	2,500	10,800
Maximum load volume	m^3	120	4,550	642	1,321	3,137	3,137	14,774
Speed (max)	km h^{-1}	80	80	5.4	5.8	6.7	8.6	9.0
Loaded trips of total trips[a]		56 %	50 %	71 %	85 %	77 %	77 %	83 %

a) Based on statistics of dry bulk in the Netherlands (average utilization including empty returns).

5.2.4 Cost and GHG emissions

The costs of solid biomass production and logistic operations required to supply biomass to final conversion capacity are calculated using eq. 5-1. Because no by-products are generated for the feedstock supply systems included in this analysis, eq. 5-1 also applies to the GHG calculation before conversion to final energy (heat, electricity).

$$C_{fd} = C_{cult} + C_h + C_{proc1} + C_{T1,2} + C_{proc2} + C_{T3} \qquad \text{eq. 5-1}$$

With:

C_{fd} = cost of biomass feedstock supply
C_{cult} = cost for cultivation
C_h = cost of harvest and collection
$C_{T1,2}$ = cost of transportation between the biomass supply source and CGP or end user if used domestically (50 km)
C_{T3} = cost of intermodal transportation between the CGP and end user (variable transport and fixed handling cost)
C_{proc1} = cost of processing at field side (e.g. baling, chipping)
C_{proc2} = cost of processing at CGP (pelletization).

For each NUTS2 region of biomass supply and each NUTS1 region of demand, the cost and GHG emissions of feedstock supply are calculated with the BIT-UU model. Based on the NUTS2 geographic distribution of biomass (Figure 5-3), the weighted average transport cost from origin countries are calculated (eq. 5-2) for each country and type of biomass. These country to NUTS1 results are processed into country-to-country matrices by assuming that 50 % will be supplied to the NUTS1 destination with the lowest cost of supply and 50 % will be distributed equally among the destinations per country assuming average supply cost.

$$C_{x,y} = \sum_{i=1}^{n} (c_{x,y,i} \times w_{x,i}) \qquad \text{eq. 5-2}$$

$C_{x,y}$ = feedstock delivery cost from EU country *x* (origin) to NUTS1 region *y* (destination)
$c_{x,y,i}$ = feedstock delivery cost from NUTS2 region *i* in EU country *x* (origin) to NUTS1 region *y* (destination)
$w_{x,,i}$ = fraction of the biomass feedstock potential in NUTS2 region *i* of EU country *x*

The GHG reduction performance relative to the fossil reference systems for electricity and heat are calculated consistent with the methodology of the European Commission [40]. The performance depends on the actual conversion efficiency and the type of bioenergy system (electricity, heat or CHP). For CHP systems, allocation by exergy is applied to calculate the system performance with the fraction of exergy in electricity set at 1.0 and in the fraction of exergy in useful heat generation is calculated with the Carnot efficiency as explained in detail in Annex I of COM(2010)11 [40]. The fossil fuel comparators used in this analysis to calculate the GHG emissions of the biomass feedstock supply chains and fossil reference systems used to calculate the GHG reduction performance are consistent with the parameters proposed by the European Commission [40] as shown in Table 5-3.

Table 5-3 GHG emission values of fossil fuels and fossil reference systems used to calculate the GHG saving performance of bioenergy generation [40, 53].

Energy source/reference	Total (direct + indirect) GHG emissions (g. CO2-eq MJ^{-1})
Diesel/MDO[a]	87.4
Heavy fuel oil (HFO)	85.0
Electricity mix EU27 (fossil)[b]	198.0
Heat[c]	77.0

a) Marine diesel oil (MDO) is assumed to have similar emissions to diesel.
b) For consistency reasons, the fossil electricity mix, used to calculate the GHG savings from biobased electricity generation, is also used in the GHG calculations of biobased supply chains.
c) Reference to calculate the GHG savings from biobased heat generation.

5.3 Scenarios

5.3.1 Renewable energy support

In this article, 4 scenarios are included, that differ in renewable energy policy and are either without or with (‘bsc’) sustainability criteria for solid biomass (Table 5-4). The business as usual (BAU) scenarios assume a continuation of the current national renewable energy support mechanisms and policies with prevailing non-economic barriers. These non-economic barriers include administrative deficiencies (e.g. a high level of bureaucracy), diminishing spatial planning, problems associated with grid access, possibly missing local acceptance, or even the nonexistence of proper market structures [54]. In Green-X this is parameterized in low diffusion settings of the diffusion curves. The diffusion rates are derived from an econometric assessment of past diffusion rates of renewable energy technologies. The strengthened national support (SNP) scenarios assume non-economic barriers to be mitigated meaning that the maximum growth rate of renewable energy deployment will be equal to best practices observed from the econometric assessment [29]. Secondly, the renewable energy policy instruments and levels of support are increased or changed to meet the overall EU target of 20 % renewable energy in gross final energy consumption in 2020.

Table 5-4 Overview of the scenarios and key scenario assumptions

Scenario name	BAU	BAU-bsc	SNP	SNP-bsc
National renewable energy policies	Business as usual	Business as usual	Strengthened national support	Strengthened national support
Fossil energy deployment	Baseline (PRIMES)	Baseline (PRIMES)	High Renewables (PRIMES)	High Renewables (PRIMES)
Sustainability constraints for biomass	No	Yes	No	Yes
Non-economic barriers mitigated	No	No	Yes	Yes

5.3.2 Biomass supply

5.3.2.1 EU Biomass supply

Resources of solid biomass included in Green-X assume actual production, import and use categories and costs. Figure 5-5 shows the Green-X potential for bioenergy that stems from solid biomass in the EU27 per feedstock type as used in this analysis. Sources of solid biomass in Green-X include energy crops (AP), agriculture residues (AR), forestry products (FP), forestry residues (FR) and the biodegradable fraction of municipal solid waste (BW). The total supply potential of domestic biomass in the EU27 is estimated to increase from 6.5 EJ in 2005 to 9.7 EJ in 2020. Growth in bioenergy supply is mainly driven by dedicated energy crops (AP), of which the total supply increases with 66 % between 2010 and 2020. The strongest growth is assumed for lignocellulosic energy crops (short rotation coppice, miscanthus, switchgrass). The average cost and cost ranges of lignocellulosic biomass supply per feedstock category are provided in Table 5-5. A detailed discussion of the biomass resource potentials in Green-X compared to other resource assessments is provided in the supplementary information and in Hoefnagels et al. [29].

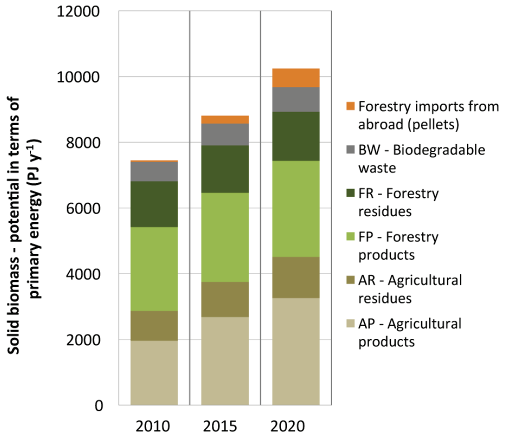

Figure 5-5 Break down and development of resource potential for biomass in Green-X between 2010 and 2020 (excluding biogas and imports of biofuels).

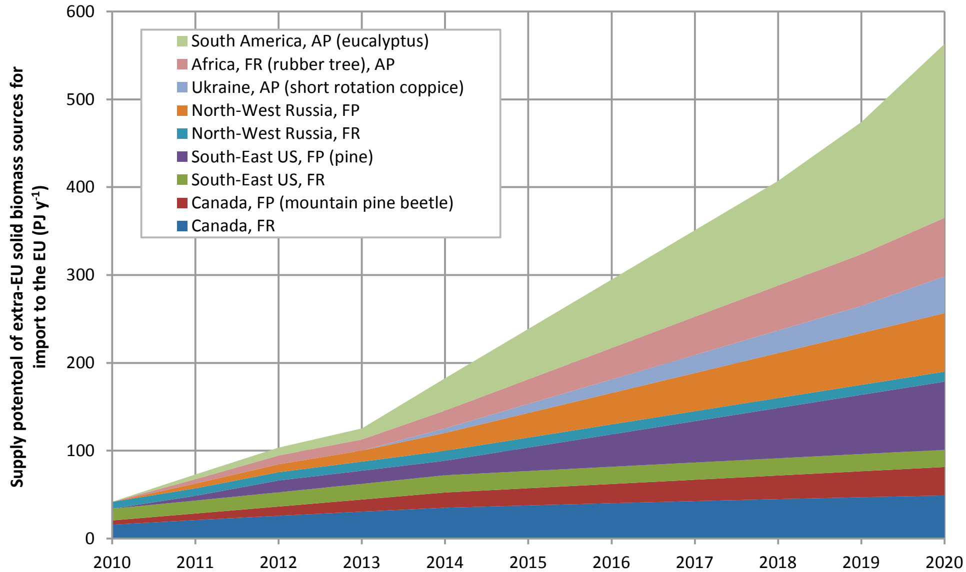

Figure 5-6 Break down of supply potentials of forestry imports from abroad (extra-EU sources available for import to the EU27) [4, 23, 55, 56].

5.3.2.2 Non-EU biomass supply potential

The future supply potential of extra-EU supply of solid biomass in the scenarios is based on actual trends of wood pellet production in major supply regions, press releases and market prognoses and scenario studies, mainly [55, 56]. Future projections of lignocellulosic biomass supply from current and potential key exporting regions are aggregated to wood pellet supply from extra-EU resources as shown in Figure 5-5. The breakdown of the total supply potential of extra EU imports is shown in Figure 5-6.

In 2010, wood pellets to Europe where mainly supplied by Canada (West and East), the Southeast of the U.S., Northwest Russia [4]. Although demand from competing regions in Asia (e.g. in South Korea and Japan), might become increasingly important in the future [57], these exporting countries are expected to remain export-oriented to Europe up to 2020. Furthermore, additional supply from short rotation coppice is anticipated from countries that have pulp wood plantations established in South America (Brazil, Uruguay) and Africa (West Africa, Mozambique). In northwest Russia, developments in wood pellet supply markets have been erratic, but might still grow substantially with large private investments [4]. Furthermore, a large supply potential of agriculture products and agriculture residues has been identified in Ukraine [34]. Currently, only wood pellets from agriculture residues are exported from Ukraine (sun flower husk are exported from Ukraine to Poland [58]) and the potential of energy crops remains untapped. The potential of pellets from Ukraine and northwest Russia, aggregated in the Common wealth of Independent States (CIS) in Figure 5-6.

In total, the potential supply of extra-EU biomass supply for the EU27 is projected to increase to 560 PJ y^{-1} primary biomass in 2020, equivalent to 32 Tg y^{-1} wood pellets. It should be noted that the supply potential, as considered in the scenarios in this article is relatively high compared to other studies. For example, in Lamers et al. [59], the total supply potential of extra-EU solid biomass available for the EU27 is anticipated to increase to 17.5 Tg in 2020. Also Goh et al. [4] show that, in a business as usual scenario, the supply potential of solid biomass might be substantially lower (269 PJ in 2020).

The estimated cost of solid biomass imports to Europe are based on CIF ARA spot prices of wood pellets at 125 $€_{2010}$ Mg^{-1} (net calorific value: 18 MJ kg^{-1}) [58] and corrected for inflation to the cost base year of Green-X (2006) to 6.3 € GJ^{-1} in 2010. In this study, supply cost are assumed to remain constant apart from the effects of increasing fossil fuel prices that partly also affect the production and supply cost of biomass (e.g. from increased transport fuel cost). Future price effects from market developments, the availability of biomass resources, competing demand, learning and supply chain optimization, e.g. the use of advanced pre-treatment methods [60] or larger ships [24] are not covered in the scenarios. Imported wood pellets from outside the EU are assumed to be available for each EU member state at 6.3 $€_{2006}$ GJ^{-1} in 2010, increasing to 6.5 $€_{2006}$ GJ^{-1} in 2015 and 7.2 € GJ^{-1} as a result of increasing crude oil prices in the scenarios.

5.3.2.3 Sustainability criteria

In this analysis, the impact of sustainability criteria for solid biomass is assessed for a GHG threshold value. Binding GHG sustainability criteria for imported solid biomass are applied in the 'bsc' scenarios. In these scenarios, minimum GHG savings of 60 % are required for solid biomass uses in electricity and heat generation which is consistent with the GHG savings from biofuels and bioliquids produced in plants that started production in 2017 [1] and will potentially also be applied to electricity and heat generation from solid biomass [61].

The impact of sustainability criteria on the total cost and supply of biomass is difficult to quantify and there are few studies that have addressed these topics. Smeets et al. [62] assessed the impact of sustainability criteria on the procurement cost and supply potential of short rotation coppice production in Ukraine and Brazil. With sustainability criteria applied, the weighted average cost could increase with 0.7 € GJ^{-1} in Brazil and 0.3 € GJ^{-1} in Ukraine, mainly as a result of additional labor cost. Sikkema et al. [63] assessed the impact of sustainable forest certification on the cost and supply of forestry biomass for bioenergy purposes. Although part of the supply potential cannot meet the sustainability criteria, the impact on supply cost remains small. Furthermore, the assumed cost of wood pellet imports from outside the EU are based on current wood pellet prices of which the major share is already certified [64].

The GHG threshold as applied in the cases with sustainability criteria takes into account emissions from biomass cultivation, processing, international trade and end use efficiencies as explained in Section 5.2.4. Thereby, possible carbon releases from forest harvesting (carbon debt) or land use change emissions are taken into account in calculating the GHG balance of the wood pellet supply chains. In this context Figure 5-7 shows the assumed potentials for solid biomass imports to the EU27 as well as specific LCA GHG emissions by country/region of origin. It should be noted that the underlying assumptions are highly uncertain, mainly as a result of data limitations.

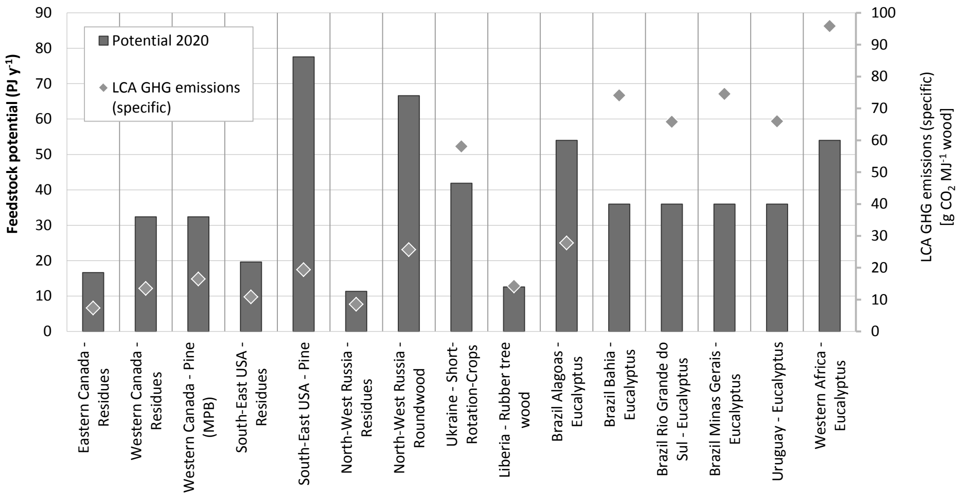

Figure 5-7 Feedstock potentials for 2020 and related GHG emissions for assumed solid biomass import streams to the EU27.

5.4 Results

5.4.1 Feedstock supply cost

Table 5-5 summarizes the average cost and ranges of feedstock supply at farm gate, the total cost of biomass if used domestically and the total supply cost if exported to other EU member states including the cost of pretreatment (chipping, baling, pelletization), transport and handling. The farm gate cost of biomass vary per feedstock type and country of origin. Wood processing residues (FR5) are cheapest (0.9 € GJ^{-1} to 2.4 € GJ^{-1}), but are assumed to need pelletization to improve the physical characteristics of sawdust. Therefore, domestic supply of wood chips from forest residues (FR2) can be supplied at lower cost if used domestically. The cost for pelletization add substantially to the total cost of biomass supply (over 3 € GJ^{-1}). The average cost of wood chips are therefore cost effective over wood pellets for intra-European biomass supply. For example, wood chips from forestry products (FP1) are on average 5.9 € GJ^{-1} compared to 8.1 € GJ^{-1} for wood pellets from the same feedstock in 2010 high cost upper ranges are the result of long distance, expensive transport routes between EU member states that will never be selected in the Green-X scenarios. At the upper cost levels of these supply chains is, for example, pellets from miscanthus cultivated in Sweden and exported to Spain (17.4 € GJ^{-1} in 2020). Pelletization of agriculture residues and grassy crops is cheaper (average 1.5 € GJ^{-1}) than forestry biomass (average 3.1 € GJ^{-1}) because drying is only required for woody biomass. Certified wood pellets imported from outside the EU can be supplied at competitive cost (6.3 € GJ^{-1} to 6.5 € GJ^{-1}) to the supply of wood chips and pellets from forestry residues imported from other EU member states (average 5.5 € GJ^{-1} to 6.0 € GJ^{-1}) depending on the regions of supply and demand.

Table 5-5 Supply chain cost of domestic and Intra-European supply per biomass feedstock type (€ GJ^{-1} primary biomass)

Feedstock	Transported as	Year	Feedstock (farm gate)[a]		Domestic[b]		Export[c]	
			Av.	Range	Av.	Range	Av.	Range
AP4 (SRC willow)	Chips	2010	6.3	5.7 - 7.1	7.1	6.4 - 7.7	9.1	6.8 - 12.8
		2020	8.1	7.3 - 9.0	8.9	8.0 - 9.7	10.9	8.4 - 14.4
	Pellets	2010	6.3	5.7 - 7.1			11.2	9.4 - 13.9
		2020	8.1	7.3 - 9.0			13.1	11.1 - 15.8
AP5 (miscanthus)	Bales/pellets[d]	2010	8.2	6.9 - 9.3	9.0	7.9 - 10.0	11.5	8.9 - 14.8
		2020	10.4	8.8 - 11.8	11.3	9.9 - 12.6	13.9	10.8 - 17.4
AP6 (switch grass)	Bales/pellets[d]	2010	8.2	6.9 - 9.3	8.2	5.2 - 9.3	10.7	6.6 - 13.7
		2020	10.4	8.8 - 11.8	10.2	6.5 - 11.7	12.8	7.9 - 16.1
AR1 (straw)	Bales/pellets[d]	2010	3.0	2.7 - 3.6	3.8	3.5 - 4.3	6.8	4.9 - 9.5
		2020	3.7	3.3 - 4.5	4.7	4.3 - 5.2	7.6	5.6 - 10.4
FP1 (forestry products - current use (wood chips, log wood) and FP2 (forestry products - complementary fellings (moderate))	Chips	2010	5.2	4.2 - 6.1	5.9	5.1 - 6.6	8.1	5.8 - 12.2
		2020	5.9	4.8 - 6.9	6.7	5.7 - 7.5	8.9	6.5 - 13.1
	Pellets	2010	5.2	4.2 - 6.1			10.2	8.3 - 13.0
		2020	5.9	4.8 - 6.9			11.1	9.2 - 14.0
FP3 (forestry products - complementary fellings (expensive))	Chips	2010	7.6	6.4 - 8.5	8.3	7.4 - 9.0	10.5	8.2 - 14.3
		2020	8.6	7.3 - 9.7	9.4	8.3 - 10.2	11.7	9.3 - 15.5
	Pellets	2010	7.6	6.4 - 8.5	11.0	10.0 - 11.8	12.6	10.8 - 15.1
		2020	8.6	7.3 - 9.7	12.2	11.1 - 13.1	13.8	11.9 - 16.4
FR2 (forestry residues - current use) and FR3 (forestry residues - additional)	Chips	2010	2.6	1.1 - 4.4	3.4	2.0 - 4.7	5.5	2.5 - 10.1
		2020	3.0	1.3 - 5.0	3.8	2.2 - 5.4	6.0	2.8 - 10.8
	Pellets	2010	2.6	1.1 - 4.4			7.6	5.2 - 11.0
		2020	3.0	1.3 - 5.0			8.1	5.6 - 11.7
FR5 (additional wood processing residues (sawmill, bark)	Pellets[e]	2010	1.6	0.9 - 2.4	4.5	3.9 - 4.9	6.0	4.6 - 8.4
		2020	1.9	1.0 - 2.8	4.9	4.1 - 5.4	6.4	4.9 - 8.9
FR6 (forestry imports from abroad)[f]	Pellets	2010					6.3	
		2020					6.5	

a) Farm gate cost excluding processing (baling/chipping/pelletization). The feedstock cost vary per country.
b) Processing (baling/chipping/pelletization and transport of 50 km by truck)
c) Intra-European transport, based on lowest cost routes between countries. Emissions depend on distance and used transport modes (ship, rail, truck).
d) Bales for domestic use, if traded internationally, bales are transported by truck to a pelletization plant (50 km). Pellets are exported.
e) No chips available (part of this stream exists of saw dust).
f) The estimated costs are based on CIF ARA spot prices of wood pellets at 125 $€_{2010}$ Mg^{-1} (net calorific value: 18 MJ kg^{-1})

The GHG emissions of the feedstock supply chains at farm gate (cultivation) and including transport for domestic uses and ranges if exported to other EU member states are depicted in Table 5-6. Wood pellets from short rotation coppice (willow) have the highest emissions, mainly resulting from pelletization and transportation if used internationally. However, the upper bound of the GHG ranges in Table 5-6 (22.9 g. CO_2-eq MJ^{-1}) still meets the GHG saving threshold value of 60 %, as imposed in the BAU-bsc and SNP-bsc scenarios, if used for electricity generation with a net conversion efficiency of 30 %.

Table 5-6 Greenhouse gas emissions related to the total supply chain of domestic and Intra-EU supply per biomass feedstock type in Green-X (g. CO2-eq MJ^{-1} primary biomass)

Feedstock category	Transported as	Cultivation[a]	Domestic use[b]	International transport[c]							
				2010				2020			
				Average	Range			Average	Range		
AP4 (SRC willow)	Chips	2.0	2.7	8.2	3.0	-	16.9	7.4	2.9	-	13.7
	Pellets	2.6	12.9	16.7	13.1	-	22.9	16.2	13.0	-	20.6
AP5 (miscanthus)	Bales/pellets[d]	3.6	5.0	13.0	9.1	-	19.5	12.4	9.0	-	17.1
AP6 (switch grass)	Bales/pellets[d]	3.6	5.0	13.0	9.1	-	19.5	12.4	9.0	-	17.1
AR1 (straw)	Bales/pellets[d]	0.5	1.7	9.4	4.9	-	17.1	8.7	4.8	-	14.3
FP1 (forestry products - current use (wood chips, log wood)	Chips	1.0	1.7	7.2	2.0	-	15.9	6.4	1.8	-	12.7
	Pellets	1.0	11.3	15.2	11.6	-	21.3	14.6	11.4	-	19.0
FP2 (forestry products - complementary fellings (moderate))	Chips	1.0	1.7	7.2	2.0	-	15.9	6.4	1.8	-	12.7
	Pellets	1.0	11.3	15.2	11.6	-	21.3	14.6	11.4	-	19.0
FP3 (forestry products - complementary fellings (expensive))	Chips	1.0	1.7	7.2	2.0	-	15.9	6.4	1.8	-	12.7
	Pellets	1.0	11.3	15.2	11.6	-	21.3	14.6	11.4	-	19.0
FR2 (forestry residues - current use)	Chips	0.0	0.7	6.2	1.1	-	14.9	5.4	0.8	-	11.7
	Pellets	0.0	10.4	14.2	10.6	-	20.3	13.7	10.5	-	18.1
FR3 (forestry residues - additional)	Chips	0.0	0.7	6.2	1.1	-	14.9	5.4	0.8	-	11.7
	Pellets	0.0	10.4	14.2	10.6	-	20.3	13.7	10.5	-	18.1
FR5 (additional wood processing residues (sawmill, bark)	Pellets[e]	0.0	5.6	9.5	5.9	-	15.5	8.9	5.7	-	13.3

a) Emissions for cultivation and harvesting are allocated to primary wood products. The emissions for cultivation of forestry residues are therefore 0. Emissions for preprocessing (chipping) are covered in domestic and international uses.
b) Transport of 50 km by truck
c) Intra-European transport, based on lowest cost routes between countries. Emissions depend on distance and used transport modes (ship, rail, truck).
d) Bales for domestic use, if traded internationally, bales are transported by truck to a pelletization plant (50 km). Pellets are exported.
e) No chips available (part of this stream exists of saw dust).

5.4.2 Renewable energy deployment

The scenarios evaluated in this study are compared with the national renewable energy deployment as provided in the NREAPs (Table 5-7). A larger set of Green-X scenario results and sensitivity cases is provided in Ragwitz et al. [7]. For all scenarios, the assumed biomass sustainability criteria (-bsc) do not result in significant changes to the outcomes of the Green-X scenario projections for the key reason that lignocellulosic biomass chains do almost always meet minimum GHG saving criteria as long as land use change emissions are not considered (Figure 5-7).

With a continuation of current support policies, the BAU scenarios show that the share of renewable energy in gross final energy consumption in the EU27 will remain below 15 % in 2020 if no further actions are taken by EU member states. Some countries, including Austria, Sweden and Finland, are projected to meet their targets with current policies in the BAU scenarios [7], but other member states show large gaps between the national renewable energy targets and the results of the BAU scenarios. These include, amongst others, Italy, Belgium, the Netherlands and the UK, that have become major importers of solid biomass from outside the EU [5].

Note that the gross final energy demands in the BAU scenarios, based on the PRIMES reference scenario, is higher than in the final energy demand in the NREAPs. The PRIMES High Renewables scenario that underlies the gross final energy demand projections in the SNP scenario projections, is more consistent with the NREAPs. Also, the biobased share in gross final energy supply in the SNP scenario (11.6 % bio-based) as well as the bioenergy contributions in electricity, heat and transport are within similar ranges to the NREAP (11.7 %). Green-X does however project larger amounts of advanced biofuels (152 PJ y^{-1} in SNP compared to 97 PJ y^{-1} in the NREAPs), but this will not affect the total amount of lignocellulosic biomass substantially compared to the demand for heat and electricity. Furthermore, at member state level, the differences between the projections of the individual member states in the NREAPs and the Green-X calculations are larger as shown for solid biomass deployment in Figure 5-8.

Figure 5-8 shows the projected growth in renewable energy generation (electricity, heat, 2nd generation transport fuels) from the Green-X scenarios compared to the NREAPs. The key difference between the NREAPs and Green-X SNP scenario results that affects solid biomass trade, is the growth in renewable electricity generation in larger member states. For example, Germany projects 21 % increase in renewable energy generation from solid biomass between 2010 and 2020 compared to 41 % in the SNP scenarios. In contrast, France and the UK expect larger contributions form solid biomass (40 % in France, 86 % in the UK) compared to 29 % in France and 68 % in the UK in the SNP scenario results. The difference is larger in smaller member states (e.g. Belgium and Cyprus), but the impact on EU levels are smaller.

Table 5-7 Renewable energy deployment in the renewable energy scenario projections in the EU27 of Green-X compared to the deployment of renewable energy in the EU27 NREAPs for 2020 [12].

	2010	2020				
		BAU	**BAU-bsc**	**SNP**	**SNP-bsc**	**NREAP[a]**
Electricity (PJ y^{-1})						
Biomass	**379**	**707**	**708**	**945**	**946**	**834**
Biogas	88	199	199	232	237	230
Solid biomass[b]	227	419	420	584	581	558
Biowaste[b]	64	90	90	128	128	
Bioliquids[b]						46
Hydro	1,274	1,344	1,344	1,352	1,352	1,306
PV & solar thermal electricity	129	424	424	392	394	372
Tide & wave and geothermal	26	44	44	48	49	63
Wind	646	902	902	1,763	1,780	1,779
Total renewable electricity	**2,455**	**3,420**	**3,421**	**4,500**	**4,522**	**4,339**
Total gross final consumption	**11,895**	**13,593**	**13,593**	**13,051**	**13,051**	**12,708**
Share	20.6 %	25.2 %	25.2 %	34.5 %	34.6 %	34.1 %
Share biobased	15.4 %	20.7 %	20.7 %	21.0 %	20.9 %	19.2 %
Heating and cooling (PJ y^{-1})						
Biomass	**2,711**	**3,290**	**3,290**	**3,700**	**3,682**	**3,763**
Biogas	49	113	113	125	128	187
Solid biomass[b]	2,538	3,014	3,014	3,354	3,334	3,391
Biowaste[b]	123	164	164	220	220	
Bioliquids[b]						185
Heat pumps, geothermal, solar thermal	154	272	272	492	506	841
Total renewable heating or cooling	**2,865**	**3,562**	**3,562**	**4,192**	**4,189**	**4,672**
Total gross final consumption	**23,502**	**23,873**	**23,873**	**21,869**	**21,869**	**21,796**
Share	12.2 %	14.9 %	14.9 %	19.2 %	19.2 %	21.4 %
Share biobased	11.5 %	13.8 %	13.8 %	16.9 %	16.8 %	17.3 %
Transport[c] (PJ y^{-1})						
First generation biofuels	491	460	460	431	430	677
Second generation biofuels	0	91	91	152	152	97
Imported biofuels	125	287	287	479	479	462
Total renewable biofuels	**616**	**838**	**838**	**1,062**	**1,062**	**1,236**
Total gross final consumption	**14,617**	**15,542**	**15,542**	**14,328**	**14,328**	**13,078**
Share biobased	4.2 %	5.4 %	5.4 %	7.4 %	7.4 %	9.5 %
Total (PJ y^{-1})						
Total renewable energy	**5,936**	**7,820**	**7,821**	**9,754**	**9,772**	**10,247**
Of which biobased	**3,706**	**4,835**	**4,836**	**5,706**	**5,690**	**5,833**
Total gross final consumption	**50,015**	**53,008**	**53,008**	**49,248**	**49,248**	**49,794**
Share	11.9 %	14.8 %	14.8 %	19.8 %	19.8 %	20.6 %
Share biobased	7.4 %	9.1 %	9.1 %	11.6 %	11.6 %	11.7 %

a) NREAP data is derived from the Renewable Energy Projections Tables 1 (Additional Energy Efficiency Scenario) and tables 10, 11, 12 [12].
b) Solid biomass in the NREAP also covers organic wastes. Renewable electricity, heating and cooling from liquid biomass are not covered in Green-X.
c) Excluding renewable electricity transport.

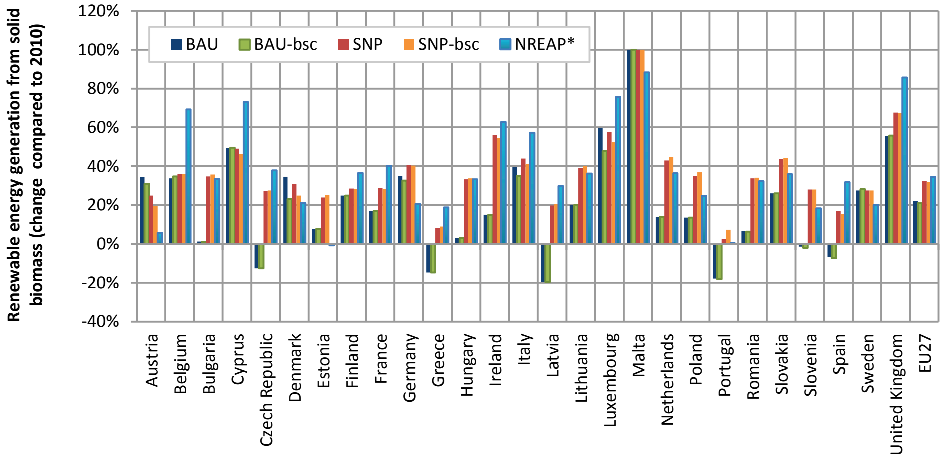

Figure 5-8 Projected changes of renewable energy generation from solid biomass (electricity, heat, second generation biofuels) in 2020 relative to 2010 in the Green-X scenarios and the NREAPs [12].

5.4.3 Solid biomass demand

The Green-X based bioenergy deployment projections and associated demand for primary biomass indicate that primary biomass demand in the EU27 could increase with 26 % from 3.98 EJ in 2010 to 5.01 EJ in the BAU-bsc scenarios in 2020 (Figure 5-9) and increase with up to 47 % (to 5.78 EJ) in the SNP-bsc scenario in 2020 (Figure 5-10). Total primary biomass demands in the scenarios without sustainability criteria (BAU and SNP) are added to illustrate the small differences from the Green-X model projections without sustainability criteria. Forestry products remain largely used for heating purposes in households and are for a large extent supplied form domestic resources. This resource category is difficult to mobilize for other markets due to the decentralized supply. Furthermore, large amounts of these wood products are used by the producers, i.e. private owners themselves or traded on informal markets [65].

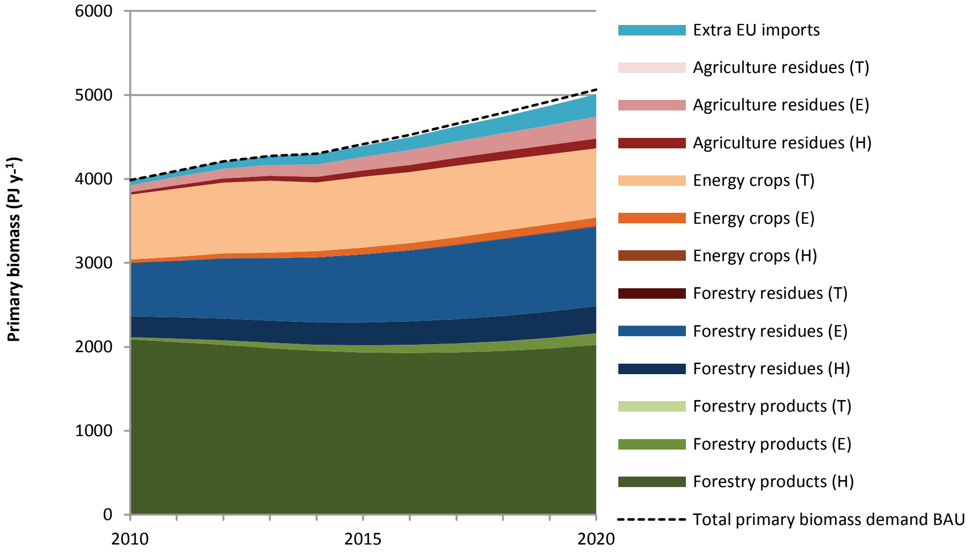

Figure 5-9 BAUbsc scenario: primary biomass demand in the EU27 (excluding wastes and biogas), per feedstock category and end use sector (electricity (E), heat (H), transport (T)) compared to the total primary biomass demand in the BAU scenario (line).

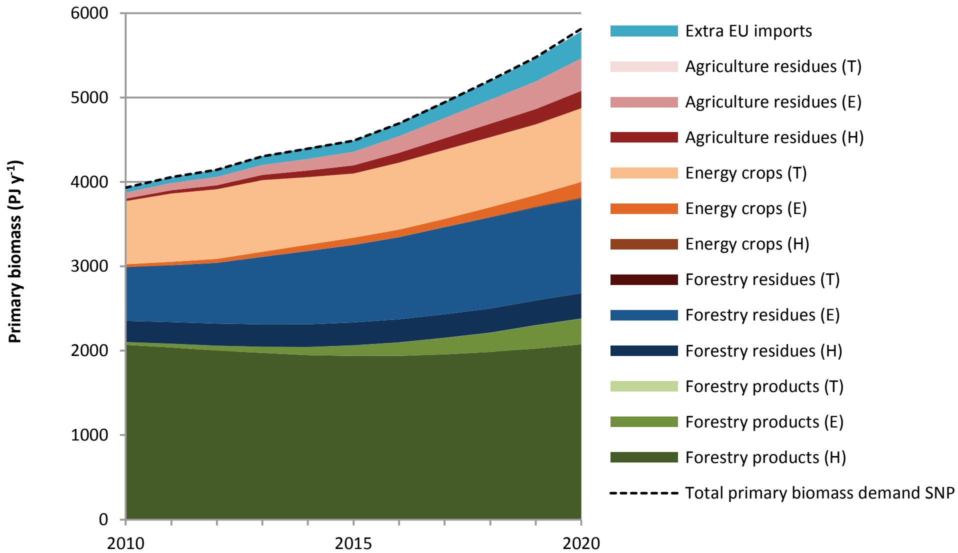

Figure 5-10 SNPbsc scenario: primary biomass demand in the EU27 (excluding wastes and biogas), per feedstock category and end use sector (electricity (E), heat (H), transport (T)) compared to the total primary biomass demand in the SNP scenario (line).

5.4.4 Solid biomass supply and trade

Domestic supply of biomass remains the main source of bioenergy generation in the EU27 in all scenarios. However, the role of internationally traded biomass sources is projected to become increasingly important as a result of growing biomass demand (Figure 5-9, Figure 5-10). Figure 5-11 depicts the trends in bioenergy trade in the EU27 according to the scenarios. In total, intra-EU and extra-EU trade of solid biomass is projected to increase to between 373 PJ (BAU-bsc) and 506 PJ (SNP) equivalent to between 21 Tg and 28 Tg wood pellets. The strongest growth is projected for imports of solid biomass from outside the EU27. Compared to current imports of wood pellets to the EU27 (4.6 Tg in 2012), imports of solid biomass are projected to become 3.2 times larger (15 Tg WPe) in the BAU-bsc scenario to 4.7 times larger (22 Tg WPe) in the SNP scenario in 2020. Intra-EU trade of solid biomass is highest in the SNP-bsc scenario (122 PJ in 2020, 6.8 Tg WPe), but the differences between the scenarios remain small up to 2020. In the scenarios, in which sustainability regulations are assumed, total imports of extra-EU biomass are 18 % (SNP-bsc scenario) to 24 % lower (BAU-bsc scenario) compared to the same scenarios without biomass sustainability criteria resulting from the exclusion of resources that do not meet the GHG saving performance.

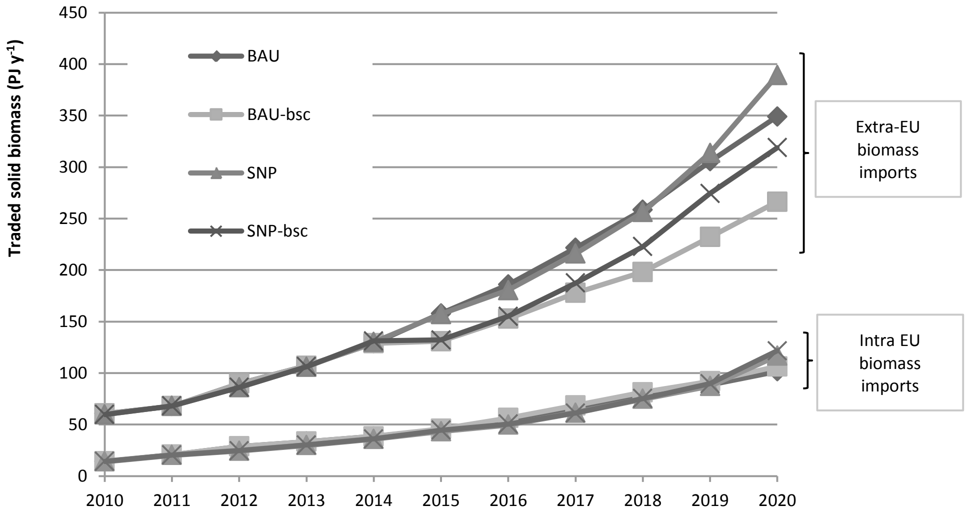

Figure 5-11 Solid biomass consumption from biomass traded within the EU or imported from non-EU resources in the EU27 according to the scenarios.

Figure 5-12 depicts the domestic production, extra-EU imports and net intra-EU imports (import – export) of biomass per EU member state according to the scenario projections for 2020. Countries are ranked based on the net domestic consumption in the scenarios. Domestic biomass production and consumption show consistent patterns between individual member states. Overall, biomass consumption is about 20 % higher in the SNP and SNP-bsc scenarios compared to the BAU and BAU-bsc scenarios.

Germany, France and Sweden remain the largest consumers of biomass for bioenergy, consuming 44 % of the total primary biomass demand in the EU27 in 2010 to 40 % to 44 % in 2020. In 2010, Germany was still a net exporting country of wood pellets (500 Gg in 2010) [58] and wood pellets are only used for heating systems supported via tax exemptions or investment grants [66]. The German feed-in tariff system in the Renewable Energy Act (EEG) only supports small scale biomass CHP systems (up to 20 MW electricity). According to the Green-X model projections, Germany is projected to become the largest importer of solid biomass from outside the EU in the scenarios. In 2020, the total share of extra-EU imports of solid biomass for Germany increases to 51 % (Table 5-8) and is substantially larger than the second largest importing country of non-EU biomass, the UK or France depending on the scenario. For example, the import share of extra-EU biomass in the SNP-bsc scenario for the UK increases only to 8 % in 2020. Note that these results deviate significantly from current market expectations for imports to the decentralized markets in Germany. Similarly, it is expected that far more woody biomass will be imported by the UK to fuel large coal power plants that are or will be converted to biomass, e.g. Drax [59]. The Green-X model projections and uncertainties inherent to these projections are discussed further in Section 5.2.

By 2020, key exporting regions of EU biomass include central and eastern European countries (Bulgaria, Czech Republic, Hungary, Poland, Slovakia, Slovenia) where cheap resources of biomass, such as straw, are abundantly available and forestry rich countries in the Baltic states (Estonia and Latvia). Key regions of intra-EU biomass imports are Germany, with largest imports from Poland and the Czech Republic (mainly agriculture residues) and Austria, with largest imports from Slovenia and Hungary (forestry products and agriculture crops).

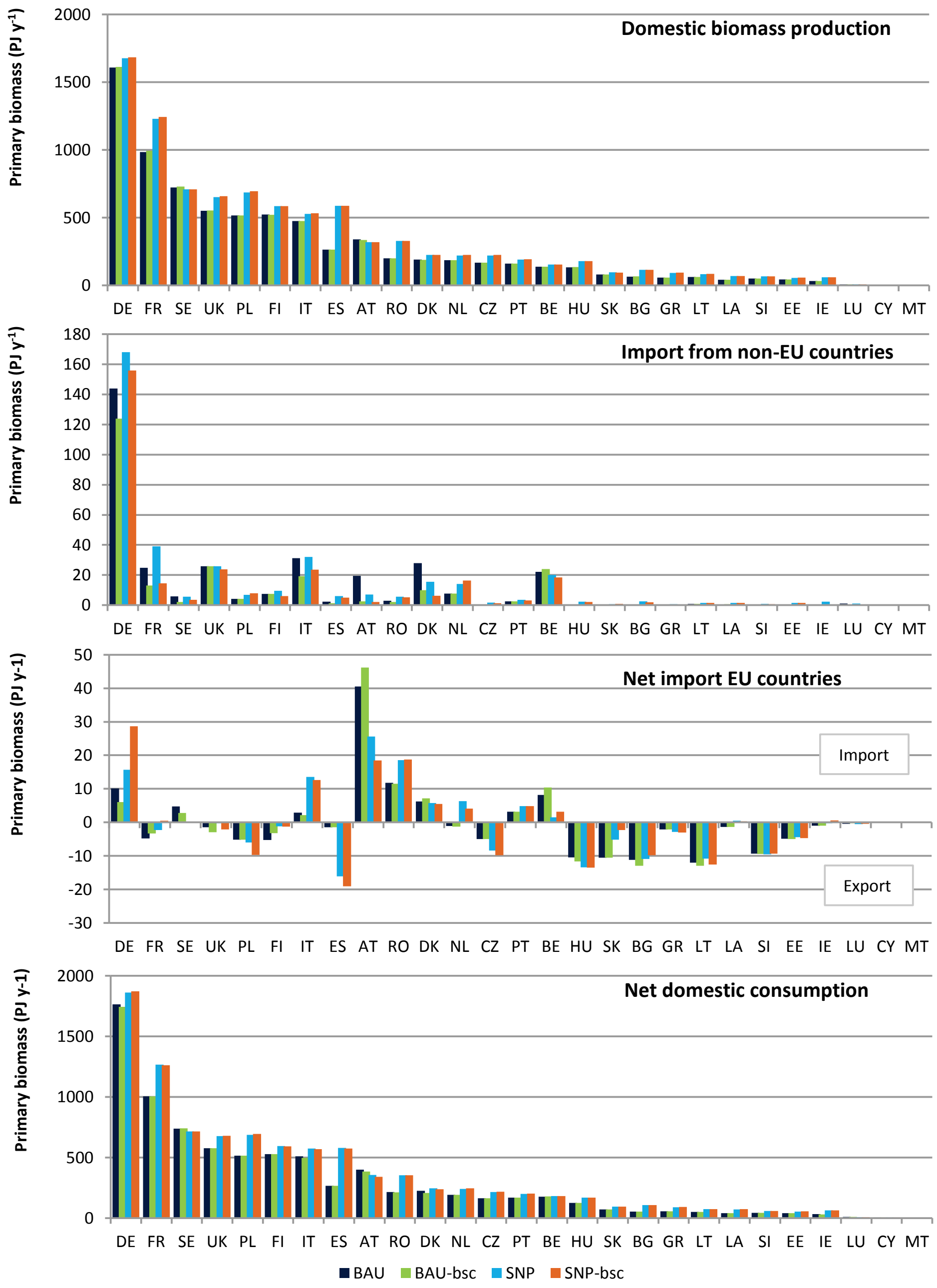

Figure 5-12 Domestic production, import from non-EU countries and net import from EU countries in the Green-X scenario projections for 2020 compared to domestic biomass production and net domestic consumption in 2010 (markers).

The exploitation of domestic biomass resources in the scenarios for 2020 are depicted in Figure 5-13. The total exploitation of the economic-implementation potential of domestic biomass resources is highest in forestry rich countries including Finland and Sweden, but remains below 86 %. In Germany, 71 % to 76 % of the domestic potential is projected to be exploited in 2020 demonstrating that it is more cost effective to import biomass than using more expensive domestic resources such as forestry products or energy crops. Similarly, the total exploitation of the supply potential of non-EU biomass sources is projected to be 47 % in the BAU-bsc scenario to up to 69 % in the SNP-bsc scenario in 2020.

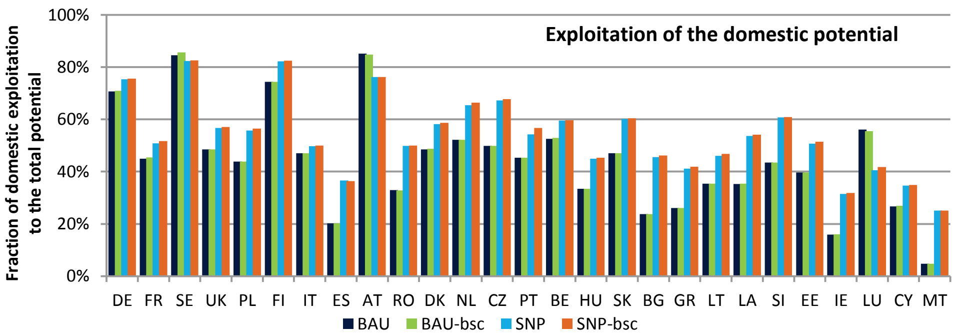

Figure 5-13 Exploitation of domestic biomass supply potentials in the Green-X scenario projections for 2020.

5.4.5 Biomass trade routes

Total intra-EU and extra-EU imports of solid biomass to the EU27 for the BAU-bsc and SNP-bsc scenarios are summarized in Table 5-8 and compared to imports of wood pellets in 2011 according to EUROSTAT [67]. Net intra-EU trade of solid biomass in Green-X is projected to be 1.1 Mg in 2011 (Figure 5-11) compared to 4.5 Tg in 2011 for trade of wood pellets according to EUROSTAT import statistics. These results show that Green-X underestimates intra-EU trade flows of solid biomass. The difference becomes larger if also other types of solid biomass trade would be considered (e.g. wood chips and fuelwood) [6]. Due to the underestimation of current intra-EU trade of solid biomass in Green-X, results for intra-EU imports of solid biomass in 2015 are still below current wood pellet trade figures (2.5 Mg).

The projected intra-EU and extra-EU biomass solid biomass trade flows are depicted for the BAU-bsc scenario in Figure 5-14 and for the SNP-bsc scenario in Figure 5-15. The non-EU origins in Figure 5-14 and in Figure 5-15 represent the aggregated imports from all non-EU regions available in this analysis including North America, South America, Africa, Russia and Ukraine. Almost all EU member states are projected to import solid biomass from outside the EU in 2020, but the main importing countries of extra-EU solid biomass are Germany, France, the UK, Belgium and Italy. Total imports of extra-EU solid biomass to the Netherlands, the second largest importing country of non-EU biomass in (25 % of total extra-EU wood pellet imports), is projected to remain relatively constant (0.9 Tg WPe in 2020 in the SNP-bsc scenario). In comparison, total solid biomass import to the Netherlands in 2011 was 1.4 Tg IEA Task 40 statistics [68] and 0.8 Tg in 2011 according to EUROSTAT. With Germany, currently a net exporting country of wood pellets, becoming the largest importing country of extra-EU biomass according to the scenarios, these model projections indicate that the role of biomass trade in individual member states might be overestimated (Germany) and underestimated (the Netherlands) by the Green-X model.

Table 5-8 Biomass imports in the BAU-bsc and SNP-bsc scenarios in 2015 and 2020.

			BAU-bsc		**SNP-bsc**	
		2011[a]	**2015**	**2020**	**2015**	**2020**
Total imported biomass	**PJ y^{-1}**	**140**	**161**	**356**	**161**	**426**
Of which intra-EU	PJ y^{-1}	82	46	106	45	122
Of which extra-EU	PJ y^{-1}	58	115	250	117	304
Total imported biomass in WPE[b]	**Tg y^{-1}**	**7.8**	**8.9**	**19.8**	**9.0**	**23.6**
Of which intra-EU	Tg y^{-1}	4.5	2.5	5.9	2.5	6.8
Of which extra-EU	Tg y^{-1}	3.2	6.4	13.9	6.5	16.9
Key EU importing countries		DK: 44 %, IT: 16 %, SE: 9 %, Others: 30 %	AT: 36 %, DE: 30 %, RO: 8 %, Others: 19 %	AT: 44 %, DE: 13 %, RO: 11 %, Others: 22 %	DE: 30 %, AT: 27 %, RO: 22 %, Others: 17 %	DE: 25 %, AT: 17 %, RO: 15 %, Others: 30 %
Key non-EU importing countries		UK: 28 %, NL: 25 %, BE: 12 %, Others: 35 %	DE: 46 %, UK: 11 %, BE: 9 %, Others: 26 %	DE: 50 %, UK: 10 %, BE: 10 %, Others: 23 %	DE: 49 %, FR: 9 %, UK: 9 %, Others: 27 %	DE: 51 %, UK: 8 %, IT: 8 %, Others: 27 %

a) Wood pellet trade, based on EUROSTAT statistics of wood pellet imports (CN code 44013020) [67].
b) Wood pellet equivalent (18 MJ kg^{-1}).

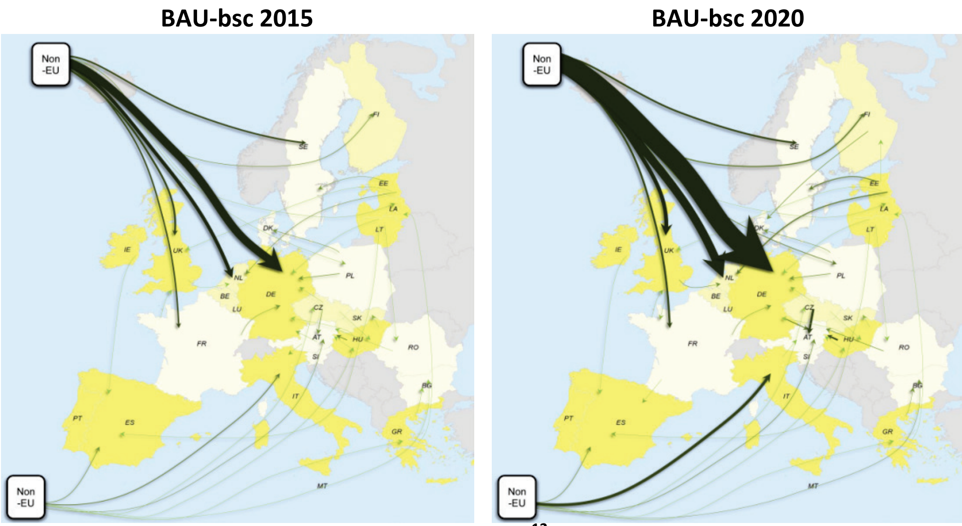

Figure 5-14 Net biomass trade flows BAU-bsc scenario[12]

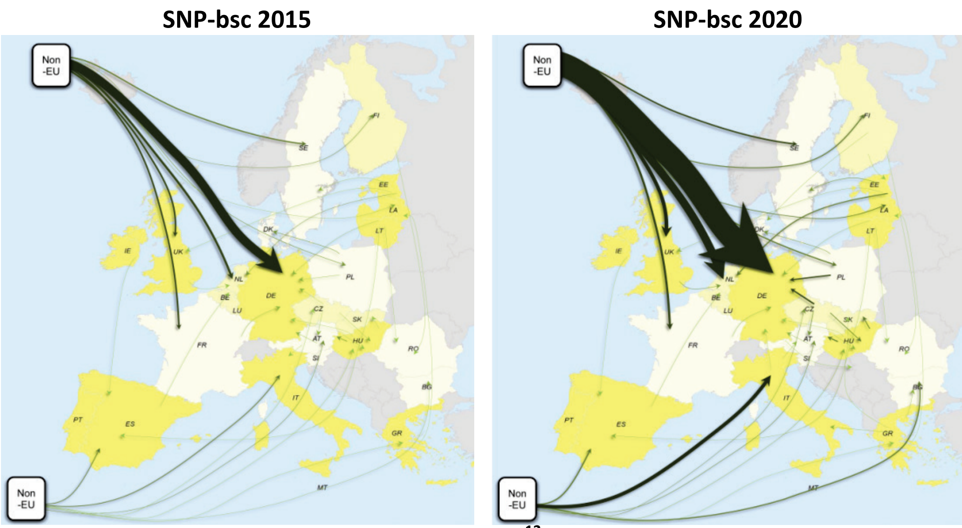

Figure 5-15 Net biomass trade flows SNP-bsc scenario[12]

---

[12] EU member states are clustered in 15 regions to improve readability: Baltic States (Estonia, Latvia, Lithuania), 2. Benelux (Belgium, Netherlands, Luxembourg), 3. Spain, Portugal, 4. Bulgaria, Romania, 5. Czech Republic, Slovakia, 6. Ireland, United Kingdom, 7. Cyprus, Greece, 8. Italy, Malta, 9. Austria, Slovenia, 10. Denmark, Sweden, 11. Finland, 12. Hungary, 13. France, 14. Poland, 15. Germany (The Green-X model does provide results for each country and biomass type if more detailed analyses are required).

5.5 Discussion

5.5.1 Methodology and input data

Green-X does not include a land use module and forestry module. Therefore, the biomass supply mix, cost and land allocation have to be predefined. One of the key limitations of this approach is that the predefined supply mix of biomass, in particular of energy crops, also influences the deployment potentials of end conversion options available to the Green-X optimization scenarios. For example, land used for the production of 1st generation energy crops cannot be used for the production of lignocellulosic crops. The REFUEL project [37, 69] has demonstrated that under different land use, agriculture management practices and crop choice scenarios, can have a large impact on the cost and supply potential of dedicated crops and agriculture residues available for bioenergy generation. The predefined crop mixes in Green-X could lead to suboptimal uses of land, biomass and end conversion (Appendix A). Note though that up to 2020, electricity and heat remain the main markets of lignocellulosic biomass largely supplied from forestry products, forestry residues and agriculture residues that are cheaper than dedicated energy crops. Therefore, the scenarios are only marginally affected by land use and crop allocation. Beyond 2020, diffusion of 2nd generation biofuels and growing competition for lignocellulosic biomass sources, increases the relevance for energy crops and therefore the importance of optimal crop selection procedures.

The scenarios in this article are used to demonstrate the capabilities of the modeling framework and the results of the scenario projections for biomass trade should therefore be considered indicative. Although scenarios for support policies and implied demand are assessed, the scenario assumptions for biomass supply are limited to one set of fixed biomass supply and costs for European and non-European biomass. Therefore, the results do not cover the uncertainties inherent to future biomass supply and costs and related ranges of biomass trade. For European biomass sources, it is relevant to evaluate the possible competition between the additional supply potentials in central and eastern Europe that might become available at competitive cost to imports of solid biomass from extra-EU countries if agriculture sectors are to be reformed in these regions, for example by targeted agriculture policies.

The results of this study show that biomass imports from outside the EU are larger than intra-European biomass trade. The current representation of non-EU biomass in the Green-X model is however highly aggregated compared to intra-EU biomass grade. Lamers et al. [59] have assessed the supply potential of solid biomass from outside Europe for multiple types of biomass (wood pellets, agriculture residues) from multiple regions under different sustainability criteria and scenarios. Similarly, the Green-X biomass trade module could be further extended with more regions of non-EU biomass supply as well as different types of biomass and the implied cost and GHG emissions.

With respect to the BIT-UU model, the cost and GHG emissions of biomass logistics are the result of the assumed performances of the different modes of transport (road, rail, inland waterways and sea) and assumed net load capacities (including empty returns) as well as pretreatment options and resulting bulk energy densities of raw biomass and transported intermediates. This study assumes that woody biomass is transported after processing into wood chips or biomass pellets. More advanced pretreatment options, including torrefaction [60] and pyrolysis oil [70] as well as transport of liquid biofuels results in higher bulk energy densities and improved handling properties and reduces transport cost. Extension of the BIT-UU model with transport of advanced intermediates and biofuels would provide insight in possible options to reduce cost and improve the GHG performance of biomass supply chains.

The cost and GHG emissions of biomass supply chains are assumed to be similar for all end use sectors. In reality, the supply chains of bulk, industrial markets, e.g. co-firing in coal power plants, CHP and district heating are different from residential, decentralized markets of wood pellets. Wood pellets for residential and decentralized uses of wood pellets are often sold in economy bags (500 kg to 1000 kg) or small bags (15 kg to 25 kg) via retailers [71] whereas large (coal) power plants are often located close to sea terminals or inland waterways for efficient fuel supply and cooling purposes and handle wood pellets in bulk. Current imports from overseas locations are therefore mainly used for electricity generation in northwest Europe rather than small scale decentralized uses. Because large individual power plants can add substantially to the demand of solid biomass, it is important to add these locations and logistic network connections to the model as applied in Lamers et al. [59]. Similarly, the representation of cost and GHG implied by distribution to decentralized end users should be improved to model competition between domestic supply and imports from intra-EU and extra-EU resources.

5.5.2 Bioenergy deployment and trade

The Green-X model results for bioenergy deployment in heat, electricity and transport sectors of the SNP and SNP-bsc scenarios meet the fulfillment of the 20 % renewable energy targets in 2020 and can be compared with the NREAPs submitted by EU member states in 2011. At the EU level, the SNP scenario projections for biobased energy generation with Green-X match with the renewable energy trajectories of the NREAPs. At EU member state level however, there are some major differences between the Green-X results and expectations from individual member states and other available studies. For countries that already rely for a large extent on imported biomass sources, including the UK and the Netherlands, solid biomass electricity generation appears to be conservative. This can be partly explained by the substitution approach in the Green-X. The approach used in Green-X builds on general diffusion theory that new commodities or technologies generally follow an S-shaped pattern [29]. For co-firing or conversion of coal power plants, the assumed substitution rate might be too low or, possibly, the diffusion approach does not reflect the substitution pathway of this technology correctly. It should be noted however that policies relevant for electricity generation from solid biomass in these countries have been subject to changes recently. For example, the Netherlands has set a maximum contribution of renewable energy generation from co-firing to 25 PJ in 2020 (6944 GWh) [72]. This is still above the projected electricity generation from solid biomass in the Green-X SNP scenario (4497 GWh in 2020), but below the anticipated share of co-firing in the NREAP of the Netherlands (8350 GWh in 2020) and model projections from ECN [73]. For the UK, Green-X projects that electricity generation from solid biomass will increase to 11181 GWh in 2020 compared to 20590 GWh in the NREAP and 25541 GWh in the NPOL scenario of Lamers et al. [59].

In contrast, bioenergy deployment in Germany, the key importing region of biomass according to the Green-X scenarios, appears to be too optimistic. Electricity generation from solid biomass is projected to increase to 31551 GWh in 2020 in the SNP scenario compared to 24569 GWh in the NREAP of Germany and 22112 GWh in the NPOL scenario in Lamers et al. [59] for 2020. Note however that biomass imports to Germany in the Green-X projections are mainly used for heat generation (86 % of imported biomass is used for heat generation in the SNP scenario for Germany in 2020). Potentially because (international) supply chains of solid biomass used for decentralized heat markets are not properly addressed in the current modeling framework. Also in the NREAP of Germany imports of biomass are anticipated. Germany expects that about 400 PJ of total biomass (electricity, heat, transport) needs to be imported in 2020 [7] compared to 188 PJ in the SNP scenario in 2020. Also for Austria, imports of biomass are anticipated in the NREAP with imports of solid biomass from neighboring countries (29 PJ in 2020) vegetable oils from countries in the Danube region (19 PJ in 2020) [7].

5.5.3 Sustainability criteria

At the EU level, binding sustainability criteria have been set for liquid biofuels in the Directive 2009/28/EC [1] related to biodiversity, risks for carbon stock changes and agriculture management practices. Up to now, solid and gaseous biofuels used for the production of heat and electricity are exempted from EU wide binding sustainability criteria. At the national level, some individual member states have set binding criteria for solid biomass with their renewable energy support schemes, including Belgium and the United Kingdom [74]. Also in the Netherlands, sustainability criteria are considered [72]. Furthermore, voluntary schemes have been developed in close relation with energy utilities, e.g. Green Gold Label (GGL), NTA8080, Laborelec), or are still under development, e.g. the Initiative Wood Pellet Buyers (IWPB) [74, 75].

Sustainability certification systems, both national and voluntary have their own individual scope in terms of markets and geography, criteria and indicators. Inconsistencies and possible conflicts between different sustainability certification systems could have a disruptive effect on biomass markets, especially for international trade of solid biomass. The European Commission is therefore proposing binding, harmonized sustainability criteria at the EU level that might include minimum GHG saving targets of 60 % [61], similar to the BAU-bsc and SNP-bsc scenarios in this article. The impact of the additional cost and GHG restrictions remains in the BAU-bsc and SNP-bsc scenario projections remains limited compared to the scenario projections without these criteria applied (BAU, SNP). Van Stralen et al. [2] found significant effects of sustainability criteria on the deployment of biomass in the EU27 to 2020 and beyond decreasing with over 14 % compared to the reference scenario. The impact of sustainability criteria in van Stralen et al. [2] applies mainly to biofuels by reduced supply of 1st generation energy crops. Sustainability criteria for biofuels were not assessed explicitly in this article.

5.6 Conclusion

The objectives of this article was to improve the renewable energy modeling framework Green-X with a geographic explicit representation of solid biomass and to demonstrate the capabilities of the updated model with scenario projections of renewable energy deployment in the EU27 to 2020. For this purpose, Green-X was extended with an international biomass trade module for intra-European and extra-European biomass trade. This module calculates optimal distribution of extra-EU and entra-European biomass sources among countries in Europe endogenously. Secondly, the biomass trade module in Green-X allows for specifications of sustainability regulations. For each type of biomass, end conversion technology (e.g. small scale heat versus electricity generation), minimum GHG savings can be specified as well as additional costs of sustainable biomass supply. The cost and GHG emissions implied by the logistic operations of each possible biomass supply chain are calculated with the geographic explicit biomass intermodal transport model BIT-UU. However, the input data required to quantify the impact of sustainability regulations on the cost and supply of global biomass is underdeveloped and uncertain. More research is therefore required to improve the required input data.

The GIS based BIT-UU model enables a detailed assessment of cost and GHG emissions of optimal (lowest) cost transport routes taking into account the geospatial features of existing transport networks (road, rail, inland waterways, sea) available in Europe. Furthermore, the tool uses consistent input variables (electricity, diesel) to the Green-X model and remains flexible in changing input assumptions and adding geographic locations of supply and demand.With the extension of international biomass trade, the Green-X model fits multiple purposes. It can be used by researchers and policy makers, both at national levels and European level, to evaluate current and future policies to 2020 and beyond. The model can be used to assess potential renewable energy deployment pathways, GHG emission reduction potentials, implied cost and required resources. Furthermore, the model enables the identification of possible weak spots or opportunities in sustainable use of domestic and imported biomass resources. For investors and industrial stakeholders, the results can be used to identify possible business opportunities and identify investment risks in biomass supply (forestry and agriculture), logistic facilities (e.g. storage and handling facilities in sea or inland waterway ports) and bioenergy conversion systems.

To 2020, the model based scenario projections demonstrate that substantial efforts are required in all sectors (electricity, heat, transport) to meet the binding RES targets in 2020. With a continuation of current policies to 2020 (BAU, BAU-bsc scenarios), the share of renewable energy in gross final energy demand will remain below 15 %. The SNP and

SNP-bsc scenarios show that the RES targets are feasible, also with sustainability criteria applied. The effect on biomass uses remain small, mainly because solid biomass chains for electricity and heat do almost always meet minimum GHG saving criteria assumed in this article (minimum GHG threshold value of 60 %). It would be relevant for policy makers and researchers to assess more strict sustainability regulations with the modeling framework, e.g. to identify possible risks of shifts in uncertified biomass uses to sectors to which sustainability criteria do not apply and related insights in biomass supply. In all scenarios, domestic supply of biomass remains the largest source of bioenergy in the EU27 to 2020, but the role of traded biomass is projected to become increasingly important increasing from 2 % in 2010 to 7 % to 9 % in 2020. Intra-EU trade is projected to increase up to 122 PJ in the SNP-bsc scenario in 2020, equivalent to 6.8 Tg wood pellets. The strongest growth is projected for extra-EU biomass imports that are projected to become 266 PJ (15 Tg WPe) in the BAU-bsc to 389 PJ (22 Tg WPe) in the SNP scenario or equivalent to 3.2 to 4.7 times the imports of wood pellets in 2012. It is important to note that the model based scenario projections only assess possible effects of the demand side with changes in support policies and mitigation of non-economic barriers. Future biomass supply and cost are highly uncertain, especially the interaction between extra-EU cost and supply versus the cost and supply of domestic resources in the EU27. With a single fixed set of biomass cost and supply, as used in this analysis to demonstrate the capabilities of the extended Green-X model, the results of biomass supply demand and trade in this article should therefore be considered illustrative.

The spatial explicit approach to represent biomass trade routes in the renewable energy model Green-X demonstrated in this article forms a basis for further research. Key topics to improve the modeling framework and to assess the potential role of international biomass supply, demand and trade are:

- The future economic and sustainable supply of biomass resources within the EU and available for import to the EU are subject to a complex and dynamic environment and therefore highly uncertain. To assess the potential role of bioenergy requires an improved representation of determining factors that could increase or decrease the supply potentials and cost and related interactions between domestic supply versus imports from extra-EU and intra-EU resources. Examples of these factors are changes in in forest practices and agriculture management that could increase the biomass supply potential substantially. Strict sustainability criteria and increased international competition could reduce the availability of especially extra-EU resources, but could also improve management practices and learning that could increase the sustainable supply potential.
- Improving the geographic resolution of biomass supply and evaluation of logistic chains, from the field or forest where the biomass is produced within Europe as well as key supply regions (e.g. from North America, South America, Africa and Russia) to demand regions, would enable more detailed evaluations of bioenergy and related biomass trade.

- With respect to the demand and logistics to supply biomass to end use facilities, the modeling framework requires an improved representation of sector specific supply chains. Domestic heat markets (e.g. pellet stoves in households) require different supply chains from industrial uses of biomass, e.g. bulk supply of wood pellets for co-firing. The BIT-UU model allows for specific modeling of end use facilities, their geographic locations and the logistic operations required. These sector supply chains could be used as input to the biomass trade module in Green-X, but this requires major efforts to update the modeling framework.
- The scenarios demonstrate the importance of biomass and increased share of traded biomass to 2020. Although the ambitions of the EU27 for renewable energy beyond 2020 are uncertain, it is expected that bioenergy, including international traded biomass resources will continue to grow. With improved representation of biomass trade in energy models, such as Green-X, the developed modeling framework can be used to support insights of possible renewable energy deployment pathways and efficient and sustainable uses of bioenergy on the longer term to 2030.
- At the long term, the role of biobased chemicals is expected to grow and might compete for biomass resources with bioenergy generation. It is important to add these sectors to the modeling framework to enable the assessment of efficient biomass uses for bioenergy or biobased chemicals, from both an economic and environmental perspective.

Appendix Chapter 5 Biomass supply

Biomass resource potentials

Biomass resources for bioenergy can be categorized in three main categories: biomass residues and organic wastes, surplus forestry and biomass produced via cropping systems (dedicated energy crops) [76]. For each of these categories, key factors have been identified that determine the total potential, but future estimations of the biomass resource potential, both from domestic sources within the EU and available from outside the remain highly uncertain. Key factors include policy and market conditions as well as developments in agriculture, forestry and their related markets (e.g. food, feed, timber, pulp products) [77]. Studies that assess resource potentials of biomass basically distinct three types of potentials in hierarchic order [77-79]:

- Theoretical potentials (the supply potential only limited by biophysical conditions);
- Technical potentials (part of the theoretical potential limited by technical and non-technical constraints as well as competition with other land uses). If environmental constraints are addressed to the technical potential, e.g. biodiversity, soil and water, the fraction is typically referred to as sustainable potential;
- Market (economic) potentials (part of the technical potential that is economically feasible to produce and mobilize under market conditions, e.g. fossil fuel prices, other renewable technologies, CO2 prices).

When also institutional and social constraints and policy incentives are also covered to estimate the amount of biomass that can be implemented in a certain time frame, it is defined as the implementation potential [36]. Figure A 5-1 illustrates the hierarchic order and overlap between the different types of biomass potential. The horizontal and vertical axes are dimensionless, but could e.g. represent ecological criteria or supply costs versus the potential biomass availability. Ideally, the role of bioenergy should be assessed taking into account the variability and uncertainties from environmental, socio-economic and technical conditions that determine and constrain the potential of biomass that is available for bioenergy purposes. However, biomass in Green-X requires predefined commodity specific implementation-economic potentials [35]. This implies that assumptions have to be made on policy incentives, e.g. subsidies for energy crop cultivation, types of agriculture management and harvest technologies applied. The main implication of this approach, with crop cultivation not internalized in the Green-X model calculations, is that Green-X cannot optimize for crop type production. In the REFUEL project, de Wit et al. [69, 80] demonstrated that selecting high yield crop types in Europe, i.e. energy grasses and short rotation coppice, increases the economic potential of dedicated energy crops substantially.

The scenario cases assessed in this article are targeted at energy support policies and do not cover the variations in bioenergy supply potentials. Supplementary information to this article shows the important implications to the selected biomass potentials in the Green-X dataset.

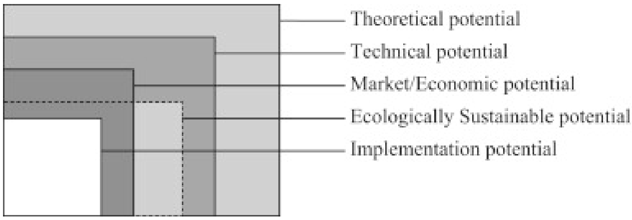

Figure A 5-1 Overlap between theoretical, technical and market potentials with chart areas illustrating the relative amounts of biomass potentials [36].

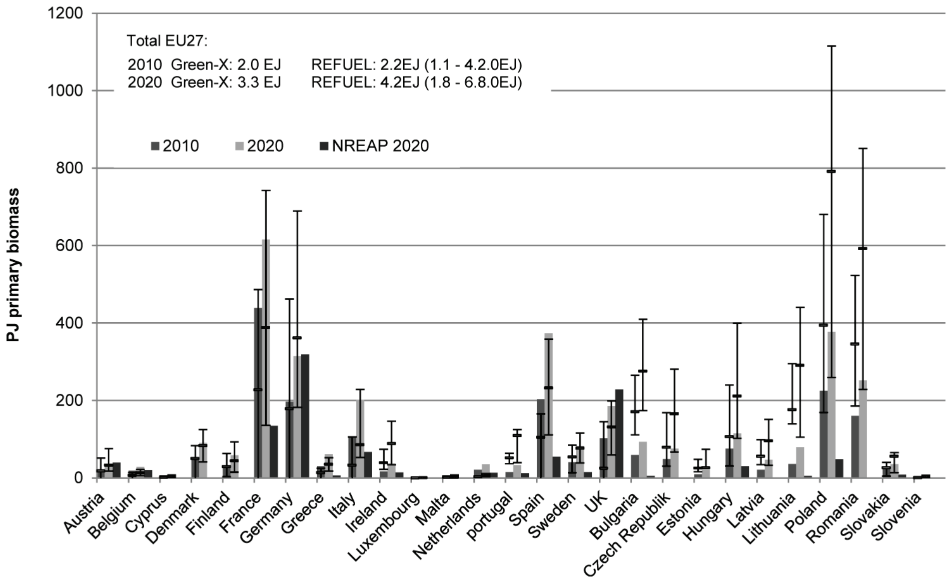

Figure A 5-2 Biomass supply in the NREAPS and Green-X for the EU27 from primary, secondary and tertiary resources [23]. The left columns are based on table 7a of the NREAPS, the right columns show the potentials that are used in the Green-X model.

Energy crop potentials in the EU27

To show the consequences of the assumptions underlying the implementation-economic potentials of biomass resources in Green-X, the potentials are compared to the biomass potentials of the REFUEL project [37, 80] and the biomass potential estimated by individual EU member states in Table 7 of the NREAPs. Figure A 5-3 depicts the potential of dedicated energy crops in the EU27 for Green-X and NREAPs (columns) and REFUEL (markers). The markers for REFUEL show the potential for the same crop mix as assumed in Green-X produced on available arable land. The crop mix in Green-X is depicted in Figure 5-6 and includes rapeseeds, sunflower, maize and wheat (corn and whole plant), short rotation coppice willow, miscanthus, sweet sorghum, etc. The negative error bars show the range if only low yield energy crops (oil crops) are produced on available land. The positive error bars show the potential if only high yield (grassy) crops are produced on available land. Results of REFUEL are based on the base scenario and exclude potentials of cultivation of lignocellulosic crops on pasture land (2009) since this option was not considered within Green-X.

The comparison of Green-X potentials and REFUEL potentials of dedicated energy crops shows that the higher estimated potentials in 2030 in REFUEL (138 Mtoe) compared to Green-X (84 Mtoe) are mainly due to differences in Central and Eastern European Countries (CEEC). In France, Spain and Italy and the UK, the estimated potentials are more conservative in REFUEL compared to Green-X. In REFUEL, the estimated potential for energy crops in CEEC increases from 33 Mtoe in 2010 to 79 Mtoe in 2030 (57 % of the EU27 potential). In Green-X, the potential in CEEC countries increases from 17 Mtoe in 2010 to 29 Mtoe in 2030 (34 % of the EU27 potential).

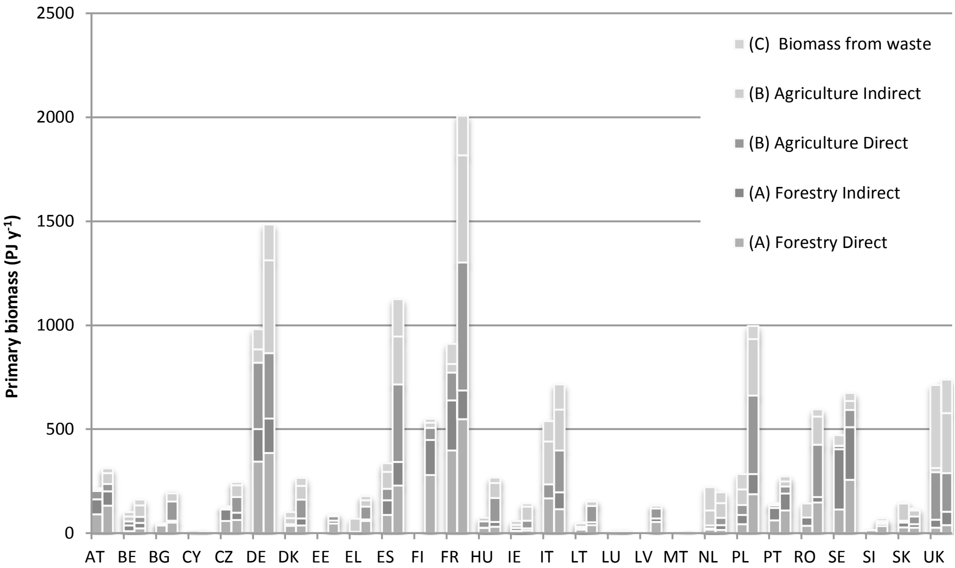

Figure A 5-3: Supply potentials of dedicated energy crops in the EU27 for Green-X and available estimates in the NREAPs (columns) and in REFUEL (markers) assuming the same energy crop supply mix to Green-X and REFUEL low yield crops only and high yield crops only ranges.

References Chapter 5

[1] European Commission. Directive 2009/28/EC of the European Parliament and of the Council - on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Brussels, Belgium; European Commission. 2009. 62 p.

[2] van Stralen JNP, Uslu A, Dalla Longa F, Panoutsou C. The role of biomass in heat, electricity, and transport markets in the EU27 under different scenarios. Biofuel Bioprod Bior 2013; 7(2): 147-63.

[3] Scarlat N, Dallemand J, Banja M. Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. Renew Sust Energ Rev 2013; 18(0): 595-606.

[4] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, et al. Wood pellet market and trade: a global perspective. Biofuel Bioprod Bior 2013; 7(1): 24-42.

[5] Lamers P, Marchal D, Heinimö J, Steierer F. Chapter 3: Global Woody Biomass Trade for Energy. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[6] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. Renew Sust Energ Rev 2012; 16(5): 3176-99.

[7] Ragwitz M, Steinhilber S, Breitschopf B, Resch G, Panzer C, Ortner A, et al. D23 Final Report: RE-Shaping: Shaping an effective and efficient European renewable energy market. Karlsruhe, Germany; 2012. 112 p.

[8] van Dam J, Junginger M. Striving to further harmonization of sustainability criteria for bioenergy in Europe: Recommendations from a stakeholder questionnaire. Energy Policy 2011; 39(7): 4051-66.

[9] Atanasiu B. The role of bioenergy in the National Renewable Energy Action Plans: a first identification of issues and uncertainties. 2010, November 2010. 22 p. . Biomass role in achieving the Climate Change & Renewables EU policy targets. Demand and Supply dynamics under the perspective of stakeholders . IEE 08 653 SI2. 529 241.

[10] Pöyry. Evaluation of National Renewable Action Plants - A report to EURELECTRIC. 2011. 68 p. . EurelectricReport_v5_0B.

[11] Szabó M, Jäger-Waldau A, Monforti-Ferrario F, Scarlat N, Bloem H, Quicheron M, et al. Technical Assessment of the Renewable Energy Action Plans. Ispra (VA) Italy; Joint Research Center (JRC) Institute for Energy and Transport, European Commission. 2011. 105 p. . Report EUR 24926 EN.

[12] Beurskens LWM, Hekkenberg M, Vethman P. Renewable Energy Projections as Published in the National Renewable Energy Action Plans of the European Member States - Covering all 27 EU Member States with updates for 20 Member States. Petten, the

Netherlands; Energy Research Center of the Netherlands (ECN), European Enironmental Agency (EEA). 2011. 270 p. . ECN-E--10-069.

[13] EREC. Mapping Renewable Energy Pathways towards 2020. Brussels, Belgium; European Renewable Energy Council (EREC). 2011, March 2011.

[14] Kranzl L, Matzenberger J, Junginger M, Daioglou V, Tromborg E, Keramidas K. Future Perspectives of International Bioenergy Trade. 2013, August.

[15] Elbersen B, Startisky I, Hengeveld G, Schelhaas MJ, Naeff H, Bottcher H. Atlas of biomass potentials - Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources. the Netherlands; Alterra. 2012. Deliverable 3.3 of Biomass Futures.

[16] Lensink SM, Londo M, Deurwaarder EP. Use of BioTrans in REFUEL Functional and technical description. Petten, the Netherlands; Energy Research Center of the Netherlands (ECN). 2007. 25 p. . REFUEL deliverable 10a.

[17] Miao Z, Shastri Y, Grift TE, Hansen AC, Ting KC. Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. Biofuel Bioprod Bior 2012; 6(3): 351-62.

[18] Cafferty KG, Searcy EM, Jacobson JJ. Biomass Logistics Model: Analyzing biomass supply systems. Submitted.

[19] Cafferty KG, Jacobson JJ, Muth DJ, Bryden KM. Model based biomass system design of feedstock supply systems for bioenergy production. IDETC/CIE 2013 2013; DETC2013-13556.

[20] Resch G, Gephart M, Steinhilber S, Klessmann C, Del Rio P, Ragwitz M. Coordination or harmonisation? Feasible pathways for a European RES strategy beyond 2020. Energy and Environment 2013; 24(1-2): 147-69.

[21] Teckenburg E, Rathmann M, Winkel T, Ragwitz M, Steinhilber S, Resch G, et al. Renewable Energy Policy Country Profiles - 2011 version. 2011. 343 p. . D9.

[22] Hoefnagels R, Junginger M, Panzer C, Resch G. Long Term Potentials and Costs of RES - Part II: The Role of International Biomass Trade. RE-Shaping (work package 5), Intelligent Energy - Europe, ALTENER. 2011, August 2011. 48 p.

[23] Hoefnagels R, Junginger M, Resch G, Matzenberger J, Panzer C, Pelkmans L. Development of a tool to model European biomass trade. IEA Bioenergy Task 40. 2011.

[24] Hoefnagels R, Searcy E, Cafferty K, Cornelissen T, Junginger M, Jacobson J, et al. Lignocellulosic feedstock supply systems with intermodal and overseas transportation Submitted.

[25] Zhang L, Hu G. Supply chain design and operational planning models for biomass to drop-in fuel production. Biomass Bioenerg; In press.

[26] Natarajan K, Leduc S, Pelkonen P, Tomppo E, Dotzauer E. Optimal locations for second generation Fischer Tropsch biodiesel production in Finland. Renew Energ 2014; 62: 319-30.

[27] Resch G, Faber T. Short characterisation of the model Green-X . Vienna, Austria; European Commission, DG Research; FP5 Programme (ENG2-CT- 2002-00607). 2007.

[28] Klessmann C, Rathmann M, de Jager D, Gazzo A, Resch G, Busch S, et al. Policy options for reducing the costs of reaching the European renewables target. Renew Energ 2013; 57(0): 390-403.

[29] Hoefnagels R, Junginger M, Panzer C, Resch G, Held A. Long Term Potentials and Costs of RES - Part I: Potentials, Diffusion and Technological learning. RE-Shaping (work package 5), Intelligent Energy - Europe, ALTENER. 2011, May 2011. 99 p.

[30] E3MLab. The PRIMES Model 2011; (2011 update).

[31] European Commission. Energy Roadmap 2050. Brussels; EUROPEAN COMMISSION. 2011. COM(2011) 885/2.

[32] ESRI. ArcGIS for Desktop Extensions - ArcGIS Network Analyst [internet]. Redlands, CA: Environmental Systems Research Institute (ESRI); 2013. [cited 2013 August]. Available at: http://www.esri.com/software/arcgis/extensions/networkanalyst.

[33] EUROSTAT. Land cover and land use, soil, and landscape – Land covered by woodland per NUTS-2 region (lan_lcv_woo) [internet]. 2012. [cited 2010Available at: http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=lan_lcv_woo&lang=en.

[34] de Wit M, Faaij A. European biomass resource potential and costs. Biomass Bioenergy 2010; 34(2): 188-202.

[35] Londo,M. (project leader COWI consortium). Technical assistance for an evaluation of international schemes to promote biomass sustainability. 2009. 169 p. . Specific invitation to Tender TREN/A2/143-2007.

[36] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials-Methodological lessons from review of state of the art bioenergy potential assessments. Renew Sust Energ Rev 2012; 16(9): 6598-630.

[37] Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M, et al. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. Biomass Bioenerg 2010; 34(2): 173-87.

[38] Fischer G, Prieler S, van Velthuizen H, Lensink SM, Londo M, de Wit M. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures. Part I: Land productivity potentials. Biomass Bioenergy 2010; 34(2): 159-72.

[39] JEC. Well-to-Wheels Study. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE),

the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre (JRC/IES). 2008.

[40] European Commission. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling - Report from the Commission to the Council and European Parliament. Brussels, Belgium; 2010, February. COM(2010)11 final.

[41] Hamelinck CN, Suurs RAA, Faaij APC. International bioenergy transport costs and energy balance. Biomass Bioenerg 2005; 29(2): 114-34.

[42] Thek G, Obernberger I. Wood pellet production costs under Austrian and in comparison to Swedish framework conditions. Biomass Bioenerg 2004; 27(6): 671-693.

[43] Joint Research Centre (JRC) - Institute for Prospective Technological Studies (IPTS). TRANS-TOOLS ("TOOLS for TRansport Forecasting ANd Scenario testing") 2009; 2.

[44] RRG Spatial Planning and Geoinformation (RRG). Short Sea Shipping Routes in Europe - RRG Database 2008.

[45] Winebrake JJ, Corbett JJ, Falzarano A, Hawker JS, Korfmacher K, Ketha S, et al. Assessing energy, environmental, and economic tradeoffs in intermodal freight transportation. Journal of the Air and Waste Management Association 2008; 58(8): 1004-13.

[46] Southworth F, Peterson BE. Intermodal and international freight network modeling. Transport Res C-Emer 2000; 8(1–6): 147-66.

[47] EUROSTAT. lc_an_costh_r2-Hourly labour costs 2008 - Nace Rev. 2 [internet]. European Commission; 2010. [cited 2010 August]. Available at: http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Wages_and_labour_costs.

[48] European Commission. EU energy and transport in figures. 2010th.Luxembourg: Publications Office of the European Union. 2010. doi: 10.2768/19814.

[49] United Nations. Inventory of Main Standards and Parameters of the E Waterway Network (Blue Book) - Revision 1 2006.

[50] NEA. Factor costs of freight transport: an analysis of the development in time (in Dutch: Factorkosten van het goederenvervoer: Een analyse van de ontwikkeling in de tijd.). Rijswijk, the Netherlands; commissioned by Adviesdienst Verkeer en Vervoer,. 2004.

[51] Transport & Mobility Leuven (TML). Tremove-II - A policy assessment model to study the effects of different transport and environment policies on the transport sector for all European countries: Freight Cost 2005.

[52] Smeets EMW, Lewandowski IM, Faaij APC. The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. Renew Sust Energ Rev 2009; 13(6–7): 1230-45.

[53] JEC. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context. European Council for Automotive R&D (EUCAR), European association for environment, health and safety in oil refining and distribution (CONCAWE), the Institute for Environment and Sustainability of the EU Commission's Joint Research Centre (JRC/IES). 2007.

[54] Resch G, Faber T, Ragwitz M, Held A, Panzer C, Haas R. FUTURES-E: 20% RES by 2020 – a balanced scenario to meet Europe's renewable energy target. EEG TU Wien/ Fraunhofer ISI. 2008.

[55] De Wolff M. Buying, Trading & Delivering Biomass 2011.

[56] Schouwenberg PP. Conversion & Operational experience on large-scale co-firing of biomass 2011.

[57] PÖYRY. Biomass imports to Europe and global availability 2011.

[58] Cocchi M, Nikolaisen L, Junginger M, Goh CS, Heinimö J, Bradley D, et al. Global Wood Pellet Industry Market and Trade Study. IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. 2011. 190 p.

[59] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A. Global solid biomass trade for energy under different sustainability constraints by 2020: an assessment of potential import streams and supply costs to North-West Europe Submitted.

[60] Batidzirai B, Hilst F, Meerman H, Junginger M, Faaij A. Optimisation potential of biomass supply chains with torrefaction technology. Submitted.

[61] Keating D. Commission floats 'weak' criteria for biomass [internet]. European Voice; 2013. [cited 2013 September]. Available at: http://www.europeanvoice.com/article/2013/august/commission-floats-less-stringent-sustainability-criteria-for-biomass/78049.aspx.

[62] Smeets EMW, Faaij APC. The impact of sustainability criteria on the costs and potentials of bioenergy production - Applied for case studies in Brazil and Ukraine. Biomass Bioenergy 2010; 34(3): 319-33.

[63] Sikkema R, Sikkema AP, Ranta T, Heinimö J, Gerasimove YT, Karjalainen T, et al. Mobilisation of biomass for energy from boreal forests in Finland & Russia under present sustainable forest management certification and new sustainability requirements for solid biofuels Submitted.

[64] Goh CS, Junginger M, Joudry J, Chum H, Pelkmans L, Smith CT, et al. Impacts of sustainability certification on bioenergy markets and trade - Strategic Inter-Task Study: Monitoring Sustainability Certification of Bioenergy. IEA Bioenergy. 2013, February. 61 p.

[65] Mantau U, Saal U, Prins K, Steierer F, Lindner M, Verkerk H, et al. Real potential for changes in growth and use of EU forest. EUwood. 2010.

[66] Ragwitz M, Held A, Breitschopf B, Rathmann M, Klessmann C, Resch G, et al. D8 Report: Review report on support schemes for renewable electricity and heating in Europe. A report compiled within the European research project RE-Shaping (work package 3) www.reshaping-res-policy.eu Intelligent Energy - Europe, ALTENER. 2011.

[67] EUROSTAT. EU27 Trade Since 1988 By CN8 [DS-016890] [internet]. 2012. [cited 2012 August 2012].

[68] Goh CS, Junginger M, Jonker G, Faaij A. IEA Bioenergy Task 40 Country report - THE NETHERLANDS 2011. Utrecht; Universiteit Utrecht - Copernicus Institute. 2011, Updated in August 2012. 2.

[69] de Wit M, Faaij A. European biomass resource potential and costs. Biomass Bioenerg 2010; 34(2): 188-202.

[70] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008; 33(8): 1206-23.

[71] Sénéchal S, Grassi G. Logistic management of wood pellets: Data collection on transportation, storage and delivery management . Brussels, Belgium; EUBIA – European Biomass Industry Association. 2009.

[72] Social and Economic Council (SER). Energy agreement (Energieakkoord). 2013, September.

[73] Verdonk M, Wetzels W. Referentieraming Energie en Emissies: Actualisatie 2012 Energie en emissies in de Planbureau voor de Leefomgeving jaren 2012, 2020 en 2030. PBL, ECN. 2012.

[74] Goh CS, Junginger M, Junginger M, Faaij A. Monitoring sustainable biomass flows in a bio-based economy: General methodology development. Submitted to Biofuels, Bioproducts & Biorefining 2013.

[75] van Dam J, Junginger M, Faaij APC. From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. Renew Sust Energ Rev 2011; 14(9): 2445-2472.

[76] Dornburg V, Van Vuuren D, Van De Ven G, Langeveld H, Meeusen M, Banse M, et al. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy and Environmental Science 2010; 3(3): 258-67.

[77] Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, et al. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, United Kingdom and New York, NY, USA.; Cambridge University Press. 2011.

[78] Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC. A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energ Combust 2007; 33(1): 56-106.

[79] Vis MW, Berg Dvd. Harmonization of biomass resource assessments - Volume I: Best Practices and Methods Handbook. 1st.Biomass Energy Europe (BEE). 2010.

[80] de Wit M, Junginger M, Lensink S, Londo M, Faaij A. Competition between biofuels: Modeling technological learning and cost reductions over time. Biomass Bioenerg 2010; 34(2): 203-17.

Chapter 6

Lignocellulosic feedstock supply systems with intermodal and overseas transportation

Keywords: Bioenergy; Biomass trade; GIS; Logistics; Pellets

Abstract: With growing demand for internationally traded biomass, the logistic operations required to economically move biomass from the field or forest to the end users have become increasingly complex. To design cost effective and sustainable feedstock supply chains, it is important to understand the economics, energy and GHG emissions, their interdependencies and related uncertainties of the logistic process operations of international supply chains. This article presents an approach to assess lignocellulosic feedstock supply systems at the operational level. For this purpose, the Biomass Logistic Model (BLM) has been linked with the Geographic Information Systems based Biomass Intermodal Transportation model (BIT-UU) and extended with inter-continental transport routes. Case studies of herbaceous and woody biomass, produced in the U.S. Midwest and U.S. Southeast, respectively, and shipped to Europe for conversion to Fischer-Tropsch (FT) diesel are included to demonstrate how intermodal transportation and, in particular, overseas shipping integrates with the bioenergy supply chains. For the cases demonstrated, biomass can be supplied at 99 € Mg^{-1} to 117 € Mg^{-1} (dry) and converted to FT-diesel at 19 € GJ^{-1} to 24 € GJ^{-1} depending on the feedstock type and location, intermediate (chips or pellets) and size of the FT-diesel production plant. With the flexibility to change the design of supply chains as well as input variables, many alternative supply chain cases can be assessed.

Submitted to *Biofuels, Bioproducts & Biorefining*. Co-authors: Erin Searcy (Idaho National Laboratory), Kara Cafferty (Idaho National Laboratory), Thijs Cornelissen (Utrecht University), Martin Junginger (Utrecht University), Jacob Jacobson (Idaho National Laboratory), André Faaij (Utrecht University)

6.1 Introduction

Although two thirds of global biomass use for energy purposes (bioenergy) is used locally for cooking and heating (traditional use), modern uses of biomass for electricity, transportation fuels and (high temperature) heating have increased rapidly in the last decade [1-3]. This expansion of biomass use for energy is likely to continue, driven by policies on climate change mitigation, fluctuating prices of fossil energy carriers, and concerns regarding security of supply [2, 3]. In contrast to the traditional uses of bioenergy, demand sectors for modern uses of biomass are often geographically remote from the source of biomass supply. The largest bioenergy supply potentials are often found in regions with low population densities, high yield potentials, and limited agricultural management, such as Latin America, or regions with large forestry areas and related wood industries such as Western Canada, Russia or the southeast of the U.S. [4-6]. Demand for modern biomass mostly occurs in populated areas with high industrial activities and strong support policies on renewable energy deployment such as in the European Union (EU). In the EU, the amounts of wood pellets imported from outside the EU increased from 1.7 Tg in 2009 to 4.6 Tg in 2012, mainly for industrial uses (electricity generation in co-fired and fully converted coal plants to biomass) in Belgium, the Netherlands, and the United Kingdom. Future imports of biomass pellets to the EU are expected to increase to 15 - 30 Tg by 2020 [3, 7], mainly for uses in industrial sectors (large scale electricity generation) that are already import dependent, but potentially, also for more advanced conversion systems such as 2nd generation biofuels.

The ongoing transition of biomass supply chains, from a local source of energy to global tradable energy commodities that are both economically and ecologically sustainable, is still a major challenge [8]. Raw biomass feedstocks often have unfavorable characteristics for transport and handling due to their bulky nature and relatively low energy densities, high moisture, and poor flowability characteristics [9]. Pre-processing, e.g. drying, chipping, densification, is therefore required to reduce the cost and increase stability during long distance transport. Large scale users of biomass require a complex feedstock supply system consisting of 'many-to-few' and 'one-to-one' collection-handling-preprocessing-storage-delivery logistics possibly over long distances and hence imply additional cost, energy use and greenhouse gas (GHG) emissions to the biomass delivered [5, 10]. An economically and ecologically sustainable feedstock supply system therefore requires optimizing all logistic processes, including preprocessing, transport route and modes of transport, handling and storage in which the optimum design depends on the geo-spatial features and sizes of supply and demand, the available modes of transport and the type of end use [10]. Furthermore, it is increasingly important to understand how the economic and ecological impacts of the logistics supply systems will alter the competition between domestic uses and exports.

There are several studies that assess feedstock supply systems, provide insights and facilitate optimization of feedstock supply systems often using dedicated modeling tools. These studies are of varying scope and often deal independently with several selected issues related to biomass logistics [10]. Models, such as the discrete-event simulation

Integrated Biomass Supply and Logistics model (IBSAL) [11] and the Biomass Logistics Model (BLM) developed by Idaho National Laboratory (INL) [8, 12-14] can simulate how a variety of feedstocks move from biomass standing in the field to the biorefinery, including logistic operations within the plant. Some studies mainly focus on separate parts of the logistic chain, e.g. pre-processing [15] or transportation logistics such as the geographic information systems (GIS) based Biomass Intermodal Transportation model (BIT-UU) [16] developed in the Network Analyst extension of ESRI ArcGIS [21]. Other studies also include conversion to and transportation of final energy carriers such as biofuels [5]. However, one aspect that could be further developed is transportation of biomass beyond a single country, region, or continent. Inter-continental supply chains of solid biomass assessed in literature [5, 17] lack geo-spatial features and are limited to pre-defined routes of intermodal transportation. Optimal (lowest cost) long distance, intermodal transport routes depend on many interdependent variables, including available transportation networks and related attributes (costs, distances, restrictions) and possibilities for and number of transfers between different modes of transport (e.g. between road and rail).

The main objective of this article is to describe an integral analysis tool of biomass feedstock supply systems capable of exploring the impact of overseas shipping routes and, specifically, how intermodal transportation integrates with herbaceous (corn stover and switchgrass) and woody (thinning residues and pulpwood) biomass feedstock supply logistics with respect to the delivered costs and GHG emissions. Secondly, this article aims to demonstrate the modeling tool with case studies of several feedstock supply chains of biomass produced in the U.S. and delivered to a refinery in Europe.

For this purpose, the BLM has been extended with a long distance intermodal transport module. To calculate intermodal transport routes that are optimized for lowest cost, the GIS based BIT-UU model has been extended with intercontinental shipping and linked with the BLM intermodal transport module. The BLM is capable of comparing various feedstock supply systems with different types of raw biomass sources, preprocessing technologies, handling and queuing and transport from field side to the throat of a refinery or conversion plant. The combination of BLM with the geospatial explicit optimization of intermodal transportation routes of the BIT-UU model results in a flexible tool to analyze long distance biomass feedstock supply chains. Such an integral analysis tool is important to evaluate feedstock supply chains, taking into account the key uncertainties and possible variations in biomass sourcing regions, types of biomass and characteristics, management practices and future policy and technical changes influencing both unit operations in the supply chains, as well as the geographic locations and types of end conversion technologies.

6.2 Methodology

6.2.1 Feedstock supply chain concept and model set-up

Feedstock supply logistics can be generally grouped into five unit operations: 1) Harvest and Collection, 2) Storage 3) Transportation, 4) Preprocessing, and 5) Handling and Queuing. The order, the occurrence and the locations of these unit operations varies per supply chain depending on the geographic locations, feedstock type, end use, and the amount of supply and demand.

A simple feedstock supply chain situates a small biorefinery (<725,000 Mg y^{-1}) near the source of biomass production, reducing the hauling radius and costs incurred due to the bulky nature and low energy density of biomass. Basic processing at field side, such as baling or chipping, enables truck transport. Supply of biomass is typically organized via direct contracting between farmers and biorefineries. For example, herbaceous biomass, such as corn stover, is harvested using a windrow followed by baling. These bales are collected and moved to the field side for storage and transported by truck to a biorefinery. As an example of a conventional woody supply system scenario, trees are felled, piled, and skidded to the landing (harvest and collection), where the trees are chipped or ground (preprocessing) prior to transport to the biorefinery or conversion plant. At the biorefinery, the biomass is received prior to additional preprocessing (usually grinding and/or drying), and finally the biomass is fed into the conversion process [8, 18]. Unlike in the herbaceous system, the woody biomass is usually stored at the biorefinery, prior to additional preprocessing (usually drying and/or hammer milling) [12].

To format raw biomass into a tradable energy commodity with international transportation, requires advanced pre-processing early in the supply chain to improve the physical characteristics (i.e., bulk densities, moisture content) (Figure 6-1). Transitioning to an advanced, uniform format system could be accomplished through gradual incorporation of supply chain technology and methodological improvements. This gradual transition is analogous to the transition of grains that have become a global traded commodity [9, 18]. In this analysis, this concept of “advanced uniform-format” developed at INL [12, 18] was adapted to extend the BLM with inter-continental transportation. Figure 6-2 shows the location-based structure and possible unit operations at each of the following locations: 1) field side 2) depot 3) export terminal, and 4) biorefinery. In any given biomass logistics scenario, one or more of these location based sub-models can be used, with various order and occurrences of unit operations. All equipment and operations involved in the flow and alteration of biomass to bioenergy are accounted for in these unit operations sub-models. To allow for inter-continental shipping, an intermodal transportation sub-model was added at the export terminal location. This implies that intermodal transportation is only possible between the locations of the export shipping terminal and the refinery.

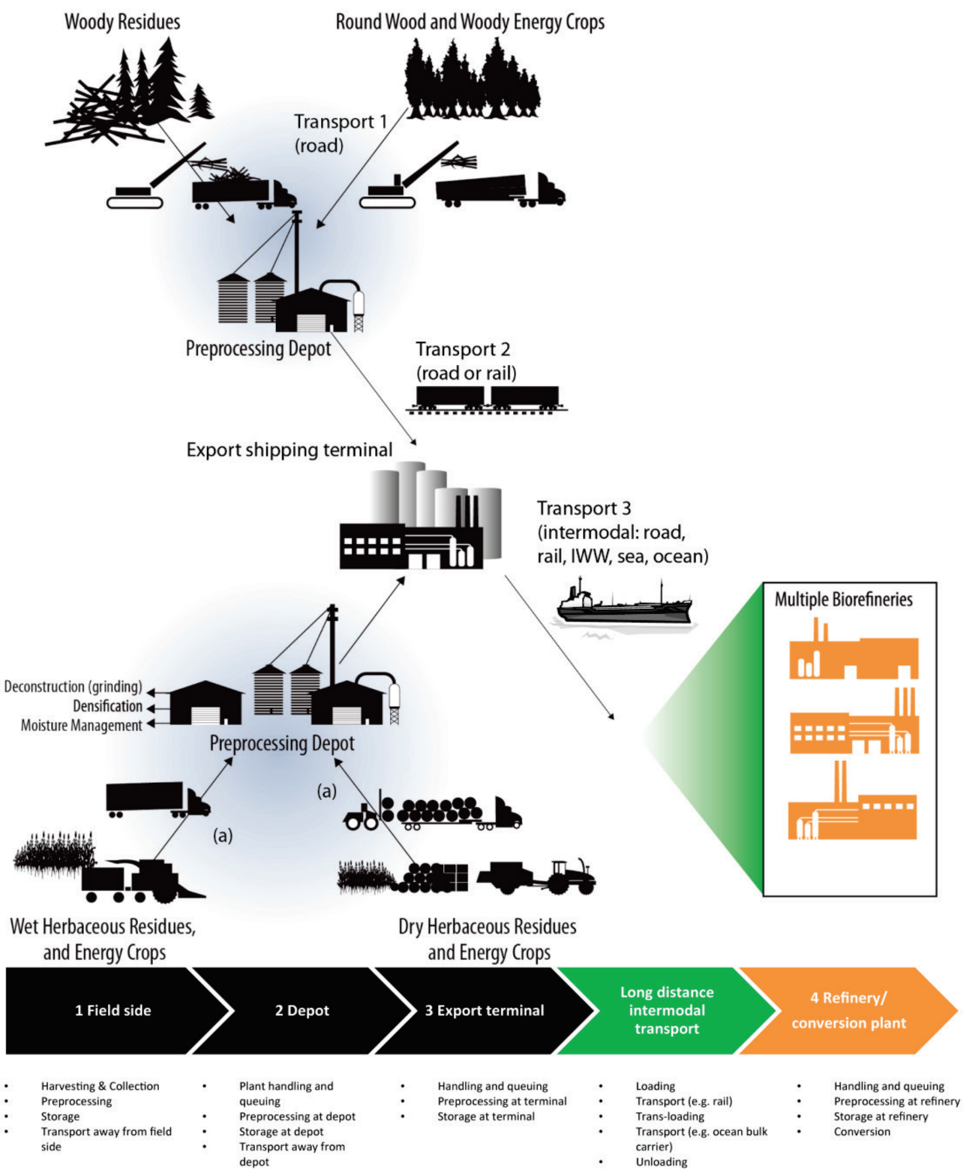

Figure 6-1 Location-based structure of the intermodal feedstock supply and conversion chain with possible components and processes. A commodity-based uniform format feedstock supply chain is shown (based on Hess et al. [18]). Truck transport between field side, forest and depot (Transport 1) and rail or truck transport between depot and export shipping terminal (Transport 2) are calculated with BLM. Long distance intermodal transport (Transport 3) is calculated with the BIT-UU model (green), linked to BLM.

The Microsoft Excel based model interface of the BLM was extended with input parameters for intermodal transportation and input parameters of FT-diesel production derived from the spreadsheet based techno-economic assessment model of van Vliet et al. [19]. All costs are updated to the reference year (2012) with 2.2% inflation and expressed in euros (Table 6-5). Based on input assumptions on the feedstock supply chain, the BLM intermodal transportation sub-model calculates the parameters required for intermodal transportation (bulk density, moisture content, fixed cost, variable cost) and updates the BIT-UU model network parameters using a VBA – Python based script tool. A detailed description of the script tool that links the Powersim based BLM and ArcGIS based BIT-UU model is provided in Cornelissen [20]. The BIT-UU model calculates the least cost route between the defined locations of the export shipping terminal and the refinery for intermodal transport networks using the advanced connectivity model and the shortest path algorithm provided in the Network Analyst extension of ESRI ArcGIS [21]. The BIT-UU model provides the results of the intermodal transport route (cost, distance, fuel consumption) to the BLM intermodal transportation sub-model. The BLM calculates the total feedstock supply and conversion chain of which the results can be analyzed in a Microsoft Excel spreadsheet output (see Figure 6-2).

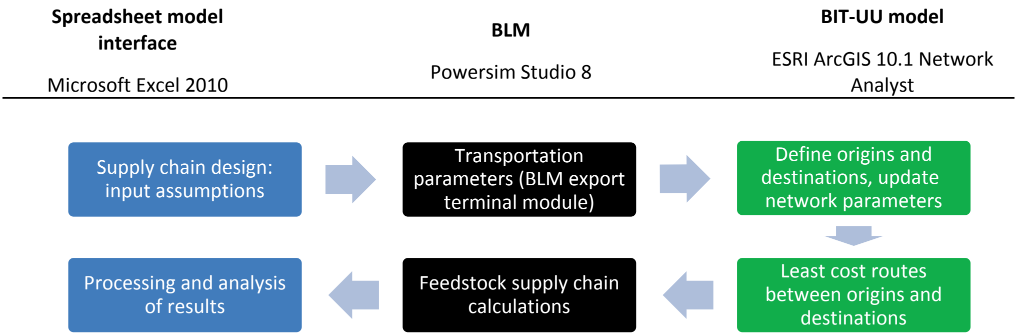

Figure 6-2 Model set-up and order of operations with the Microsoft Excel based input and output interface of the BLM and linkage between the BLM and BIT-UU model

6.2.2 Total cost and greenhouse gas emissions

The total cost of the biofuel production chain covers all costs from field side, depot, and terminal to final conversion in the refinery (Equation 6-1). Total GHG emissions (M_{total}) are calculated analogous to the costs with Equation 6-1 [22]. The individual contributing factors are explained in detail in the following sections.

$$C_{total} = C_{cult} + C_h + C_{T1,2} + C_{T3} + C_{hq} + C_s + C_{proc} + C_{rf} - Cr_E \qquad \text{Eq. 6-1}$$

C_{total} = total biofuel production cost
C_{cult} = cost for cultivation (growers payment/stumpage fee)
C_h = cost of harvest and collection

$C_{T1,2}$ = cost of unimodal transportation between field side, depot and terminal
C_{T3} = cost of intermodal transportation between the shipping terminal and refinery/conversion plant
C_{hq} = cost of handling and queuing at field side, depot, terminal and refinery
C_s = cost of storage
C_{proc} = cost of processing at field side (e.g. baling), depot/terminal (e.g. drying, pelletization) and refinery (e.g. drying, grinding)
C_{rf} = cost associated with biomass conversion to FT-diesel
Cr_E = credit for co-generation of electricity (electricity surplus at the FT-diesel plant, exported to the grid).

For the GHG emissions comparison between the fossil reference and biofuel production chains, the emissions from the production of resources (cradle) to the production of final energy carriers and combustion in an internal combustion engine are considered. Both direct and indirect emissions, i.e. the emissions that occur upstream for the production of utilities and raw materials, are taken into account, but exclude possible emissions that occur from direct or indirect land use change. Emissions from the production of capital goods are excluded in this analysis, consistent with the Directive 2009/28/EC [23]. The global warming potential of nitrous oxide (N_2O) and methane (CH_4) are calculated in CO_2 equivalent over a calculated period of 100 years [24].

Excess generation of electricity in the FT-diesel production plant is accounted for with a GHG saving credit (Equation 6-1). The credit is based on if an equal amount of electricity is produced in a reference plant. Consistent with the Directive 2009/28/EC [23], the reference plant is assumed to use the same fuel, thus biomass feedstock, as the cogeneration unit. The results are also calculated with a fossil reference plant assuming electricity generation in a natural gas combined cycle plant (NGCC) with a net conversion efficiency of 40%. For the economic analysis, a credit is considered for revenues from electricity exported to the grid.

GHG savings for FT-diesel production and electricity generation are calculated with Equation 6-2 [23] using the fossil fuel comparators for marginal production of transport fuels and electricity as defined by the European Commission.

$$SAVING = (M_f - M_{total}) / M_f \qquad \text{Eq. 6-2}$$

M_f = total emissions from the fossil fuel comparators for transport fuels (83.8 g CO_2-eq/MJ_f) [23] and electricity (198 g CO_2-eq/MJ_e) [22].
M_{total} = total emissions from the biobased system (calculated similar to C_{total} with Equation 6-1).

6.2.3 Field side

6.2.3.1 Cultivation

Cultivation of biomass, including land rent, soil preparation, seeding/planning, fertilizing, weed, pest and insect control, and required inputs (agriculture machinery, fertilizers and nutrient replacement, herbicides, insecticides and labor) do not directly affect the engineering operations or logistics of the feedstock supply system and are therefore not modeled in detail in the BLM, but these are addressed indirectly by a growers payment or stumpage fee for agriculture and forest resources respectively [12]. This parameter reflects the farm gate price of the biomass feedstock minus harvest and collection cost [25].

The input assumptions to calculate the stumpage fee/grower payment of the supply chains assessed in this article are summarized in Table 6-1. The grower payments are based on the demand-run simulations to meet the demand for the EISA mandate and biopower for the year 2015 [25] using a combined assessment of exogenously calculated forest stumpage prices with the agriculture simulation model. Energy requirements and agricultural inputs are based on the GREET model database [26].

Emissions from agricultural inputs (e.g. fertilizers, herbicides, pesticides) and related direct and indirect energy and GHG emissions are based on the background data of the GREET model [26]. The required fertilizer and energy inputs for cultivation of pulpwood and thinnings are based on the medium-productive plantation scenario of Jonker et al. [27]. Fertilizer-induced N_2O emissions are calculated assuming 1.3% of nitrogen (N) in N-fertilizer applied will be emitted as N_2O similar to the GREET model.

6.2.3.2 Field side logistics

The biomass collection radius is for herbaceous biomass is calculated endogenously in the BLM depending on the annual feedstock demand of the primary intermediate location (depot), the biomass yield, and the distribution of available biomass (Equation 6-3) [18]. For forestry biomass, the distance between forest and depot is predefined (see Table A2). The feedstock specific assumptions are provided in Table 6-1. Parameters related to land use and sustainable removable yields are based on default supply chains in the BLM. Cultivation parameter are added for this analysis. Typically, herbaceous biomass (i.e. switchgrass and corn stover), is harvested, baled, and collected then trucked on a flatbed trailer to the depot for pelletization. Woody biomass is harvested, then chipped at the landing and trucked to a depot for pelletization or directly transported by truck from the forest landing to the export shipping terminal if wood chips are exported to Europe.

$$SR_a = \sqrt{\frac{\left(\frac{D}{Y_a}\right)}{\pi(\%C_a)(\%TC_a)(\%GP_a)}} \qquad \text{Eq. 6-3}$$

D = annual feedstock demand (Mg y^{-1})
SR_a = supply radius at location a
Y_a = yield of biomass feedstock at location a (Mg y^{-1})
$\%C_a$ = share of cultivated land at location a
$\%TC_a$ = share of cultivated land planted in target feedstock at location a
$\%GP_a$ = share of growers participation in supplying biomass at location a

Table 6-1 BLM feedstock cultivation input parameters [25-28]

Location		Indiana, Kansas, Illinois		Alabama, Georgia, Virginia	
Crop type		Corn Stover	Switchgrass	Southern Pine Thinning	Pulp Plantation
Fraction of agriculture land	%	50	50	90	90
Farms in usable crop	%	50	10	90	90
Farms participating	%	50	100	100	100
Biomass removal limit	%	100	100	100	100
Sustainable removable yield	$Mg\ ha^{-1}\ yr^{-1}$ (dry)	0.73	1.10	4.41	7.34
Growers payment/access fee[a]	€ Mg^{-1} (dry)	23.3	20.4	12.7	12.7
Fertilizer input[b]					
N-fertilizer	g Mg^{-1} (dry)		7,716	19	3,768
P2O5	g Mg^{-1} (dry)	3,100	110	36	105
K2O	g Mg^{-1} (dry)	16,500	220	0	0
Pesticides	g Mg^{-1} (dry)				
Herbicides	g Mg^{-1} (dry)		31		
Diesel (only cultivation)[c]	L Mg^{-1} (dry)			0.27	0.99

a) Grower payment, access fee or stumpage price in the case of forestry biomass is defined by Langholtz and Matthew [25] as "*the price required for rights to harvest material from the field, and includes cost of production, profit, and, in the case of crop residues, compensation for soil nutrient removal Succinctly, grower payment is farm gate price minus harvest cost. Similarly, for forest resources, stumpage price is the price of roadside chips, minus harvest and chipping costs*". The grower payment of 2015 is based on the demand-run simulations to meet the demand for the EISA mandate and biopower in Langholz and Matthew [25].

b) Corn stover: nutrient replacement of corn stover removal with fertilizers, no need for N-fertilizer because soybean cultivation is assumed after corn in the next rotation [28]. Switchgrass: fertilizer inputs based on the GREET model database [26]. Fertilizer inputs for southern pine thinning and pulp plantation are based on the medium-productive plantation scenario of Jonker et al. [27].

c) The diesel requirement for cultivation, excluding harvesting, is not provided in the GREET model database. Diesel requirements for woody biomass are based on Jonker et al. [27].

6.2.4 Depot and terminal

Two high-yielding regions of biomass resource supply were examined in this analysis: the Midwestern U.S. for herbaceous energy crops and residues, and the southeast U.S. for woody biomass. (see Table 6-1). Raw biomass (bales or wood chips) is transported to the depots that are sited based on transportation distance from the point of production. At these depots, biomass is dried, ground, and densified to pellets. Pellets are assumed to be transported by rail to the export shipping terminals. Supply chains with long distance transportation of herbaceous biomass in bales, thus without pelletization, are not assessed because such inter-continental shipping chains are impractical as a result of the low bulk density and handling properties.

For long distance, intermodal transportation between the export shipping terminal and the biorefinery, the GIS based module is used that links the BLM to the BIT-UU model (Figure 6-2). Exact geographic locations of shipping terminals and the biorefinery are required as an input to the GIS model. The locations of the export shipping terminals are based on existing intermodal terminals in the U.S. For herbaceous biomass, these terminals will most likely be located where there is access to barge shipping for transportation to an international shipping port. For woody biomass, the southeast U.S. is a prime location and terminals will most likely be located near a seaport (Mobile, Savannah and Norfolk, see Figure 6-5). Based on these criteria, a terminal was selected in each of the relevant US states for each scenario.

6.2.5 Biomass transportation and handling

6.2.5.1 Transportation and handling cost

The total cost of biomass transportation consists of fixed cost and variable cost components, and the capacity utilization of a roundtrip (Equation 6-4) [29]. The variable, or rolling, cost component covers variables that are time or distance dependent (Equation 6-5). The fixed cost, or handling cost, component includes the loading, unloading and transloading cost of biomass between different modes of transport (Equation 6-6, [30]). In general, road transport by truck is flexible and has low fixed cost (high handling efficiency) and high variable cost (fuel consumption, labor and repair and maintenance) compared to transport by rail or ship. Thus, for short distances (<100 km), when multiple sites have to be accessed (many-to-few) to collect biomass, or when alternative transport infrastructure such as railways or waterways is insufficient [5, 10], transport by truck is the preferred option. Also, when multiple end consumers have to be supplied, such as residential use of bagged wood pellets for heating (few-to-many), trucks are typically used [17, 31]. For longer distances, different unimodal or intermodal transport chains become more cost effective depending on the available transportation networks and physical properties of the transported feedstock [5, 18].

For transportation of biomass from the field side to a depot or export terminal, the transportation mode (truck or rail), distance and fixed and variable cost are calculated in the BLM. Transportation parameters between the export shipping terminal and the biorefinery are calculated with the BIT-UU model based on minimizing the total cost of transportation (C_T) taking country and transport specific attribute parameters from the network database into account for fixed cost (country specific loading, unloading and transloading cost), variable distance cost (e.g. tolls, fuel taxes and excise duty, labor cost, rail freight rates) and variable time cost (e.g. speed limitations, labor cost).

$$C_T = C_f + C_v * (1/CU) \qquad \text{Eq. 6-4}$$

With:

C_T = total cost of biomass transportation (€ Mg^{-1})
C_f = fixed cost of biomass transportation (€ Mg^{-1})
C_v = variable cost of biomass transportation (€ Mg^{-1})
CU = capacity used in a roundtrip (%)

$$C_v = \sum_{ijk} \left((V_k * D_{ijk}) + (F_k * T_{ijk}) \right) \qquad \text{Eq. 6-5}$$

With:

V_k = variable cost of transport mode *k* (€ Mg^{-1} km^{-1}), including fuel cost, repair & maintenance, freight rates of rail, road tolls.

D_{ijk} = distance between node *i* and *j* of transportation mode *k* (km)
F_k = time variable cost of transport mode *k* (€ Mg^{-1} h^{-1}), including labor cost, capital cost, time charter rates for ocean shipping.
T_{ijk} = transportation time between node *i* and *j* over transportation mode *k* (hour). Based on the distance and average speed plus loading/unloading time.

$$C_f = \sum_{ijk}\left(L_k * X_{ijk}\right) + \sum_{jik}\left(U_k * X_{jik}\right) \qquad \text{Eq. 6-6}$$

L_k = fixed cost of loading bulk cargo of mode carrier *k* (€ Mg^{-1})
U_k = fixed cost of unloading bulk cargo of mode carrier *k* (€ Mg^{-1})
X_{ijk} = binary value that is 1 if biomass is transported from transport mode *k* specific network node *i* to terminal node *j* and otherwise 0.
X_{jik} = binary value that is 1 if biomass is transported from terminal node *j* to transport mode *k* specific network node *i* and otherwise 0.

6.2.5.2 Fuel consumption and cost

Fuel consumption and the implied cost and GHG emissions are calculated based on the capacity utilization of each transport mode (Equation 6-7) [32]. The consumption of full loaded and empty transport vehicles and the type of fuel used are specific per mode of transport.

$$ECF = ECF_{empty} + \left(ECF_{full} - ECF_{empty}\right) * CU \qquad \text{Eq. 6-7}$$

where:

ECF = final energy consumption (MJ km^{-1})
ECF_{empty} = final energy consumption empty (MJ km^{-1})
EFF_{full} = final energy consumption full load (MJ km^{-1})
CU = capacity used (weight load / load capacity)

6.2.5.3 Transportation networks in the BIT-UU model

The GIS based BIT-UU model was originally developed to identify likely trade routes of solid biomass in Europe using intermodal transportation (road, rail, inland waterways and short sea shipping routes) [33, 34]. The model uses different layers for each mode of transportation (Figure 6-3). Network data for road, rail and inland waterways in Europe are based on the freight sub-model of TRANS-TOOLS, a European transport network model for transport impact analyses [35]. For short sea shipping in Europe, the RRG GIS database on Short Sea Shipping Routes and Ports of Europe was used [36]. For the U.S. and ocean shipping routes, the Oakridge National Laboratory Center for Transportation Analysis (ORNL-CTA) transportation network database was used. This database covers transportation networks for road, rail, inland waterways, great lakes and deep sea for North America [37]. To link the global seaways of the ORNL-CTA network to ports in Europe, ports have been added from the World Port Index [38]. Links and the related distances between the global seaways and these ports have been added using ESRI ArcGIS.

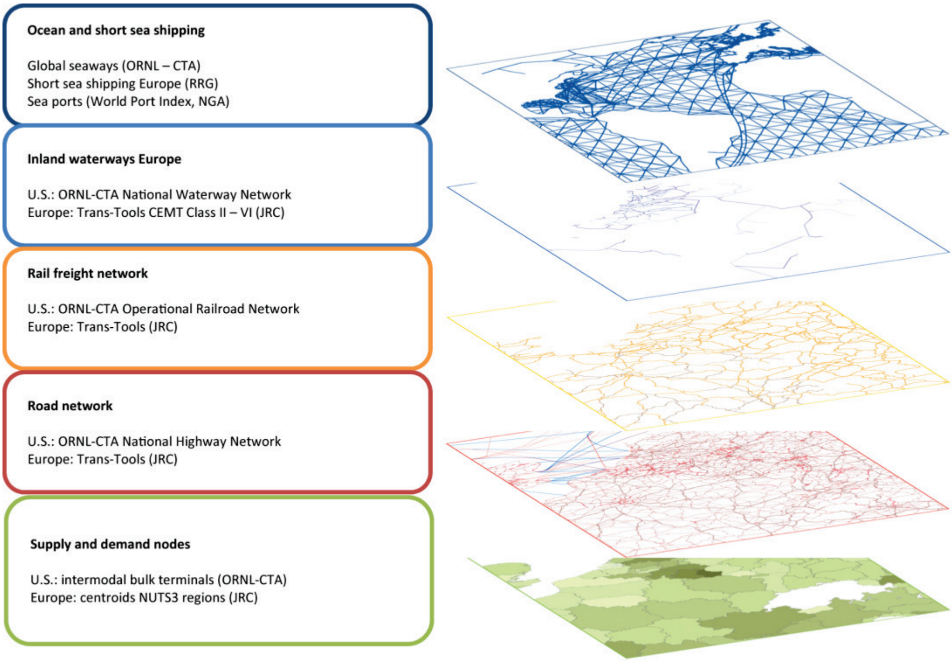

Figure 6-3 Transport network layers in the updated BIT-UU model. Sources: ORNL-CTA [37], RRG [36], NGA [38], JRC [35].

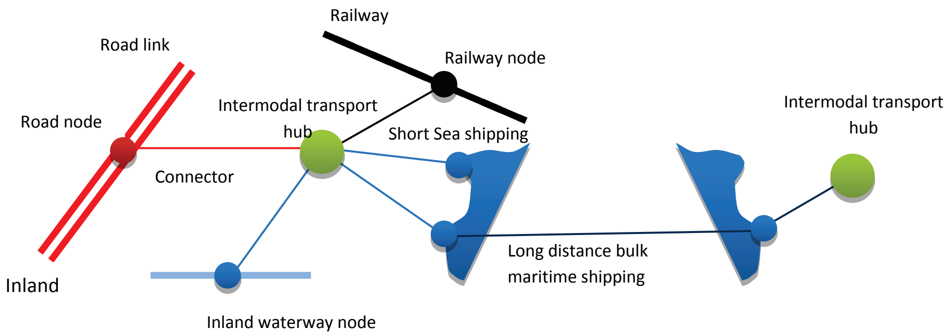

Figure 6-4 The hub-spoke approach to link different modes of transport in the UU ArcGIS transport model (adapted from Winebrake et al. [30]).

6.2.5.4 Intermodal terminals

If more than one transport mode is used to move biomass between the export shipping terminal and the biorefinery, facilities are required to transfer biomass between the different modes of transport either directly or with intermediate storage. These intermodal freight terminals include the facilities required to receive biomass by one type of transportation, for example road, and ship it out by another mode of transportation, for example rail. Port complexes usually have many intermodal terminals for handling of individual types of cargo such as containers, liquid bulk or dry bulk or with a single operator [39]. The total handling cost (fixed transport cost), time and energy requirement, associated with transloading biomass between different modes of transport (handling efficiency) can add substantially to the total cost of transport, but can effectively reduce the variable (rolling) cost, energy consumption and GHG emissions of transport compared to transportation using a single mode of transportation (unimodal transport) [10].

To link the different transportation networks of road, rail, inland waterways and sea via intermodal terminals, a hub-spoke approach was used similar to Winebrake et al. [30]. Figure 6-4 shows the concept of different transportation networks (links) of which the mode specific nodes are linked to intermodal terminals via terminal connectors. The terminal connectors include attribute fields relevant to calculate the fixed cost of biomass transport (time, energy use, costs) (Equation 6-6). Note that each connector consists of a from-to segment and a to-from segment to allocate loading or unloading parameters.

In the U.S., the geographic locations and transloading facilities of intermodal terminals are based on the CTA Intermodal Terminal database [39]. Furthermore, these intermodal terminal facilities were also assumed to represent the locations of processing/shipping terminals in the feedstock supply chains (Figure 6-2). The locations of the selected processing/shipping terminals are shown in Figure 6-5. For Europe, the transportation networks are based on the TRANS-TOOLS database [35] that assumes intermodal transportation hubs to be hypothetically located in the geographic centers of NUTS-3 regions with link nodes to represent existing road exists, ports and rail terminals.

6.2.5.5 Inland transportation

Road transportation

The payload capacity, fuel economy and cost of road transportation depends on the structure, bulk density of biomass, and the type of truck used. The maximum dimensions and gross weight of trucks is limited in many countries and, as is the case of the U.S., also specific per state (Table 6-2). In most European countries the gross weight is limited to 40 Mg. However, in countries with large forest industries such as Sweden and Finland, higher weight and larger trucks are allowed.

Corn stover and switchgrass are transported in square bales on flatbed trailers. Wood from thinning operations and pulp plantations are assumed to be chipped and loaded in enclosed or covered chip trailers, also known as vans [12]. For truck transport between the depot and the shipping terminal and long distance intermodal transport, similar vans are used. Table 6-2 shows the details on road transportation used in this article.

For transport of biomass between field side, depot and export shipping terminal in the U.S., the type and performance data for truck transport are based on the existing transportation calculations within the BLM. For long distance, intermodal transportation, the input parameters are based on European studies [40, 41]. The EU based assumptions for intermodal transport are consistent with other studies. For example, EcoTransit [32] estimates an fuel consumption of 0.30 L km^{-1} assuming 50% average load for trucks >24-40 Mg.

Rail transportation

The economics and energy requirement of rail freight transportation differs widely because of rail infrastructure charges, the availability of electric or non-electrified rail networks, the used locomotives and capacity and number of freight cars. These factors have a substantial impact on the total cost and GHG emissions of rail transport and vary per country or rail network. For example, in North America, the gross weight of trains is usually significantly higher than European trains. In Europe, the typical average gross weight is 1,000 Mg for national trains and maximum 2,000 Mg for international trains, whereas in the U.S., trains of about 5,000 Mg are used [32].

To estimate the cost of rail transportation, rail freight rates (€ Mg^{-1} km^{-1}) where therefore used in combination with a fuel cost component to address for variable fuel prices. For the European rail network, country specific differences between rail freight rates are addressed using a country factor based on the relative differences in rail bulk transport tariffs in Europe from the TREMOVE database [42]. For the U.S., a single rail freight rate is considered for all rail networks based on the BLM.

The energy requirement for rail transportation is based on the EcoTransit function for trains between 600 and 1,800 gross Mg. For trains above 2,200 gross Mg, the specific energy consumption is assumed to remain constant and confirmed by heavy trains of 4,000 gross Mg [32]. Because the rail freight network data used in the intermodal transport model for the US and Europe do not include attribute fields on the availability of railway electrification systems (Figure 6-3), all rail locomotives are assumed to be diesel powered with a diesel-electric conversion efficiency of 37 %. The impact of terrain factors (flat, hilly or mountainous) are not included in the model, but could increase or decrease fuel consumption with 10 % [32].

Inland waterways transportation

The inland waterway network in the intermodal transport model covers rivers and canals in Europe that are classified for different ship sizes using the ECMT (European Conference of Ministers of Transport) classification [43]. In the network model, Class I canals and rivers are excluded because they are not considered to be cost effective for transportation of solid biomass compared to road transportation. Class II ships, for example a Kempenaar or Euro-barge, can navigate through all available inland waterways in the transport model.

Ships with larger capacities, such as push-convoys, can only navigate in large waterways (Class V or higher). For each inland waterway network in Europe, ship specific parameters can be defined in the model. In the U.S., inland waterway capacities are assumed to be similar to ECMT-VI or higher. All inland ships are assumed to use marine diesel oil (MDO).

Table 6-2 BLM and BIT-UU transport mode parameters for inland transportation [40, 41]

Network	Unit	Road		Rail	Rail	Inland waterways per CEMT class				
						Cl II	Cl III	Cl IV	Cl V	Cl VI, US[b]
Transport mode		Truck (BLM, US)[a]	Truck (EU)	Hopper cars (US)	Hopper cars (EU)	Small, dry bulk	Middle, dry bulk	Large dry bulk	Large dry bulk 2	Large dry bulk push tug
Labor (FTEs)	Person h^{-1}		1.0			1.3	1.4	2.6	2.6	3.8
Time cost	€ h^{-1}		18.4			10.3	21.9	72.2	106.7	214.2
Variable cost	€ km^{-1}		0.30			0.00	0.00	0.74	0.93	17.84
Rail freight rates	€ Mg^{-1} km^{-1}			0.03	0.03-0.15					
Fuel type		Diesel	Diesel	Diesel	Diesel	MDO	MDO	MDO	MDO	MDO
Fuel consumption full	MJ km^{-1}	14	13		207	220	314	470	470	717
Fuel consumption empty	MJ km^{-1}	14	8		207	177	272	425	425	661
Maximum load weight	Mg	22-23	27		1,820	550	950	2,500	2,500	10,800
Maximum load volume	m^3	102	120		4,550	642	1,321	3,137	3,137	14,774
Speed (max)	km h^{-1}	80	80		80	5.42	5.80	6.71	8.64	9.00
Loaded trips of total trips[c]		50%	56%		50%	71%	85%	77%	77%	83%

a) BLM database: Kenworth T800 3-axle day cab with C1453' flatbed trailer (bales) or C14 Western Trailer 48' Flat Floor Chip Trailer (wood chips and pellets). Costs are calculated in BLM. The maximum weight load varies per state, based on the maximum vehicle load (MGV): 36 Mg in Georgia, Illinois, Indiana and Virginia, 39 Mg in Kansas, 45 Mg in Alabama.
b) Inland waterways in the U.S. are assumed similar to EU CEMT Class VI ships (push barges).
c) Based on statistics of dry bulk in the Netherlands (average utilization including empty returns) [41].

6.2.5.6 Maritime transportation (short sea and deep sea)

There are two types of sea shipping: short sea shipping and deep sea or ocean shipping. When goods are transported by sea without crossing an ocean, for example between ports that are both situated in Europe or in the Great Lakes in North America, this is referred to as 'short sea shipping', also called 'motorway of the sea' or 'marine highway' [44]. Deep sea or ocean shipping refers to sea shipping that requires ocean crossing between the port of origin and destination, for example between North America and Europe. If, due to draft limitations or port limitations, deep sea bulk carriers cannot enter sea ports, cargo can be transloaded from deep sea ships to short sea ships in large ports, for example by using floating cranes, before transport to smaller sea ports. The intermodal transport model used in this article includes short sea shipping transport networks only for Europe (Figure 6-3). If required, additional transport networks and mode parameters such as the Great Lakes in North America, could be added to the BIT-UU model, but were beyond the scope of this analysis.

For short sea shipping of solid biomass in Europe, dry bulk ships with a capacity of 5000 – 7500 DWT[13] are assumed with cost and performance data from NEA [41]. For deep sea shipping, there are four main size segments [45, 46]: handysize (30,000-35,000 DWT), Handymax or Supramax (40,000 – 60,000 DWT), Panamax (60,000-75,000 DWT) and Capesize (170,000 – 180,000 DWT). Economies of scale can reduce the specific cost of

[13] Dead weight tonnage (DWT) is the total weight that a ship can carry including cargo, fuel, fresh water, crew etc. [45]

freight transport substantially when larger ships are used. However, the draught, length or beam of the ship could limit the accessibility to ports. For example, Panamax ships of average 61,000 DWT, with a draught of 11.7 - 13.4 m, can only access 27% of global sea ports [45]. Furthermore, the optimal size of a ship depends on the parcel sizes of cargo availability and allowed size of the delivery as, in contrast to container ships, bulk carriers often only visit a limited number of ports [47]. The net cargo capacity of ships depends on the stowage factor of the cargo, the inverse of the bulk transport density freight and the design of the cargo hull. Ships, for transport of heavy grains with a designed capacity of 1.3 m^3 Mg^{-1}, as assumed in this article, could transport to full deadweight of wood pellets because wood pellets have similar stowage to heavy grains, but not to full deadweight when wood chips are transport due to the lower stowage factor (2.5 m^3 Mg^{-1}) [45].

Multiple (macro-) economic external factors have a large impact on shipping costs, such as supply and demand of ship freight volume and global trade that cannot be modeled without using multi-sector, multi-regional economic modeling tools capable of addressing for these complex and indirect effects. The cost of ocean shipping in this analysis is therefore based on a simplified approach that considers the cost for the ship owner, reflected in time charter rates and the cost of the ship charterer (voyage cost). Table 6-3 shows the cost covered by time charter rates and the voyage cost. In reality, individual freight rates may also depend on the opportunity to collect up new cargo in the destination harbor. Such factors are however difficult to include in a model.

The fuel consumption of bulk carriers comes from the main engine, used for ship propulsion, and the auxiliary engine, used for onboard electricity consumption that remains on during berth when the main engine is turned off [46]. In this analysis, the total fuel consumption is based on the average fuel consumption for Handysize, Supramax, and Panamax ships as calculated by the International Marine Organization using activity data and fuel statistics of 2007 [46]. It should be noted that fuel consumption depends for a large extent on the navigation speed. When shipping demand is low, reducing time charter rates and fuel prices are high, shippers choose to navigate at lower speeds to reduce fuel cost [45]. Such effects are not taken into account in this analysis.

Table 6-3 Shipping cost parameters [48].

Time charter (US$ d^{-1})	Voyage cost
Depreciations	Fuel Oil
Interest on Capital	Harbor and canal dues
Financial Charges	Loading and Discharging Costs
Insurance of Hull and Machinery	Stowage Material
Survey Classification	Cleaning of Holds
Maintenance and Repairs	Damage to Cargo
General Costs	
Stock, Supply Crew	
Lubricating Oil	
Fresh Water	

Table 6-4 BIT-UU model transport mode parameters for sea and ocean transportation [32, 46, 49].

Parameter	Unit	Short sea >7,500 DWT	Ocean		
			Handysize	Supramax	Panamax
Charter rates[a]	€ h^{-1}	123	451	628	735
Variable cost	€ km^{-1}	5.71			
Fuel type		IFO380	IFO380	IFO380	IFO380
Fuel consumption full	MJ km^{-1}	1,430	1,761	2,185	2,553
Fuel consumption empty	MJ km-1	1,430	1,466	1,742	1,987
Maximum load by weight	Mg	5,700	26,000	37,000	53,400
Maximum load by volume	m^3	9,500	43,333	61,667	89,000
Speed	km h^{-1}	28.7	26.4	26.7	26.7
Loaded trips of total trips[b]		74 %	55 %	55 %	5 5%

a) Median charter rates 2007 -2011 [49].

b) Net loaded trips for short sea shipping based on NEA statistics for international dry bulk shipping. Ocean shipping based on IMO [46].

6.2.6 Biorefinery

There are many possible pathways for converting lignocellulosic biomass into products and intermediates that can be upgraded via various routes into liquid or gaseous biofuels [50, 51]. Fischer-Tropsch (FT) diesel production from solid biomass requires gasification to produce syngas (a mixture of hydrogen and carbon monoxide) that can be catalytically reformed into hydrocarbons. FT-diesel has a high cetane number, is free of nitrogen and sulphur, and can directly substitute fossil diesel in existing markets [19]. FT diesel is one of the key second generation biofuel production technologies that might become commercially available in the near future, but faces some challenges associated with increasing the scale to take advantage of economies of scale [51]. The key performance and cost parameters for the biorefinery are provided as supporting information (Table A 6-2) based on the pellets to liquids (PTL) 400 and PTL 2000 production chains in the carbon, energy flow and cost analysis of FT-diesel production by van Vliet et al. [19]. Similarly, capacities of 400 and 2000 MW_{th} biomass input were selected to demonstrate the impact of economies of scale. At larger plant sizes, most processing equipment of the FT-synfuel production plant has to be installed in parallel trains, reducing the advantages of economies of scale. The thermal input capacity of the selected FT plant configurations is also in range with co-firing and full conversion projects of coal fired power plants in northwest Europe. The option of carbon capture and storage (CCS) was not assessed, but could add substantially to the GHG mitigation performance [19].

6.2.7 Case studies

Two case studies were analyzed in this paper. The first supply chain analyzed herbaceous biomass (corn stover and switchgrass) produced in the U.S. Midwest and the second supply chain analyzed woody biomass (thinnings and pulpwood) produced in the U.S. Southeast and each supplied to a biorefinery located in the port area of Rotterdam in the Netherlands. The general supply chain assumptions used for the base cases and sensitivity cases are provided in Table 6-5. Detailed information on the supply chain assumptions is supplied as supporting information (Table A6-1).

Table 6-5 Supply chain assumptions and sensitivity cases.

Parameter	Base case	Sensitivity cases	
		High fuel	Panamax
Reference year	2012	2012	2012
Euro to dollar exchange rate	1.322	1.322	1.322
Energy prices			
Diesel/MDO, excl. excise duties and VAT (€ L^{-1})	0.56	0.78	0.56
Electricity (€ kWh)	0.043	0.060	0.043
Natural gas (€ GJ^{-1})	5.4	7.6	5.4
HFO (€ Mg^{-1})	454	636	454
Ocean ship size	Supramax	Supramax	Panamax

Although only pellets from woody biomass are currently exported from the U.S. to Europe [2], herbaceous supply chains are included to evaluate the implications of biomass supply from alternative geographic locations (U.S. Midwest) and their cost competitiveness compared to existing trade routes of wood pellets between sea shipping terminals in the U.S. Southeast and northwest Europe. If liquid biofuel was produced in the U.S. and transported as liquid biofuel to Europe, the supply system could be more efficient due to the improved energy density of the transported commodity. However, transportation of liquid biofuels on road, railways or waterways as well as transport of processed biomass through pipelines is not considered in this analysis. The port of Rotterdam was selected as the European port destination because it is a strategic location for international supply of biomass sources because of its good hinterland network connections for distribution of refined biofuels [52]. The selected FT-plant sizes of 400 MW and 2000 MW thermal input are added to demonstrate the total cost of a biofuel production system, but the main focus is on the feedstock supply chain that could also supply other types of biorefineries or conversion plants such as co-firing in a coal fired power plant. The results therefore also assess the GHG mitigation performance if the feedstock is used for electricity generation. Also, depending on future U.S. policy on climate change and security of supply, the domestic demand for biomass might reduce the export potential of the U.S. substantially [53]. However, understanding the competition between domestic and export markets is critical to meeting a growing demand.

6.3 Results

6.3.1 Feedstock supply chains

Transport modes and routes between field or forest, depot, export shipping terminals are predefined transport routes based on default cases of the BLM. Transport modes and routes between the export shipping terminal and biorefinery are calculated with the BIT-UU model for least cost routes. Table 6-6 summarizes the distances per transport operation and mode of transport used. The different routes between export shipping terminals and the location of the biorefinery are depicted in Figure 6-5. Switchgrass and cornstover cultivated in the U.S., are baled and transported by road (truck with a flatbed trailer) to depots for pelletization. After pelletization, the pellets are transported by rail to the export shipping terminals where the material is transloaded on to barges and transported via inland waterways to the port of Mobile, Alabama. Pellets from wood sources are transported by rail to the terminals located in sea ports of Alabama (Mobile), Georgia (Savannah) and Virginia (Norfolk).

The transport routes of herbaceous biomass and woody biomass are similar between sea ports and the biorefinery. Wood chips or pellets are loaded onto ocean bulk carriers and transported to the port of Rotterdam. The location of the refinery is artificially assumed to be located in the geographic center of NUTS3 region NL335 (Groot Rijnmond) in the Netherlands. This is due to database used for terminals in Europe of the TransTools model [35] that does not include actual terminal locations. Therefore, biomass pellets and wood chips have to be transported by rail from the sea terminal to the final destination of the refinery over a short distance of 14 km.

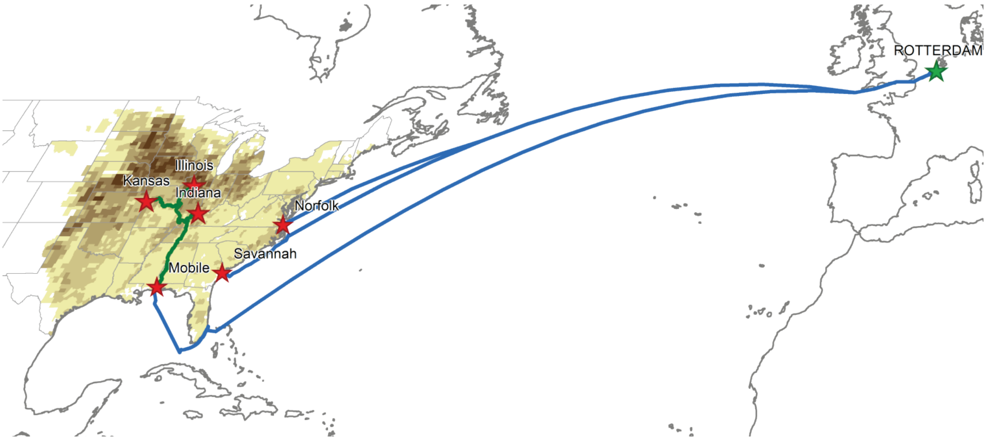

Figure 6-5 Lowest cost shipping routes of solid biomass between the export shipping terminals in the U.S. and the biorefinery located in Rotterdam (the Netherlands) as projected with the BIT-UU model. Inland transportation (road, rail, inland waterways): green lines, ocean transportation: blue lines, background: geographic distribution of the potential of herbaceous biomass (perennial grasses and corn stover) per county in the U.S. in 2015 [54].

Table 6-6 Transportation distances (km) between the source of biomass production (field or forest) in the U.S. to the refinery in Rotterdam area, the Netherlands.

Type/origin		From field side (road)[a]	From depot to terminal (rail)	From export terminal to refinery[b]					Total distance
				Road	Rail	IWW	Ocean	Transloading[c]	
Pellets	Corn stover (KS)	30 - 69	161	0	14	2023	8933	3	11161 - 11200
	Corn stover (IL)	30 - 69	161	0	14	1736	8933	3	10874 - 10913
	Corn stover (IN)	30 - 69	161	0	14	1293	8933	3	10431 - 10470
	Switchgrass (KS)	22 - 26	161	0	14	2023	8933	3	11153 - 11157
	Switchgrass (IL)	22 - 26	161	0	14	1736	8933	3	10867 - 10871
	Switchgrass (IN)	22 - 26	161	0	14	1293	8933	3	10423 - 10427
	Thinnings (GA)	80	161	0	14	0	7260	2	7516
	Thinnings (AL)	80	161	0	14	0	8930	2	9186
	Thinnings (VA)	80	161	0	14	0	6506	2	6762
	Pulpwood (GA)	80	161	0	14	0	7260	2	7516
	Pulpwood (AL)	80	161	0	14	0	8930	2	9186
	Pulpwood (VA)	80	161	0	14	0	6506	2	6762
Chips	Thinnings (GA)	241		0	14	0	7260	2	7516
	Thinnings (AL)	241		0	14	0	8930	2	9186
	Thinnings (VA)	241		0	14	0	6506	2	6762
	Pulpwood (GA)	241		0	14	0	7260	2	7516
	Pulpwood (AL)	241		0	14	0	8930	2	9186
	Pulpwood (VA)	241		0	14	0	6506	2	6762

a) The distance between field side and depot is calculated endogenously in BLM for herbaceous (equation 6-3) biomass and predefined for forest (woody) biomass. The ranges result from the demand of the refinery (400 MW and 2000 MW thermal input).
b) Calculated with the BIT-UU model
c) Number of transloading operations between the terminal and the refinery.

The costs of feedstock procurement (grower payment or stumpage fee) and feedstock supply logistics, up to the throat of the thermochemical conversion process of the biorefinery in the Netherlands are depicted in Figure 6-6 and range between 99 € Mg^{-1} to 107 € Mg^{-1} for pellets and 105 € Mg^{-1} to 117 € Mg^{-1} for wood chip supply chains. Transport and preprocessing, required for long distance transportation, make up the largest cost factors of the feedstock supply chain. For wood chip supply chains, transport makes up to 50 % of the total supply costs whereas for wood pellets, the cost fraction of preprocessing could be up to 38 % with 34 % for transport. For domestic uses of biomass in the U.S., feedstock supply costs should be below 61 € Mg^{-1} dry for biofuel production and 38 € Mg^{-1} to 57 € Mg^{-1} dry for heat and power to be cost effective without support [9]. In Europe, support mechanisms and lack of mobilized cheap domestic biomass resources, have already resulted in large imports of wood pellets for higher prices. CIF (Cost, Insurance and Freight) spot prices of wood pellets imported to the Antwerp, Rotterdam Amsterdam region (ARA) have been added to Figure 6-6 based on available weekly and monthly indices of Argus Media [55] assuming a moisture content of 7 %. Over longer periods, larger spot price fluctuations have been observed, but not below the estimated supply costs (120 € Mg^{-1} and 151 € Mg^{-1} (dry)) [3]. The results suggest that, with CIF wood pellet prices in 2012, a gross profit margin of 20 % to 26 % could be achieved over the total supply chain for wood pellets exported to Europe. Similar profit margins of 20.7 % have been calculated for wood pellet production in the U.S. compared to FOB (Free on Board) wood pellet prices [56]. These profit margins are below the average profit margins of manufacturing industries, but higher than most forest industries in the U.S. [56].

Although herbaceous pellets and wood pellets have different cost structures, the total feedstock supply cost delivered in the Netherlands are within the same price range. This is mainly due to the higher grower payment of herbaceous biomass compared to the stumpage fee of woody biomass and the higher preprocessing requirements and implied dry matter losses of woody biomass compared to herbaceous biomass pellets. When biomass moves through the feedstock supply chain, logistic costs are accumulated and value is added [14]. Dry matter losses that occur later in the supply chain therefore have higher costs than dry matter losses early in the supply chain. The BLM allocates these costs to the processes where dry matter losses occur. Wood chip supply chains require grinding and drying within the biorefinery ("Preprocessing 3"). The associated dry matter losses increase the total cost substantially and reduce the cost effectiveness of wood chip supply chains.

Herbaceous pellets from Indiana are slightly cheaper than herbaceous pellets from Kansas or Illinois due to the shorter transport distance by inland waterways to the port of Mobile in Alabama (Table 6-6). Larger truck loads are allowed in Alabama compared to Georgia and Virginia due to the higher maximum vehicle weight allowed (MGV). Truck loads are 31 Mg in Alabama compared to 22 Mg in Georgia and Virginia (Table 6-2). Road transport cost of wood from the forest to the depot (pellets) or export shipping terminal (chips) are therefore 28 % lower for Alabama compared to Georgia and Virginia.

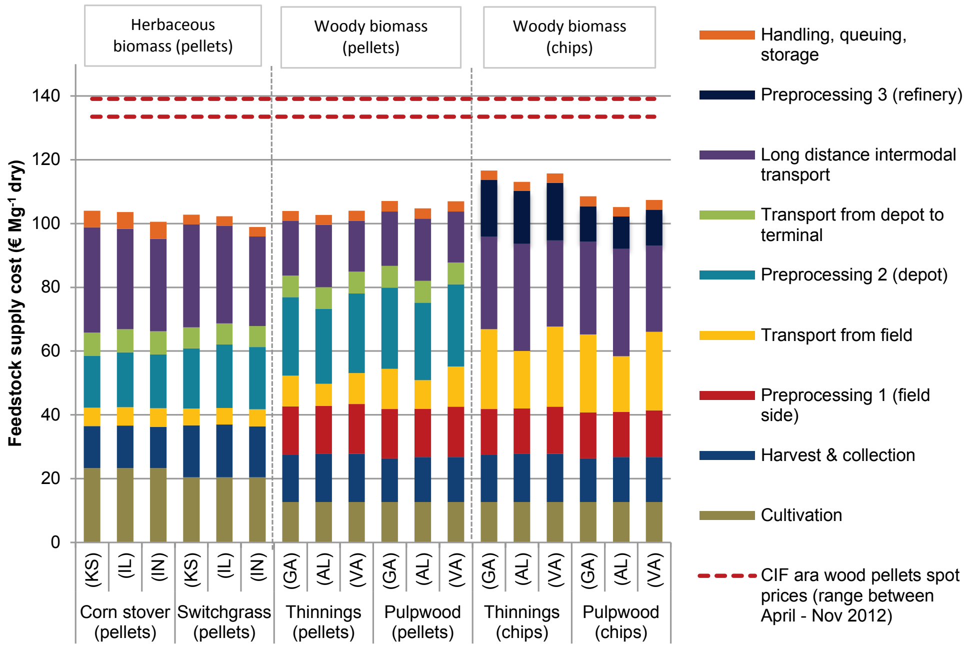

Figure 6-6 Biomass feedstock supply costs from U.S. biomass sources supplied to a biorefinery of 400 MW thermal input in Rotterdam, the Netherlands (€ Mg^{-1} dry) and CIF ARA spot prices of wood pellets in 2012 [55].

6.3.2 FT-diesel production

Figure 6-7 illustrates the cost break down of thermo-chemical conversion of the herbaceous and woody biomass produced in the U.S. and conversion into FT-diesel in the Netherlands. Each plant of 400 MW and 2000 MW thermal input is assumed to be supplied by three locations of the same feedstock (Table A6-1). At 400 MW thermal input, FT-diesel production cost are calculated between 22.2 (wood pellets from thinnings) and 23.7 € GJ^{-1} (wood chips from thinnings) FT-diesel. FT-diesel from herbaceous pellets can be produced within the same cost range to wood pellets implying that, if densified to pellets, herbaceous biomass could become competitive with exports of wood pellets despite the required inland transportation. Note however that pellets from herbaceous pellets might not meet the specifications required by end users in Europe, e.g. due to high ash and chlorine contents compared to wood pellets. At 2000 MW thermal input, conversion costs reduce with 3.3 € GJ^{-1} FT-diesel as a result of economies of scale of the conversion plant to € GJ^{-1} 18.9 to 21.4 € GJ^{-1}. The different demand sizes only have a small impact on the feedstock supply cost because sufficient supply is considered in the selected regions. Additional grinding of biomass required for wood chips and the implied electricity requirement, reduces the credit for excess electricity exported to the grid, but the effect is small compared to the additional costs implied by transport and dry matter losses within the refinery for drying wood chips.

The calculated FT-diesel production costs are higher than the fossil diesel price excluding excise duties and VAT assumed in the supply chain (15.6 € GJ^{-1}). These results do not take into account future crude oil price changes as well as the effect of CO_2 emission prices as discussed in detail in [19]. The effect of alternative (high) fuel prices is covered in the sensitivity analysis section (6.3.4).

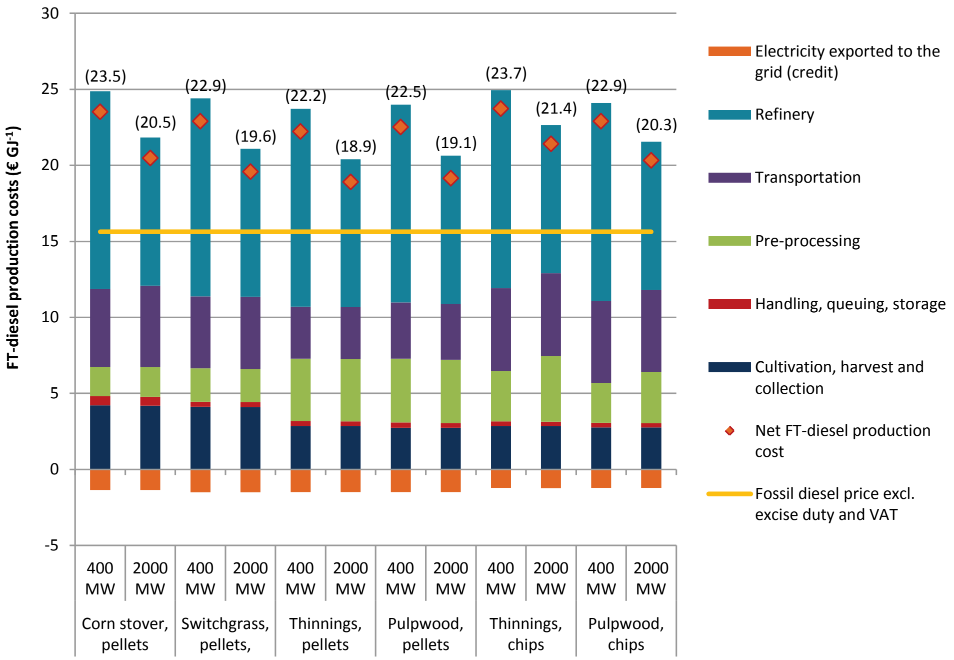

Figure 6-7 Break-down of FT-diesel production cost (€ GJ^{-1}) at 400 MW and 20000 MW thermal input capacities from herbaceous biomass (corn stover and switchgrass pellets) and woody biomass (thinnings and pulpwood pellets and chips) cultivated in the U.S. and delivered to Rotterdam (Netherlands). The fossil diesel price assumed in the supply chain calculations are added for comparison.

6.3.3 Greenhouse gas analysis

The GHG performance of the herbaceous and woody biomass supply chains including emissions from all energy and material inputs from field side to the throat of the refinery or conversion plant are depicted in Table 6-7. For each supply chain, the total GHG savings are calculated for FT-diesel production and electricity generation consistent with the RED and COM(2010)11 [22, 23]. For FT-diesel production, the GHG savings are also calculated consistent with van Vliet et al. [19]. For these results, the GHG savings from excess electricity exported to the grid are calculated assuming a natural gas fired reference plant (NGCC).

Long distance, international transportation (Table 6-7 , “Transport 3”) adds between 20 % (pellets from pulpwood) to 48 % (wood chips from thinnings) to the total GHG emissions of the feedstock supply chains. The low bulk density and high moisture content of wood chips compared to wood pellets reduces the net load capacity of ocean shipping resulting in a higher specific fuel consumption per Mg biomass transported. Nevertheless, for all feedstock supply chains assumed and conversion routes, the GHG reduction potential is well above the European minimum GHG savings of 60 % for biofuels produced in installations started in 2017 or later. It is still unclear whether the European Commission will also apply binding sustainability criteria for solid biomass used for electricity generation, but they are not expected to be above 80 %. Note however that emissions from (indirect) land use change or an upfront carbon debt are not considered in the results.

Table 6-7 GHG balance of solid biomass cultivated in the U.S. and supplied to the Netherlands (kg CO_2-eq Mg^{-1} dry) and the GHG emission savings when used for FT-diesel production or electricity generation.

	GHG emissions of feedstock supply						GHG emission savings		
Feedstock type and intermediate	Culti-vation	Handling, queuing, storage	Pre-processing	Transport 1, 2	Transport 3	Total	FT-diesel (NGCC)[a]	FT-diesel (IGCC biomass)[b]	Electricity generation[c]
			kg. CO2-eq Mg^{-1} (dry)						
Pellets									
Corn stover (KS)	33.7	2.0	66.1	9.4 - 14.6	73.7	185 - 190	92 % - 92 %	77 % - 78 %	86 % - 86 %
Corn stover (IL)	33.7	2.0	66.1	9.4 - 14.6	71.5	183 - 188	92 % - 92 %	78 % - 78 %	86 % - 86 %
Corn stover (IN)	33.7	2.0	66.1	9.4 - 14.6	68.1	179 - 185	92 % - 93 %	78 % - 79 %	86 % - 86 %
Switchgrass (KS)	94.0	1.6	75.5	8.2 - 8.7	70.6	250 - 250	86 % - 86 %	72 % - 72 %	82 % - 82 %
Switchgrass (IL)	94.0	1.6	75.5	8.2 - 8.7	68.4	248 - 248	86 % - 87 %	72 % - 72 %	82 % - 82 %
Switchgrass (IN)	94.0	1.6	75.5	8.2 - 8.7	65.0	244 - 245	87 % - 87 %	72 % - 72 %	82 % - 82 %
Thinnings (GA)	21.2	2.1	91.5	22.5	45.3	183	97 %	81 %	88 %
Thinnings (AL)	21.2	2.1	91.5	16.6	54.5	186	97 %	81 %	87 %
Thinnings (VA)	21.2	2.1	91.5	22.5	41.2	179	97 %	81 %	88 %
Pulpwood (GA)	66.1	2.1	72.4	22.5	45.3	208	94 %	78 %	86 %
Pulpwood (AL)	66.1	2.1	72.4	16.6	54.5	212	93 %	78 %	86 %
Pulpwood (VA)	66.1	2.1	72.4	22.5	41.2	204	94 %	79 %	86 %
Wood chips									
Thinnings (GA)	21.1	2.3	39.9	48.5	75.1	187	93 %	80 %	87 %
Thinnings (AL)	21.1	2.3	39.9	34.4	90.5	188	93 %	80 %	87 %
Thinnings (VA)	21.1	2.3	39.9	48.5	68.1	180	94 %	81 %	88 %
Pulpwood (GA)	64.1	2.3	39.9	47.7	75.1	229	88 %	75 %	84 %
Pulpwood (AL)	64.1	2.3	39.9	33.6	90.5	230	87 %	75 %	84 %
Pulpwood (VA)	64.1	2.3	39.9	47.7	68.1	222	88 %	76 %	85 %

a) GHG savings compared to fossil diesel comparator, credit for co-generation: NGCC plant. Consistent with van Vliet et al. [19].
b) GHG savings compared to fossil diesel comparator, credit for co-generation: BIGCC plant (Biomass Integrated Gasification Combined Cycle) using similar biomass feedstock. Consistent with the RED [23].
c) Biomass used for electricity generation, efficiency = 40% LHV. GHG savings relative to marginal electricity generation in the EU (Section 6.2.2).

6.3.4 Sensitivity analysis

Many of the input assumptions used to calculate the supply chains in this analysis are highly variable. For illustration, the feedstock supply chain costs have been calculated with alternative values for selected key variables (Table 6-5). Figure 6-8 shows the impact of alternative fuel price assumptions and the use of larger bulk ocean carriers (Panamax instead of Supramax) on the total feedstock supply cost. Note that many input parameters, including exchange rates, freight rates, moisture contents of raw biomass materials, are subject to uncertainty or are highly variable in time, but not covered in this analysis.

Diesel fuels are used for machinery in all logistic operations including harvesting machinery as well as preprocessing (e.g. chipping) and transport. Electricity is mainly used for preprocessing. A 40 % increase in fossil energy and electricity prices causes the total cost of feedstock supply to increase 8 % to 12 % compared to the base case assumptions. The use of larger ships reduces the total supply chain costs as much as 2 % for the shortest shipping distance (port of Savannah) and up to 4 % for the largest ocean shipping distance (port of Mobile) for the charter rates assumed in this analysis (Table 6-5). Note that charter rates are highly variable independent of the ship size. Furthermore, Panamax size ships cannot enter all sea ports due to draft and length restrictions as well as required port facilities [38, 45].

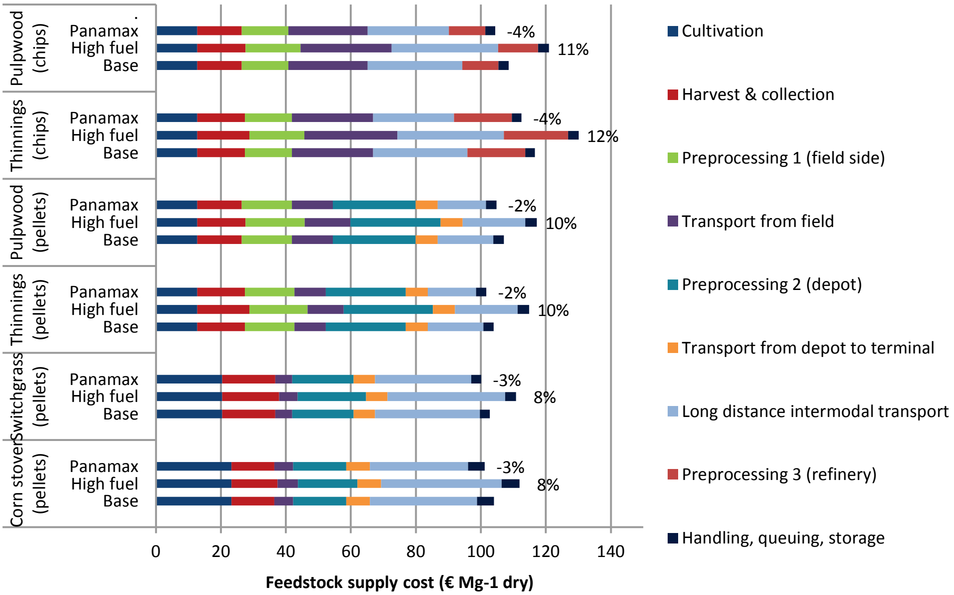

Figure 6-8 Sensitivity of alternative fuel price assumptions (High fuel) and ocean ship size (Panamax) on the supply chain costs of herbaceous biomass (Kansas to Rotterdam) and wood biomass (Georgia to Rotterdam). The result labels show the relative changes in total feedstock supply costs to the base case assumptions.

6.4 Discussion and recommendations for further research

6.4.1 Validation of the supply chains

Both wood chips and wood pellets are already traded internationally with large exports of wood pellets from the southeast of the U.S. to northwest Europe [2, 57]. However, pellets from herbaceous biomass for bioenergy purposes are also traded internationally, but mainly within Europe. For example, sun flower husk are exported from Ukraine to Poland [3]. It is therefore not possible to validate the shipping routes of herbaceous pellets. The use of inland waterways for export of wood pellets is found to be consistent with other studies and export of grains. Barge transport has been identified as the cheapest option to transport densified biomass from the Midwestern U.S. to the Southeast of the U.S. [58]. Furthermore, the supply chain shipping routes are consistent with corn shipments for export markets produced in the same states. For U.S. domestic markets, corn is mainly shipped by truck (80 % in 2011). However, for export markets of corn, barge transport is the main mode of transport (54 % in 2011) [59]. For export to Europe, the Great Lake shipping routes could be an option as both Indiana and Illinois border on the Great Lakes. However, these shipping networks are not available in the BIT-UU model (Figure 6-3).

All transport between depots (pellet plants) and export shipping terminals are assumed to go via rail. Large pellet plants, e.g. Georgia Biomass in Georgia, [60], use rail connections, but many pellet plants actually use trucks to transport pellets from the pellet mill to terminals in sea ports because they are too small or not located near a railway network. For ocean transport, the distances and related costs in the BIT-UU model are based on network data from short sea and ocean shipping networks [36, 37]. The distances calculated with the BIT-UU model (Table 6-6) have been found to be consistent with online voyage calculator tools. For example, the difference between distances calculated with Sea-Distances [61] and the results in this article are found to be 1.2 % or lower. Also the sea ports used in the supply chains already export pellets to Europe [56, 62]. The cost for ocean shipping in this study for wood pellets are calculated at 11 € Mg^{-1} for wood pellets from Savannah (GA) and 14 € Mg^{-1} for wood pellets exported from the port of Mobile (AL). In comparison, spot cargo prices of transporting wood pellets from the same ports to Rotterdam (ARA region) with a 45,000 Mg capacity ship in 2012 were 13 € Mg^{-1} to 20 € Mg^{-1} (port of Savannah) and 14 € Mg^{-1} to 23 € Mg^{-1} (port of Mobile) [55]. The results of this analysis are therefore within low ranges compared to real shipping price available.

The production of Biomass to Liquids (BtL) biofuels has not yet been commercialized and the available cost estimates in literature should therefore be considered prospective [63]. Based on a literature survey of 14 studies between 2000 and 2011, Haarlemmer et al. [63] concluded that the production cost of BtL type fuels is likely 1.0 to 1.4 € L^{-1} for a 400 MW thermal input plant on a greenfield location at feedstock supply costs similar to the results of the supply chains in this analysis (100 € Mg^{-1} dry). The techno-economic performance data of FT-diesel conversion plants in this analysis are however based on future technologies as assumed in van Vliet et al. [19] showing FT-diesel production costs that are substantially lower: 0.64 € L^{-1} to 0.69 € L^{-1} (22.2 € GJ^{-1} to 23.7 € GJ^{-1}). The FT-diesel production cost estimated in this analysis are therefore highly uncertain and can only be achieved when these technologies become commercially available. Beyond 2020, deeper FT-diesel production cost reductions are expected as a result of technological learning [64-66]. Furthermore, advanced preprocessing options, such as torrefaction or pyrolysis, could also reduce the total cost of advanced biofuel production with long distance supply chains [64].

6.4.2 Model approach and input assumptions

The linked BLM and BIT-UU model approach results in an integrated, flexible analysis tool that combines geospatial features of biomass intermodal transportation using the BIT-UU model with the biomass supply chain simulation tool BLM and background data (spatial data, engineering performance data, labor data). The lack of geospatial features has been identified as one of the key missing features of feedstock supply chain models [10].

Although this article demonstrates that such a combined modeling approach is possible, there are still limitations that requires further extension or redesign of the analysis tool.

The supply chain assumptions and input parameters in this analysis are mainly based on default feedstock supply chains available in the BLM and default transport assumptions available in the BIT-UU model. Many of these parameters are uncertain or highly variable in time, e.g. moisture content of raw biomass or macro-economic developments, e.g. charter rates and fuel prices, exchange rates. Further model integration between BLM and BIT-UU is required to enable advanced sensitivity analysis and explore the impact of variable parameters, e.g. with Monte Carlo simulations as conducted with the BLM for U.S. domestic supply chains of corn stover by Cafferty et al. [13].

The database of the BLM is developed for supply chains in the U.S. whereas the transport network dataset for inland transportation is limited to the U.S. and Europe. Global supply or demand nodes at sea shipping terminals can be added with minor efforts because they can be linked to the available ocean shipping network, for example as demonstrated with the BIT-UU model in [67]. However, the BLM dataset needs to be extended with engineering performance data, labor data, spatial data which is specific per country in order to extent the supply chains to other regions. Furthermore, inland transportation networks and related geospatial attribute data have to be added to the BIT-UU model for extension to countries outside the U.S. or Europe. These extensions would allow the assessment of international feedstock supply chains and the impact of different engineering designs, variations in feedstock characteristics and comparison of different regions of existing and potential future supply chains.

The intermodal transport module in the BLM is fixed to transport between the export shipping terminal and the biorefinery (Figure 6-2). This implies that supply chains always require an export shipping terminal and that the location has to be selected from the available terminals in the network dataset. Several studies have demonstrated that also the locations of pellet plants or biorefineries can be optimized using GIS software and linear solvers. For example, Zhang and Hu [68] determined the optimal locations and sizes of biorefineries in Iowa (U.S.) using a mixed integer linear programming model (MILP). Similar approaches have also been used to determine the locations of biorefineries (FT-diesel) in Finland [69]. Similar assessments could be possible with the analysis tool developed in this article with further integration of the BLM and BIT-UU models to calculate both the optimal locations, capacities and types of preprocessing and the optimal transport routes between locations.

6.5 Conclusion

The growing demand of biomass for centralized industrial energy purposes, including electricity generation, CHP and district heating, has also increased the complexity of the supply chain logistics involving long distance, international transportation implying additional costs, energy consumption and GHG emissions. This analysis has linked the two analysis tools BLM and BIT-UU extended with international shipping routes to develop an integrated analytical tool. The integrated analytical tool combines the strength of a detailed process model with geospatial features of a GIS model and enables a detailed assessment of costs, energy and GHG emissions implied by the logistic operations required to move biomass from the field or forest of production up until the conversion process within a biorefinery at an overseas location. The tool is flexible in changing feedstock characteristics, input variables (e.g. fossil fuel prices, labor cost, freight rates), as well as to add or omit unit operations and change their locations (e.g. drying, grinding, densification).

We conclude that the developed integrated tool can adequately model existing and future biomass supply chains and fits multiple purposes. It can be used for design engineering of feedstock supply chains, reveal bottlenecks, assess alternative logistic options and analyze the impact of uncertainties, from the field or forest up until conversion to final energy carriers. Examples of such design improvements demonstrated in this article are the addition of pelletization to the supply chain or increasing ship sizes. The calculated wood supply chains demonstrate that densification to pellets reduces the feedstock supply costs with up to 11 % compared to exports of wood chips as a result of additional transport cost as a result of the low dry bulk density of wood chips and dry matter losses for required preprocessing in the biorefinery. Further cost reductions are possible by economies of scale. For example, the use of larger ocean bulk carriers (Panamax instead of Supramax) would reduce the total cost of feedstock supply with 2 % to 4 % for the demonstrated supply chains. Note that these results could change depending on the charter rates and fossil fuel prices assumed and would be larger for supply chains that require longer transport routes, e.g. wood pellets from British Columbia (Canada). For biorefineries using international biomass supply, increasing demand hardly affects the feedstock supply costs because the model allows for an optimal number of depots (pellet mills) located in a fixed distance to the shipping terminal. Because increasing the scale of the FT-diesel production plant from 400 MW to 2000 MW reduces conversion costs substantially (with 3.3 € GJ) due to economies of scale, FT-diesel production cost are calculated at 19 € GJ^{-1} to 21 € GJ^{-1} (2000 MW) under preconditions that such supply chains could be developed.

The cost, energy and GHG performance estimates as well as insights in its variability and uncertainty could also support policy makers to evaluate the effectiveness of existing or calculate required support mechanisms or criteria for bioenergy. Although international transport adds substantially to the total GHG balance of the demonstrated supply chains, the resulted GHG savings are well over 70 % if used for FT-diesel production or electricity generation and thereby well above the minimum GHG savings of 60 % as required by the RED for installations commissioned beyond 2017. In other cases that could be assessed, for example destinations that require longer inland transport routes, e.g. land locked countries in Europe, the GHG performance might be worse and affect biomass trade depending on the GHG criteria applied.

For all supply chains demonstrated in this analysis, biomass could be delivered to a refinery in the ARA region at calculated costs below CIF ARA spot prices of wood pellets (fluctuating between 120 and 151 € Mg^{-1} (dry)). The U.S. Southeast is already one of the key exporting regions to Europe for wood pellets. The results show that, despite the required transport via inland waterways to a sea shipping port, pellets from agriculture biomass cultivated in the U.S. Midwest could also be exported to Europe for competitive costs compared to wood pellets from the U.S. Southeast because of lower preprocessing requirements and related dry matter losses. These insights in cost structures of possible international feedstock supply chains could, for example, reveal possible risks of unwanted exports and resource competition between domestic users and international users.

Many of the uncertainties that are intrinsic to the variables of biomass logistic chains (e.g. freight rates, empty returns, biomass yields) have not been assessed in this article, but can be analyzed with the tool. Possible improvements to the analytical tool include firstly, further integration to enable a full GIS based assessment of the feedstock supply chains that are limited in this article to the logistic operations between the export shipping terminals and biorefineries. Example of possible analysis include optimal location selection of supply regions, locations of preprocessing (depots), shipping terminals and end users as well as the impact of competitive uses. Further integration is also required to conduct more advanced sensitivity analysis, e.g. Monte Carlo simulations to understand the impact of uncontrollable parameters, e.g. seasonal variations. Secondly, the extension of the tool with the addition of liquid biomass intermediates (e.g. pyrolysis oil) and biofuels logistics and the extension of the model approach to other regions important to international biomass trade (e.g. Brazil, Canada, Russia). And thirdly, the integrated biomass logistic tool could be linked to biomass modules in e.g. energy models to improve the representation costs, energy and GHG emissions implied by biomass logistics for a wide range of possible geographic variations in supply and demand locations.

Appendix Chapter 6

Table A 6-1: Supply chain case assumptions

Location		Pellets Corn stover (KS, IL, IN)	Pellets Switchgrass (KS, IL, IN)	Pellets Thinnings (GA, AL, VA)	Pellets Pulpwood (GA, AL, VA)	Chips Thinnings (GA, AL, VA)	Chips Pulpwood (GA, AL, VA)
	Biomass type	Corn stover	Switchgrass	Thinnings	Pulpwood	Thinnings	Pulpwood
	Net calorific value (MJ kg^{-1} dry)	16.85	17.36	18.75	18.75	18.75	18.75
Field	Field / forest location	Kansas, Illinois, Indiana		Georgia, Alabama, Virginia			
	Harvesting moisture content	50 %	34 %	50 %	50 %	50 %	50 %
	Harvest	Harvest (Class 7 Combine), Rake (Twin Bar), Baler (Square bales)	Windrower, Baler (square bales)	Feller buncher			
	Collection	Bale stacker	Bale stacker	Medium Grapple Skidder			
	Storage	Field side stack (tarped)					
	Preprocessing			Flail delimber/debarker, Chipper			
	Transportation moisture content	10 %	12 %	50 %	50 %	38 %	38 %
	Loading and transport	Loading (Telehandler), Transport to depot (truck, calculated distance)		Transport to depot (truck, 80 km)		Transport to terminal (truck, 241 km)	
Depot	Storage	Concrete path					
	Grinding	Double ground		Single ground			
	Drying			Laudig Bin Dryer	Anco-Eaglin Dryer 300K		
	Densification	Pelletization (6 Mg h^{-1} pellet mill)					
	Transportation moisture content	10 %	5 %	9 %	9 %	38 %	38 %
	Transportation to export shipping terminal	Rail (Jumbo hopper cars, 161 km)					
Terminal	Terminal location	Kansas, Illinois, Indiana		Georgia, Alabama, Virginia			
	Transportation moisture content	10 %	5 %	9 %	9 %	38 %	38 %
	Loading and transport	Transport from the export shipping terminals to the refinery in Rotterdam (the Netherlands) using intermodal transportation (Table 6-6).					
Refinery	Handling, storage	Tipper hopper, conveyer belts, bulk storage, dust collection, misc. equipment					
	Preprocessing	Pellet crumbler				Single ground	
	Drying					Laudig Bin Dryer	
	Moisture content (refinery throat)	10 %	5 %	9 %	9 %	10 %	10 %

Table A 6-2: Techno-economic performance of FT-synfuel production of the selected plant configuration and scales [19]

Plant name	FT400[a]	FT2000[a]
Gasifier	Carbon-V	Carbon-V
Type	Two stage (entrained flow)	Two stage (entrained flow)
FT-process	Shell middle distillate synthesis (SMDS)	Shell middle distillate synthesis (SMDS)
Input		
Thermal (MW_{th} lhv)	400	2000
Output		
FT gasoline (MW_{fuel})[b]	32	158
FT diesel (MW_{fuel})[b]	177	887
Electricity (MW_e)[c]	27	133
Total investment cost (M€)[d]	451	1680
Ownership cost (M€/a)[e]	61	228
Operation and maintenance (M€/a)[f]	17	66
Capacity factor	0.91	0.91

a) Based on the Fischer Tropsch plant configurations and techno-economic performance parameters of the pellet to liquid (PTL) plants PTL400 (FT400) and PTL2000 (FT2000) in van Vliet et al. [19].
b) Allocation of costs, feedstock input and credits for co-generation of electricity based on the share of FT-diesel relative to the total liquid fuel output (FT-diesel and FT-gasoline).
c) Excess electricity generation (co-generation of electricity - electricity requirement FT-plant).
d) With contingency cost = 15 % of capital investment, annual inflation = 2.2% (2005 - 2012), and exchange rate = 1.32 $€_{2012}$ per $\$_{2012}$
e) Depreciation period = 10 years, interest rate = 6 %.
f) Annual labor cost: 3.1 $\$/kW_{th}$ gasifier capacity, annual R&M cost: 4% of capital investment cost, annual insurance cost: 0.1 % of capital investment cost.

References Chapter 6

[1] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, et al. Wood pellet market and trade: a global perspective. Biofuel Bioprod Bior 2013; 7(1): 24-42.

[2] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. Renew Sust Energ Rev 2012; 16(5): 3176-99.

[3] Cocchi M, Nikolaisen L, Junginger M, Goh CS, Heinimö J, Bradley D, et al. Global Wood Pellet Industry Market and Trade Study. IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. 2011. 190 p.

[4] Sikkema R, Steiner M, Junginger M, Hiegl W, Hansen MT, Faaij A. The European wood pellet markets: current status and prospects for 2020. Biofuel Bioprod Bior 2011; 5(3): 250-78.

[5] Hamelinck CN, Suurs RAA, Faaij APC. International bioenergy transport costs and energy balance. Biomass Bioenerg 2005; 29(2): 114-34.

[6] Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC. A bottom-up assessment and review of global bio-energy potentials to 2050. Prog Energ Combust 2007; 33(1): 56-106.

[7] Lamers P, Marchal D, Heinimö J, Steierer F. Chapter 3: Global Woody Biomass Trade for Energy. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[8] Hess JR, Wright CT, Kenney KL. Cellulosic biomass feedstocks and logistics for ethanol production. Biofuel Bioprod Bior 2007; 1(3): 181-90.

[9] Searcy M, Hess JR, Tumuluru J, Ovard L, Muth DJ, Jacobson JJ, et al. Chapter 5: Optimization of Biomass Transport and Logistics. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[10] Miao Z, Shastri Y, Grift TE, Hansen AC, Ting KC. Lignocellulosic biomass feedstock transportation alternatives, logistics, equipment configurations, and modeling. Biofuel Bioprod Bior 2012; 6(3): 351-62.

[11] Sokhansanj S, Kumar A, Turhollow AF. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass Bioenergy 2006; 30(10): 838-47.

[12] Searcy EM, Hess JR. Uniform-Format Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass. 2010. INL/EXT-10-20372.

[13] Cafferty KG, Searcy EM, Jacobson JJ. Biomass Logistics Model: Analyzing biomass supply systems. Submitted.

[14] Cafferty KG, Jacobson JJ, Muth DJ, Bryden KM. Model based biomass system design of feedstock supply systems for bioenergy production. IDETC/CIE 2013 2013; DETC2013-13556.

[15] Uslu A, Faaij APC, Bergman PCA. Pre-treatment technologies, and their effect on international bioenergy supply chain logistics. Techno-economic evaluation of torrefaction, fast pyrolysis and pelletisation. Energy 2008; 33(8): 1206-23.

[16] Hoefnagels R, Junginger M, Resch G, Matzenberger J, Panzer C, Pelkmans L. Development of a tool to model European biomass trade. IEA Bioenergy Task 40. 2011.

[17] Sikkema R, Junginger M, Pichler W, Hayes S, Faaij APC. The international logistics of wood pellets for heating and power production in Europe: Costs, energy-input and greenhouse gas balances of pellet consumption in Italy, Sweden and the Netherlands. Biofuels, Bioproducts and Biorefining 2010; 4(2): 132-53.

[18] Hess JR, Wright CT, Kenney KL, Searcy EM. Uniform-Format Solid Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Bulk Solid from Lignocellulosic Biomass - Executive Summary. 2009. INL/EXT-09-15423.

[19] van Vliet OPR, Faaij APC, Turkenburg WC. Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis. Energ Convers Manage 2009; 50(4): 855-76.

[20] Cornelissen T. Modeling the biomass supply-chain using a discrete, geospatial explicit approach - Master Thesis 2013.

[21] ESRI. ArcGIS for Desktop Extensions - ArcGIS Network Analyst [internet]. Redlands, CA: Environmental Systems Research Institute (ESRI); 2013. [cited 2013 August]. Available at: http://www.esri.com/software/arcgis/extensions/networkanalyst.

[22] European Commission. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling - Report from the Commission to the Council and European Parliament. Brussels, Belgium; 2010, February. COM(2010)11 final.

[23] European Commission. Directive 2009/28/EC of the European Parliament and of the Council - on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Brussels, Belgium; European Commission. 2009. 62 p.

[24] Pachauri, RK and Reisinger, A (Editors). IPCC Fourth Assessment Report (AR4) - Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Geneva, Switzerland; Intergovernmental Panel on Climate Change (IPCC). 2007. 104 p.

[25] Langholtz M, Graham R, Eaton L, Perlack R, Hellwinkel C, De La Torre Ugarte,Daniel G. Price projections of feedstocks for biofuels and biopower in the U.S. Energ Policy 2012; 41(0): 484-93.

[26] Argonne National Laboratory (ANL). The GREET model - The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model 2012; 1 (rev2).

[27] Jonker JGG, Junginger M, Faaij A. Carbon payback period and carbon offset parity point of wood pellet production in the South-eastern United States. GCB Bioenergy 2013.

[28] Petrolia DR. The economics of harvesting and transporting corn stover for conversion to fuel ethanol: A case study for Minnesota. Biomass Bioenerg 2008; 32(7): 603-12.

[29] Lin T, Rodríguez LF, Shastri YN, Hansen AC, Ting K. GIS-enabled biomass-ethanol supply chain optimization: model development and Miscanthus application. Biofuel Bioprod Bior 2013; 7(3): 314-33.

[30] Winebrake JJ, Corbett JJ, Falzarano A, Hawker JS, Korfmacher K, Ketha S, et al. Assessing energy, environmental, and economic tradeoffs in intermodal freight transportation. Journal of the Air and Waste Management Association 2008; 58(8): 1004-13.

[31] Obernberger I, Thek G. The Pellet Handbook - The production and thermal utilisation of biomass pellets. London, Washington DC: Earthscan; 2010.

[32] Knörr W, Seum S, Schmied M, Kutzner F, Anthes R. Ecological Transport Information Tool for Worldwide Transports - Methodology and Data Update. Berlin – Hannover - Heidelberg; Commissioned by DB Schenker Germany, UIC (International Union of Railways). 2011.

[33] Hoefnagels R, Junginger M, Panzer C, Resch G. Long Term Potentials and Costs of RES - Part II: The Role of International Biomass Trade. RE-Shaping (work package 5), Intelligent Energy - Europe, ALTENER. 2011, August 2011. 48 p.

[34] Hoefnagels R, Resch G, Junginger M, Panzer C, Faaij A. International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union. Submitted.

[35] Joint Research Centre (JRC) - Institute for Prospective Technological Studies (IPTS). TRANS-TOOLS ("TOOLS for TRansport Forecasting ANd Scenario testing") 2009; 2.

[36] RRG Spatial Planning and Geoinformation (RRG). Short Sea Shipping Routes in Europe - RRG Database 2008.

[37] ORNL. Intermodal Transportation Network [internet]. Oak Ridge National Laboratory (ORNL); 2000. [cited 2011 September]. Available at: http://cta.ornl.gov/transnet/Intermodal_Network.html.

[38] National Geospatial Intelligence Agency. World Port Index (Pub 150). Bethesda, Maryland; National Geospatial Intelligence Agency (NGA). 2011.

[39] Middendorf DP. Intermodal Terminals Database: Concepts, Design, Implementation, and Maintenance [internet]. Knoxville, TN: Center for Transportation Analysis Energy

Division Oak Ridge National Laboratory; 1998. [cited 2011 September]. Available at: http://cta.ornl.gov/transnet/terminal_doc/.

[40] Smeets EMW, Lewandowski IM, Faaij APC. The economical and environmental performance of miscanthus and switchgrass production and supply chains in a European setting. Renew Sust Energ Rev 2009; 13(6–7): 1230-45.

[41] NEA. Factor costs of freight transport: an analysis of the development in time (in Dutch: Factorkosten van het goederenvervoer: Een analyse van de ontwikkeling in de tijd.). Rijswijk, the Netherlands; commissioned by Adviesdienst Verkeer en Vervoer,. 2004.

[42] Transport & Mobility Leuven (TML). Tremove-II - A policy assessment model to study the effects of different transport and environment policies on the transport sector for all European countries: Freight Cost 2005.

[43] United Nations. Inventory of Main Standards and Parameters of the E Waterway Network (Blue Book) - Revision 1 2006.

[44] Morales-Fusco P, Saurí S, de Melo G. Short Sea Shipping in Supply Chains. A Strategic Assessment. Transport Reviews 2013: 1-21.

[45] Stopford M. Maritime Economics. 3 edition ed: Taylor & Francis; 2009.

[46] IMO. Second IMO GHG Study 2009. London, United Kingdom; International Maritime Organization (IMO). 2009.

[47] Kaluza P, Kölzsch A, Gastner MT, Blasius B. The complex network of global cargo ship movements. J R Soc Interface 2010; 7(48): 1093-103.

[48] Deseck P and Lams J. MaritimeKnowHow [internet]. 2011. [cited 2011 September]. Available at: http://maritimeknowhow.com/.

[49] Baltic Exchange. The Baltic Exchange Dry Index [internet]. 2012. [cited 2012Available at: http://www.balticexchange.com/.

[50] Hamelinck CN, Faaij APC. Outlook for advanced biofuels. Energ Policy 2006; 34(17): 3268-83.

[51] Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, et al. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, United Kingdom and New York, NY, USA.; Cambridge University Press. 2011.

[52] Sanders JPM, Annevelink B, van der Hoeven D. The development of biocommodities and the role of North West European ports in biomass chains. Biofuel Bioprod Bior 2009; 3(3): 395-409.

[53] IEA. World Energy Outlook 2012. Paris; International Energy Agency (IEA). 2012.

[54] Perlack RD, Stokes BJ, (Lead Authors). U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. Oak Ridge, TN; Prepared by Oak Ridge National Laboratory for the U.S. Department of Energy under contract DE-AC05-00OR22725. 2011, August. 227 p. . ORNL/TM-2012/224.

[55] Argus. Argus Biomass Markets - Weekly Biomass Markets, News and Analysis 2012; May 2012, July 2012, October 2012, November 2012.

[56] Qian Y, McDow W. The Wood Pellet Value Chain - An economic analysis of the wood pellet supply chain from the Southeast United States to European Consumers. The USDA Forest Service and The US Endowment for Forestry and Communities. 2013, March. 59 p.

[57] Lamers P, Junginger M, Marchal D, Schouwenberg PP, Cocchi M. Global Wood Chip Trade for Energy. IEA Bioenergy Task 40: Sustainable International Bioenergy Trade. 2012, June 2012. 20 p.

[58] Gonzales D, Searcy EM, Ekşioğlu SD. Cost analysis for high-volume and long-haul transportation of densified biomass feedstock. Transport Res A-Pol 2013; 49: 48-61.

[59] Sparger A, Marathon N. Transportation of U.S. Grains: A Modal Share Analysis. 1978-2011 Update.U.S. Dept. of Agriculture, Agricultural Marketing Service. 2013, May. 21 p.

[60] Ferre P. Sustainable Forestry in Georgia Meets Tomorrow's Energy Needs [internet]. Georgia Biomass; 2012. Available at: http://www.caes.uga.edu/extension/camden/anr/documents/GBLLCandSustainableForestry3-22-12.pdf.

[61] Sea Distances. Sea Distances - Voyage calculator (nautical miles) [internet]. 2013. [cited 2013 September]. Available at: http://sea-distances.com/.

[62] SELC. Biomass Energy in the South - MAPS [internet]. 2013. [cited 2013 July]. Available at: http://www.southernenvironment.org/cases/biomass_energy_in_the_south/maps/.

[63] Haarlemmer G, Boissonnet G, Imbach J, Setier P, Peduzzi E. Second generation BtL type biofuels - a production cost analysis. Energy Environ Sci 2012; 5(9): 8445-56.

[64] Batidzirai B, Hilst F, Meerman H, Junginger M, Faaij A. Optimisation potential of biomass supply chains with torrefaction technology. Submitted.

[65] Knoope MMJ, Meerman JC, Ramírez A, Faaij APC. Future technological and economic performance of IGCC and FT production facilities with and without CO2 capture: Combining component based learning curve and bottom-up analysis. Int J Greenh Gas Con 2013; 16: 287-310.

[66] de Wit M, Junginger M, Lensink S, Londo M, Faaij A. Competition between biofuels: Modeling technological learning and cost reductions over time. Biomass Bioenerg 2010; 34(2): 203-17.

[67] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A. Global solid biomass trade for energy under different sustainability constraints by 2020: an assessment of potential import streams and supply costs to North-West Europe. GCB BIOENERGY 2013.

[68] Zhang L, Hu G. Supply chain design and operational planning models for biomass to drop-in fuel production. Biomass Bioenerg; In press.

[69] Natarajan K, Leduc S, Pelkonen P, Tomppo E, Dotzauer E. Optimal locations for second generation Fischer Tropsch biodiesel production in Finland. Renew Energ 2014; 62: 319-30.

Chapter 7

Summary and conclusions

The transition towards a sustainable energy system is a major challenge which requires deep reductions in GHG emissions, reduced consumption of fossil fuels by means of substitution with renewable energy and improved energy efficiency. The substitution of fossil fuels by biomass in energy sectors (bioenergy) and non-energy use by biobased products is considered one of the most important options to meet this challenge. Current bioenergy supply is estimated to be 50 EJ supplying roughly 10 % of the world energy needs (549 EJ in 2011). Fossil energy sources contributed 82 % to the TPES in 2011 [1]. Bioenergy is still predominantly used traditionally (37 to 43 EJ y^{-1}) [2], i.e. for local usage, mainly for cooking and heating fuels in developing countries where access to modern sources of energy is limited. In the last decade, 'modern' biomass uses for electricity generation, efficient heating, combined heat and power (CHP) and transport fuels, have increased rapidly. Key drivers for this are GHG mitigation policies, increased price levels and volatility of fossil energy carriers and improving energy supply security. These drivers are expected to continue shaping the deployment of bioenergy in the future. According to the IEA New Policy scenario[3], modern bioenergy demand will more than double by 2035 if policies are applied to keep global temperature rises below 3.6 °C compared to pre-industrial levels. In the longer run, primary bioenergy supply is likely to increase to the range of 80 to 190 EJ y^{-1} by 2050 with upper ranges of 265 to 300 EJ y^{-1} depending on the maximum atmospheric GHG concentration target, according to the IPCC SRREN scenario assessment [2].

In contrast to traditional biomass uses, modern biomass use is especially observed in regions with high industrial activities and strong support for renewable energy deployment. Such regions are often geographically remote from the locations that have the larger economic biomass supply potentials. The rapid growth in modern biomass uses has therefore also shifted bioenergy supply chains (feedstock production, logistics and conversion) from local uses to more complex bioenergy supply chains with cross-boundary and intercontinental trade. Solid biomass trade increased to 302 PJ in 2010 [4, 5] and trade of liquid biofuels has grown exponentially since 2000 to the range of 119 to 129 PJ y^{-1} in 2009 [6]. The European Union (EU) has become the main trade and importing region for liquid and solid biomass. In order to meet the binding targets of 20 % renewable in gross final energy generation in 2020, bioenergy trade will become increasingly important. According to the National Renewable Action Plans (NREAPs), bioenergy is expected to remain the largest source of renewable energy generation and projected to contribute 54 % to the RED target in 2020 [7, 8]. Long term targets beyond 2020 are being negotiated and depend amongst others on the ambitions to curb greenhouse gas emissions. If such targets are taken seriously, these are expected to increase the shares of renewable energy and bioenergy trade substantially.

Such developments create a need for better understanding of the many opportunities, risks and uncertainties on how bioenergy can contribute to this transition. Policy makers and other stakeholders have to deal with different policy areas that are relevant for bioenergy deployment (climate and environment, energy, agriculture, forestry, economy) intertwined in different sectors of the economy (energy, industry, transport, agriculture, forestry, etc.) [9]. This includes different geographic scales, from regional to international due to global trade and interlinked markets. However, the future role of bioenergy in the transition to a sustainable energy system is characterized by a number of important knowledge gaps and uncertainties. Assessment models from different scientific disciplines are used to deliver insights in the current and possible impacts of bioenergy deployment. For example, economic computable general equilibrium (CGE) and partial equilibrium (PE) models are used to assess the possible effects of bioenergy in interlinked sectors of the economy. Energy system models enable assessments of the role of bioenergy within the (changing) energy system (electricity, heat, transport fuels, with overall increasing shares of renewable energy). These models include detailed representations within their respective area, but often rely on default and aggregated input parameters for variables that are not or cannot be endogenized in the modeling approaches. These procedures are required to facilitate efficient analyses and avoid to become too complex, which in turn could reduce the credibility of the model outcomes. However, this also implies that up to now, these models have not been able to provide consistent and sufficiently detailed assessments taking into account the dynamic and case specific characteristics of bioenergy production systems and its interlinkages to other markets [10].

Very relevant for new research, as presented in this thesis, are the high variabilities of cost and GHG balances of bioenergy systems, which can both be caused by methodological choices as the inherent dependency of the performance of bioenergy production systems to specific geo-spatial setting. This includes feedstock production, the design of logistic supply chains as well as the conversion and reference energy systems.

7.1 Objective and research questions

This thesis aimed to bridge some of the key knowledge gaps on the deployment of bioenergy at the national and European level with inclusion of international biomass trade. The main objective of this thesis was to improve the inclusion of bioenergy chains in economic, environmental and energy assessment tools next to modeling approaches to enable generation of improved insights in the potential direct and indirect impacts with respect to mitigation and economics of bio-based substitution of fossil energy carriers. To this purpose, the following research questions are addressed in this thesis:

I. What are the current and potential future cost and GHG balances of domestic and international bioenergy production chains?
II. How can system analyses contribute to the improved description and analysis of domestic and international bioenergy production chains in (established) energy and economic models and to what extent can different modelling approaches complement each other?

III. What are the prospects of bioenergy in fulfilling national and European renewable energy targets, what is the role of international biomass trade, key trade regions and potential resources and what factors affect biomass trade and deployment?

Chapter 2 to chapter 6 address these research questions in relation to each other as indicated in Table 7-1. Chapter 2 provides insight in the possible ranges of GHG and energy balances as a result of input assumptions and methodological choices. The role of bio-based substitution of fossil energy carriers at the national level for the Netherlands is assessed using the CGE model LEITAP (Chapter 3) and the renewable energy model Green-X for the EU (Chapter 5). Chapter 4 focuses on the economic potential of low-value wood sources and wood wastes for wood pellet production, taking the geographic dispersed supply of these resources into account. Chapter 5 and 6 describe approaches to improve the inclusion of international logistics related to bioenergy trade using a geographic explicit approach.

Table 7-1 Overview matrix of research questions covered within each chapter

Chapter		Research questions		
		I	II	III
2	Greenhouse gas footprints of different biofuel production systems	●		
3	Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level - a combined approach for the Netherlands	●	●	●
4	The economic potential of wood pellet production from alternative, low-value wood sources in the southeast of the U.S.	●		
5	International and domestic uses of solid biofuels under different renewable energy support scenarios in the European Union	●	●	●
6	Lignocellulosic feedstock supply systems with intermodal and overseas transportation	●	●	

7.2 Summary of the findings

Chapter 2 demonstrates the impact of different assumptions and methodological choices on the GHG balance and energy efficiency of biofuel production chains (feedstock and conversion combination). These include 1st generation ethanol (from corn, wheat, sugar beet, sugar cane, sorghum) and biodiesel (from palm fruit, rapeseed, soybean, jatropha) and 2nd generation ethanol and FT-diesel from herbaceous crops (switchgrass, miscanthus) and woody crops (eucalyptus). The results of these were compared for each of these biofuel production chains on a consistent basis and with variations in key parameters. These included co-products allocation or system expansion, N_2O emissions from crop cultivation, conversion systems and co-product applications and direct land-use change emissions.

The GHG balances of 2nd generation biofuel production systems were found to be in the range of (-2 g. CO_2eq MJ^{-1} to 25 g. CO_2eq MJ^{-1}) taking method induced variability into account. These production systems are therefore in most cases found to be better than 1st generation biofuels regardless of the accounting method for co-products. This could be explained by the higher crop yields for 2nd generation biofuels, requiring less fertilizers compared to most 1st generation crop types and credits for co-generation of electricity if system expansion is applied.

For 1st generation biofuels (starch, sugar, oil seeds), the difference between method induced variability (e.g. accounting methods) and real system differences (e.g. the location of production), results in substantially larger ranges. If emissions from land-use change are excluded, the location of crop cultivation and related yields, fertilizer application and soil N_2O emissions are key factors that determine the GHG performance of biofuel production. For example, GHG emissions from rapeseed methyl ester (RME) can be almost twice as high as fossil diesel (140 g. CO_2eq MJ^{-1}) if cultivated in East Europe and if no reference land is selected for N_2O emissions. If both rapeseed cake and glycerine are used for energy purposes and if cultivated in Western Europe, GHG emissions are 17 g. CO_2eq MJ^{-1} for the same type of biofuel.

If land is converted into crop land for cultivation of bioenergy crops, it depends strongly on the type of reference land whether the carbon content of cropland is higher or lower than the reference situation.

If bioenergy crops are cultivated on degraded land, more carbon will potentially be stored if the land is converted for energy crop production resulting in additional GHG credits for biofuel production. For example, changing degraded land to oil palm plantations in South East Asia can result in net change in carbon stock of -90 Mg CO_2 ha^{-1} (net storage). In contrast, when logged over forest in the same region is converted in to oil palm plantations, the net land use change emissions are over 433 Mg CO_2 ha^{-1} and up to 1580 Mg CO_2 ha^{-1} when peatland tropical rainforest is converted to palm oil plantations [14]. The impact of LUC emissions depend on the years of allocation. If LUC emissions are allocated over 20 years, emissions from biodiesel range from 25 g CO_2eq MJ^{-1} (degraded land) to 541 g CO_2eq MJ^{-1} (peatland natural rainforest).

The approach to calculate the lifecycle GHG balance (GHG-LCA) in the EU RED [12] is largely consistent with attributional LCA. Co-products are accounted for using energy allocation, but for co-generation of electricity, a restricted system expansion method is applied (consequential GHG-LCA) [13]. For example, a wheat ethanol plant that uses a straw fuelled CHP plant with excess electricity exported to the grid gets credits for the avoided emissions of dedicated biomass to electricity process assuming a straw fueled power plant. The difference between energy allocation (total emissions: 23 g. CO_2eq. MJ^{-1}) and the EU RED approach (total emissions: 27 g. CO_2eq. MJ^{-1}) remains small, but could be larger if credits are given based on the average EU electricity mix (total emissions: 15 g. CO_2eq. MJ^{-1}). Similar effects were observed for the 2nd generation biofuel production systems included with co-generation of electricity.

Chapter 3 explores the possible economic impact of bioenergy deployment at the national level for the Netherlands on value added, employment shares and trade balance next to the avoided use of fossil resources and GHG emissions for different scenarios. The scenarios are different regarding technology development and trade orientation. In order to develop strategic roadmaps and targeted policies that facilitate the economic and ecologic efficient deployment of bioenergy from domestic and imported resources, insight is required in the potential benefits, risks and uncertainties from the future deployment of bioenergy. To assess the direct and indirect economic effects of bioenergy deployment at the national level, while taking international and cross sector effects into account, the CGE model LEITAP has been used in combination with a spreadsheet tool to improve the level of detailed technology characterization of bioenergy conversion systems for heat, electricity and transport fuels as well as bio-based chemicals. The scenarios demonstrate that, if ambitious targets for bioenergy are pursued, it results in net positive impacts on value added in agriculture, energy and chemical industry sectors and trade balance, mainly by avoiding crude oil imports. Key prerequisites for achieving these targets sustainably are enhanced technology development and the availability of sustainable biomass resources for import to the Netherlands.

According to the LEITAP scenario projections, South America will become the largest exporting region of biomass to the Netherlands, followed by North America in 2030. For solid biomass, North America has already become the key exporting region (wood pellets) to Europe. Especially in the south-east of the U.S., the wood pellet production capacity has grown rapidly driven by the demand in Europe. In this region, increasing amounts of primary forestry products of pulp quality wood are being used to produce wood pellets due to a current decline of other markets. Nevertheless, the use of primary forestry products for energy purposes is debated because of ecological concerns and the possible temporal imbalances between forest harvesting and regrowth. In the same region, large quantities of wood residues and wood wastes are potentially available.

Chapter 4 assesses the economic potential of wood pellets produced from alternative, low-value resources available in the south-east of the U.S. (Florida, Georgia, North Carolina, South Carolina). For three types of alternative resources, the resource potential has been assessed. These include: primary forestry residues from pre-merchantable thinning operations and land clearing activities, secondary forestry residues from pole mills and post-consumer wood wastes from discarded wooden transport pallets. These wood resources are currently underutilized or used for low-efficient purposes such as low temperature heat generation. The total dry wood potential of these resources in the south-east of the U.S, was estimated to be 1.9 Tg y^{-1} available at roadside (excluding transport cost) for 22 \$ Mg^{-1} (dry) increasing to over 5.1 Tg y^{-1} at 33 \$ Mg^{-1} (dry). In theory, 4.1 Tg pellets could be produced from the estimated potential. However, due to the geographic dispersed supply of these resources, the cost of feedstock supply at a pellet plant increases rapidly for larger pellet plants. It is therefore not expected that the complete potential can be processed into wood pellets at competitive costs. The optimal size of a pellet plant varies between 55 Gg y^{-1} pellets and 315 Gg y^{-1} pellets depending on the location and feedstock supply assumptions. Depending on these locations and these plant sizes, pellets could be produced at competitive costs between 82 \$ Mg^{-1} to 100 \$ Mg^{-1} pellets.

Chapter 5 describes the development of improving the representation of biomass logistics and trade in the European renewable energy model Green-X using the Geographic Information Systems (GIS) based biomass transport model BIT-UU. Route specific cost and related GHG emissions of intermodal transport (by road, rail, inland waterway or sea) are calculated with the BIT-UU model and used as input to the biomass trade module of Green-X. The extension of Green-X with extra-EU and intra-EU biomass trade enabled the scenario assessment of renewable energy deployment taking the role of bioenergy and bioenergy trade into account. Since Green-X also includes other renewable energy sources (e.g. photovoltaic and wind), the competition between bioenergy and alternative renewable energy sources can be assessed. Scenario projections until 2020, used to demonstrate the developed modeling framework, show that although biomass from domestic (i.e. European) sources remains the most important source of bioenergy (91 % to 93 % in 2020), the role of traded solid biomass will become increasingly important. With a continuation of current renewable energy policies to 2020, the binding renewable energy targets will not be achieved, but trade of solid biomass will still increase up to 451 PJ in 2020. In the scenario that aims to achieve the 20 % renewable energy target in 2020, traded solid biomass is projected to increase to 440 PJ if sustainability criteria are applied and 506 PJ without sustainability regulations.

The scenarios assessed in Chapter 5, demonstrate the importance of imports of solid biomass from outside the EU and the need to improve the representation of the bioenergy supply chains from international resources.

Chapter 6 presents an approach to assess international lignocellulosic feedstock supply systems at the level of individual logistic system operations. For this purpose, the Biomass Logistic Model (BLM) has been linked with the Geographic Information Systems based Biomass Intermodal Transportation model (BIT-UU) and extended with inter-continental transport routes. Case studies of herbaceous and woody biomass, produced in the U.S. Midwest and U.S. Southeast, respectively, and shipped to Europe for conversion to Fischer-Tropsch (FT) diesel are included. These case studies demonstrate how intermodal transportation and, in particular, overseas shipping integrates with the bioenergy supply chains. For the cases demonstrated, biomass can be supplied at 99 € Mg^{-1} to 117 € Mg^{-1} (dry) and converted to FT-diesel at 19 € GJ^{-1} to 24 € GJ^{-1} depending on the feedstock type and location, intermediate (chips or pellets) and size of the FT-diesel production plant.

7.3 Answers to the research questions

RQ I. What are the current and potential future cost and GHG balances of domestic and international bioenergy production chains?

Input assumptions as well as procedures to calculate the GHG emissions and cost of bioenergy production systems result in different outcomes. Table 7-2 summarizes the key factors in cost and GHG balances of bioenergy production chains and the aspects covered in each individual chapter of this thesis. The main focus of this thesis was on improving insights in supply chains and required logistics. The model assessments with LEITAP (Chapter 3) uses an established CGE framework to calculate biomass commodity prices as well as bottom-up cost calculations using the spreadsheet based accounting tool. The Green-X model used in Chapter 5, also uses an existing database of economic-implementation potentials of bioenergy in the EU27.

Table 7-2 Aspects of cost and greenhouse gas balances of bioenergy production chains covered in the chapters of this thesis using different approaches and key factors affecting costs [2] and GHG emission.

	Stage in the bioenergy production chain					
	Production		Logistics		Conversion	
Chapter	Cost/prices	GHG balance	Cost	GHG balance	Cost	GHG balance
2		√		√		√
3	○[a] ●[b]	√	√	√	√	√
4	√		√			
5	●	√	√	√	●	●
6	○	√	√	√	●	●
Key factors	· Crop production · Land · Labor · Crop yields · Material prices · Management system · Production of agro-chemicals, fertilizers · Fertilizer induced emissions (in particular N_2O) · Emissions from land use changes		· Spatial distribution of biomass · Handling, queuing, storage · Availability of (existing) infrastructure · Transport modes used and distances · Locations, scale and type of pretreatment		· Type of energy carriers produced · Energy efficiency · The consumption of materials (e.g. chemicals) · Scale · Financing mechanisms · Load factors · Production, value and destined market of co-products · Capital and operating expenditures	

Legend:
√ Determined with system analyses in this thesis
● As available in the used models
○ From literature

a) The cost of bioenergy crops and residues in the bottom-up spreadsheet tool are based on literature.
b) Prices of bioenergy commodities are calculated endogenously in LEITAP based on land supply curves from model outcomes of the bio-physical model IMAGE. No changes have been made in this thesis.

GHG balance

Scenario analyses of large scale substitution of fossil energy carriers with biomass towards a bio-based economy in the Netherlands in Chapter 3 show that large reductions in GHG emissions are possible in 2030 (up to 54 Tg CO_2eq y^{-1} change compared to fossil fuel) avoiding up to 790 PJ primary fossil energy. Pursuing bio-based production of energy and materials also has net positive impact on the trade balance of the Netherlands and enhances economic activities within agriculture, industry and energy sectors. However, the magnitude of these positive impacts depends strongly on the rate of technological development and the mobilization potential of international, sustainable biomass resources and their price compared to fossil fuels (most notably oil). Key in achieving these targets are the commercialization of lignocellullosic bioenergy conversion systems as assumed in the HighTech scenarios of Chapter 3. These systems could use high yield lignocellulosic crops, residues (forestry and agriculture) and organic wastes to produce syngas (chemicals), electricity and transport fuels (ethanol, FT-diesel).

The yield of biofuel production systems varies substantially between different crop types. The highest yield for biofuel production systems in Chapter 2 was found for ethanol produced from eucalyptus in Brazil (246 GJ ha^{-1} y^{-1}), from 22 Mg ha^{-1} y^{-1} eucalyptus wood (dry). The lowest yield was found for biodiesel from rapeseed if currently cultivated in Eastern Europe (9.4 GJ ha^{-1} y^{-1}). In western Europe, yields of rapeseed diesel are already substantially higher (40.6 GJ ha^{-1} y^{-1}). The difference in yield between Western Europe and Eastern Europe demonstrates the improvement potential in Eastern Europe. If lignocellulosic crops are cultivated (miscanthus, switchgrass and eucalyptus), yields are found to be higher than oil, sugar and starch crops. The highest improvement potential could therefore be achieved if agriculture efficiencies are improved and if lignocellulosic crops are cultivated.

However, it is important to note that the GHG performance of bioenergy production systems varies considerably depending on the allocation procedure applied and the type of reference land use on which the biomass is assumed to be cultivated and the use of co-products.

A key limitation to the combined approach in Chapter 3 is that, although system expansion is used to account for co-products, the assumed application and reference products is static in the scenarios and based on literature. Ideally, the GHG calculation procedure of the bio-based production systems should be endogenised in the LEITAP model to account for marginal system changes and uses of co-products. Potentially, also consequences of land use allocation should be addressed in the modeling framework as well as land use selection and the variability of emissions caused by differences in environmental conditions, crop type and its management. System expansion is the preferred method to account for co-products. However, this method also introduces some major difficulties when e.g. reference products are also produced in multiple output systems or when the reference system cannot be identified.

Cost of bioenergy production

Based on the bottom-up cost calculations in Chapter 3, and assuming crude oil prices of 112 US$ per barrel, all scenarios have net negative mitigation costs up to −51 € Mg^{-1} CO_2 in the GlobHighTech scenario in 2030. The LEITAP results show that at the same oil price, hardly any subsidy is needed if competing with high fuel prices (0.015 € L^{-1}). However, biofuels remain still more expensive than fossil fuels in the LEITAP scenarios. This implies that either the LEITAP model is too conservative on possible cost reductions and resulting prices of bio-based production or that the bottom-up production costs are underestimated.

Logistics make up the largest cost of solid biomass supply chains if long distance transport is required. For example, in the southeast of the U.S., low value wood resources available at 17 € Mg^{-1} (dry)[14] need to be transported to a pellet plant and processed into wood pellets. The total production cost of pellets are calculated to be 69 € Mg^{-1} (dry) at assuming the best (lowest production cost) out of existing locations biomass supply in the state of Georgia. The logistic cost to transport wood pellets from the pellet plants to a sea port for export are not taken into account for these supply chains (see Chapter 4). If transported to a refinery in the Netherlands (see chapter 6), the cost of supply range between 99 to 104 € Mg^{-1} (dry) (5.7 to 6.4 € GJ^{-1})[15] for pellets from herbaceous biomass cultivated in the U.S. Midwest (corn stover and switchgrass) and 103 to 107 € Mg^{-1} (dry) (5.5 to 5.7 € GJ^{-1}) for wood pellets from the southeast of the U.S.. If wood chips are exported from the same region to the Netherlands, the total supply cost increase to 105 to 117 € Mg^{-1} (dry) (6.1 to 6.8 € GJ^{-1}). These supply chains take into account the cost of transport between the origins of supply (forest, field) , transport between the pellet plant and the export shipping terminal (sea port) and transport to the Netherlands. The results suggest that, with CIF wood pellet prices in 2012, a gross profit margin of 20 % to 26 % could be achieved over the total supply chain for wood pellets exported to Europe. The developed linked BLM – BIT-UU model tool allows for detailed analyses of many more supply chains and sensitivity analysis to reveal potential uncertainty ranges, but have not been conducted in this thesis. For the demonstrated supply chain cases, transport and preprocessing, required for long distance transportation, make up the largest cost factors of the feedstock supply chain. For wood chip supply chains, transport makes up to 50 % of the total supply costs whereas for wood pellets, the cost fraction of preprocessing could be up to 38 % with 34 % for transport.

Preprocessing of wood into wood pellets before long distance transport reduces the total cost of transport with up to 11 % compared to transport of wood chips as a result of the increased bulk density and reduced processing cost in the refinery (drying, grinding). Further cost reductions are possible by exploiting economies of scale. For example, the use of larger ocean bulk carriers (Panamax instead of Supramax) would reduce the total cost of feedstock supply with 2 % to 4 % for the demonstrated supply chains. However, Panamax size ships cannot enter all sea ports due to draft and length restrictions as well as required port facilities. Transport of herbaceous pellets from the U.S. Midwest to a sea terminal in Alabama, use inland waterways and are therefore already optimized for lowest cost. These supply chains are consistent with export of feed grains, but do not exist yet for bioenergy and would require major investments in logistic facilities. For deep cost

14 Exchange rate: 1.0 € = 1.32 US$

15 Net calorific value of herbaceous pellets: 15-16 MJ kg-1 (5 % - 10 % moist). Wood pellets and wood chips: 17 MJ kg-1 (9 % - 10 % moist).

reductions, more advanced logistic operations are required with low cost resources, optimal locations and sizes of processing units, advanced processing (e.g. torrefaction or pyrolysis) and advanced hub-spoke logistics.

For most sources of biomass in Europe, domestic supply of biomass is often cheaper than imports of extra-EU resources. For example, wood chips forestry residues can be supplied at average 5.5 € GJ^{-1} if exported to other member states in Europe (depending on the regions of supply and demand) in 2010 compared to 6.3 € GJ^{-1} for extra-EU imports of wood pellets (Chapter 5). For some domestic resources, e.g. sawdust, pelletization is required to improve handling and storage characteristics. However, for most European lignocellulosic biomass resources, pelletization is not cost effective compared to transport of wood chips.

RQ II. How can system analyses contribute to the improved description and analysis of domestic and international bioenergy production chains in (established) energy and economic models and to what extent can different modelling approaches complement each other?

Bioenergy is embedded in a complex, dynamic and interlinked environment. To provide detailed, comprehensive and consistent insights in bioenergy deployment in this context requires model collaboration between bottom-up and top-down approaches [15, 16]. There are different approaches of model collaboration [10]: the harmonization and alignment of input data and scenarios, e.g. in Edwards et al. [17], model comparison or actual model integration. The type of model collaboration required depends on the intended goal, scope and limitations of the models. This thesis explored different approaches of model collaboration to overcome shortcomings related to the representation of bioenergy production systems and to reveal limitations and opportunities for further improvements. The model collaborations covered in this thesis are summarized in Table 7-3. In the sections below, we discuss the improvements and remaining challenges of three cases in which different models have been linked.

Table 7-3 Overview of different model collaborations in this thesis

Chapter[a]	3	5	6
Model name	LEITAP	Green-X	BLM
Institute	LEI-WUR	TU Wien - EEG	Idaho National Laboratory
Model type	Computable general equilibrium	(Renewable) Energy system partial equilibrium	Bottom-up, logistics operations model
Scale	Global	Europe	Regional (U.S.)
Time frame	2006 - 2030	2006 - 2030	2015
Model adjustments	Split of chemical sectors, implicit representation of bioenergy	Biomass trade module	GIS module
Bottom-up collaboration			
Model name	Spreadsheet tool	BIT-UU	BIT-UU
Type	Static, BU technology characterization	GIS - Excel	GIS
Collaboration type	Calibration and harmonization of input and data and results	Input data	Integration (hard-link)
Main purpose	Add sector and technology details (electricity, transport, chemicals). Accounting for physical flows.	Country to country specific details of biomass transport cost and GHG emissions	Enable the assessment of long distance intercontinental biomass supply chains with geospatial features of intermodal transport.
Key limitations	Sector and technology detail only applied to the Netherlands. Lack of details for heat.	Detailed logistic chains for Europe. Aggregated representation of non-EU biomass. No transport of liquid fuels.	Covers only the U.S. (supply) and Europe (demand). No transport of liquid fuels.

a) Chapter 2 and chapter 4 show bottom-up approaches of GHG-LCA and resource assessments but are not linked to other models in this thesis.

LEITAP - Bottom-up spreadsheet accounting tool

Economic models, such as LEITAP, are able to assess the marginal production and consumption changes induced by the substitution of fossil energy with bioenergy. However, one of the key concessions of top-down CGE models is the lack of sector and technology details, technological learning and physical flows of materials and energy [10, 18]. Several studies have linked top-down models to bottom-up energy system models to address for technological details of the energy system [19, 20]. CGE models have also been extended with bioenergy, but the emphasis lies mainly on biofuels to assess the possible consequences on land use change and the effects on food and feed markets and trade [15, 21]. On the demand site, these models are still highly aggregated [10].

Improvements: This thesis used the CGE model LEITAP combined with a spreadsheet accounting tool. This tool enables the combined assessment of economic and environmental effects of bio-based substitution of fossil energy carriers in electricity, transport fuels and chemical sectors at the national level for the Netherlands. The scenarios assessed show that bio-based substitution of fossil energy carriers could significantly decrease both domestic fossil fuel dependency and GHG emissions. Sub-sectorial changes (due to technological change and shifts from fossil fuels to biomass resources) also have a major positive impact on the trade balance of the Netherlands and added value in bio-based industries.

Remaining challenges: The combination of the LEITAP model and the spreadsheet accounting tool also reveals key limitations to which bottom-up information can effectively be represented in the CGE modeling tools, without substantial changes to the modeling structure. One of the key determining uncertain factors that determines the future potential of bioenergy is the rate of technology development and diffusion rate of advanced bioenergy conversion options. The HighTech scenarios show that under strong technological development, production cost can be reduced substantially and become competitive with fossil fuels as a result of technological change. These include the cultivation of high yield crops and advanced bioenergy conversion technologies, e.g. thermochemical and biochemical production of lignocellulosic biofuels and advanced biorefinery concepts with possible cascading schemes [2]. However, these advanced systems are still under development and cost projections remain highly uncertain, e.g. of FT-diesel production [22]. The diffusion rate of advanced bioenergy conversion technologies in LEITAP are important, but also poorly understood. Further model collaboration of bottom-up energy system models and top-down approaches is required to improve the representation of technology diffusion and the understanding of the underlying drivers.

Secondly, scenario outcomes of the LEITAP model for the supply, demand and trade of biomass commodities could not be converted to absolute quantities of materials (e.g. Mg wood) because the LEITAP model results (in monetary flows) were too aggregated. These results are important to compare bottom-up production costs, actual commodity prices and yield levels and conversion efficiencies of bioenergy production systems.

Green-X - Biomass Intermodal Transportation model (BIT-UU)

Green-X is a dynamic toolbox that covers electricity, heat and transport sectors and models the future deployment of renewable energy in the EU27 under different scenarios for current and future (energy) policy conditions. It calculates the deployment of renewable energy at country and technology level for lowest cost optimization and provides the associated capital expenditures, consumer expenditures and fossil fuel and GHG avoidance compared to the reference scenarios on a yearly basis up to 2030. The role of bioenergy trade is becoming increasingly important, especially for scenario projections beyond 2020 [23].

In this thesis, the GIS based biomass transport analysis tool BIT-UU has been developed. This tool is used to identify likely trade routes of solid biomass in Europe using intermodal transportation (road, rail, inland waterways and short sea shipping routes). Routes are based on lowest cost optimization on intermodal transport networks taking into account the fixed loading and unloading between different modes of transport and variable cost of transport. The BIT-UU model also calculates the associated GHG emissions of lowest cost routes based on fuel consumption and fuel emission factors. The BIT-UU mode is used in combination with the development of a biomass trade module in Green-X to model bioenergy trade. This module uses the existing Green-X biomass database: for each tradable commodity (excluding mainly gaseous biomass), time period and possible route of intra-European biomass trade, it adds the cost and GHG emissions caused by the logistic operations required. Green-X then calculates the combined cost and revenues for each possible bioenergy resource and conversion system combinations allowed within the policy framework conditions.

Improvements: The combination of Green-X with BIT-UU allows for two major improvements:

- It enables a detailed assessment of cost and GHG emissions of optimal (lowest) cost transport routes taking into account the geospatial features of existing transport networks (road, rail, inland waterways, sea) available in Europe. Furthermore, the tool uses consistent input variables (electricity, diesel). It also provides flexibility to change input assumptions and adding geographic locations of supply and demand. The module calculates optimal distribution of Extra-EU and Intra-European biomass sources among countries in Europe endogenously.
- Secondly, the biomass trade module in Green-X allows for specifications of sustainability regulations. For each type of biomass, end conversion technology (e.g. small scale heat versus electricity generation), minimum GHG savings can be specified as well as additional costs of sustainable biomass supply.

Remaining challenges: The Green-X model can be used to identify likely regions of biomass supply and biomass demand. However, Green-X does not include a land use and forestry module that would enable the assessment of different scenarios and possible consequences of (agriculture) policies that can impact the economic potential substantially. Furthermore, the input data required to quantify the impact of sustainability regulations on the cost and supply of global biomass is underdeveloped and uncertain. More research is therefore required to improve the required input data.

Biomass Logistic Model (BLM) - BIT-UU

The expected growing demand of biomass for centralized industrial scale conversion, including electricity generation, CHP and district heating as well as biochemicals, has also increased the complexity of the supply chain logistics involving long distance, international transportation, resulting in additional costs, energy consumption and GHG emissions. The logistic cost and GHG emissions can add substantially to the total bioenergy production. To determine the cost and GHG emissions of bioenergy supply chains, requires a model that captures the characteristics of logistics at the operational level including harvest and collection, handling queuing, storage, pre-treatment and transportation. The Biomass Logistics Model (BLM) developed by Idaho National Laboratory (INL) [24-27] can simulate how a variety of feedstocks move from biomass standing in the field to the biorefinery, including logistic operations within the plant. However, transportation in BLM is based on aggregated predefined input assumptions. This thesis has linked BLM with the geographic explicit biomass intermodal transport model BIT-UU. For this purpose, the BIT-UU model has been extended with ocean shipping routes, and networks for road, rail, inland waterways, great lakes and deep sea for North America.

Improvements: The combination of detailed logistic operations modeling in BLM with the geospatial explicit optimization of intermodal transportation routes of the BIT-UU model, results in a flexible and powerful tool to analyze long distance biomass feedstock supply chains. Key improvements are the inclusion of geo-spatial features in BLM and the option to calculate optimal (lowest cost) long distance, intermodal transport routes depend on many interdependent variables, including available transportation networks and related attributes (costs, distances, restrictions) and possibilities for and number of transfers between different modes of transport (e.g. between road and rail). Such an integral analysis tool is important to evaluate feedstock supply chains, taking into account the key uncertainties and possible variations in biomass sourcing regions, types of biomass and characteristics, management practices and future policy and technical changes influencing both unit operations in the supply chains, as well as the geographic locations and types of end conversion technologies. The tool is flexible in changing feedstock characteristics, input variables (e.g. fossil fuel prices, labor cost, freight rates), as well as to add or omit unit operations and change their locations (e.g. drying, grinding, densification).

Remaining challenges:

- The GIS based assessment of the feedstock supply chains has so far been limited to the logistic operations between the export shipping terminals and biorefineries. Possible further improvements to the analytical tool would include further integration, such as possible analysis of optimal location selection of supply regions, locations of preprocessing (depots), shipping terminals and end users as well as the impact of competitive uses. Further integration is also required to conduct more advanced sensitivity analysis, e.g. Monte Carlo simulations to understand the impact of exogeneous parameters, e.g. seasonal variations.
- The extension of the tool with the addition of liquid biomass intermediates (e.g. pyrolysis oil) and biofuels logistics and the extension of the model approach to other regions (e.g. Brazil, Canada, Russia) is important to fully model (future) international biomass trade and competition between technologies and different intermediate carriers.
- The integrated biomass logistic tool could be linked to biomass modules in e.g. energy models to improve the representation costs, energy and GHG emissions implied by biomass logistics for a wide range of possible geographic variations in supply and demand locations.

RQ III. What are the prospects of bioenergy in fulfilling national and European renewable energy targets, what is the role of international biomass trade, key trade regions and potential resources and what factors affect biomass trade and deployment?

The role of bioenergy (EU)

With a continuation of current support policies, the Green-X BAU (Business as Usual) scenario projections, the total renewable energy generation in the EU is projected to increase from 5.9 EJ y^{-1} in 2010 to 7.8 EJ in 2020 resulting in an increased share of gross final energy consumption from 11.9 % in 2010 to 15 % (Table 7-4). To meet the binding renewable energy targets in 2020, requires strengthened national support (SNP scenario) in all sectors (heat, electricity, transport fuels). In the SNP scenario and SNP-bsc scenarios, renewable energy generation increases to 9.7 EJ in 2020 compared to 10.2 EJ as estimated by the EU member states in the NREAPs. Bioenergy has a key role in fulfilling the renewable energy targets in the EU27. Total bioenergy generation is projected to increase with over 30 % in the BAU and BAU-bsc scenario to 4.8 EJ in 2020 and over 64 % in the SNP and SNP-bsc scenario to 5.7 EJ in 2020. These scenarios confirm the expectations of EU member states in the NREAPs that bioenergy will remain the largest source of bioenergy to 2020 and contribute over half of the renewable energy target.

The key difference between the NREAPs and Green-X SNP scenario results that affects solid biomass trade, is the growth in renewable electricity generation in larger member states. For example, Germany projects 21% increase in renewable energy generation from solid biomass between 2010 and 2020 compared to 41% in the SNP scenarios. In contrast, France and the UK expect larger contributions from solid biomass (40% in France, 86% in the UK) compared to 29% in France and 68% in the UK in the SNP scenario results.

Primary bioenergy demand and trade (EU)

Primary bioenergy in the EU27 could increase with 26 % from 3.98 EJ in 2010 to 5.01 EJ in the BAU-bsc scenarios in 2020 and increase with up to 47 % (to 5.78 EJ) in the SNP-bsc scenario in 2020. Domestic supply of biomass remains the main source of bioenergy generation in the EU27 in all scenarios, but the role of internationally traded biomass sources is projected to become increasingly important as a result of growing biomass use. In total, intra-EU and extra-EU trade of solid biomass is projected to increase to between 373 PJ (BAU-bsc) and 506 PJ (SNP) equivalent to between 21 Tg and 28 Tg wood pellets. The strongest growth is projected for imports of solid biomass from outside the EU27. Compared to current imports of wood pellets to the EU27 (4.6 Tg in 2012), imports of solid biomass are projected to become 3.2 times larger (15 Tg wood pellet eq.) in the BAU-bsc scenario to 4.7 times larger (22 Tg wood pellet eq.) in the SNP scenario in 2020. Intra-EU trade of solid biomass is highest in the SNP-bsc scenario (122 PJ in 2020, 7 Tg wood pellet eq.), but the differences between the scenarios remain small up to 2020. By 2020, key exporting regions of EU biomass include central and eastern European countries (Bulgaria, Czech Republic, Hungary, Poland, Slovakia, Slovenia) where cheap resources of biomass, such as straw, are abundantly available and forestry rich countries in the Baltic states (Estonia and Latvia). Key regions of intra-EU biomass imports are Germany, with largest imports from Poland and the Czech Republic (mainly agriculture residues) and Austria, with largest imports from Slovenia and Hungary (forestry products and agriculture crops).

Prospects of bioenergy beyond 2020 in Europe depend for a large extent on the policy ambitions to increase the share of renewable energy and to ambitions to mitigate climate change. If deep GHG emission reduction are strived for, the share of renewable energy is expected to grow substantially beyond 2020. For example, if renewable energy support to meet the 2020 targets is assumed to continue to 2030 in the EU27, the renewable energy share will increase from 20 % in 2020 to 31 % in 2030 according to Green-X [28]. The PRIMES High Renewables scenario, used in the EU Energy: Roadmap 2050 projects the same share of renewable energy in 2030 (31 %) [28, 29].

Table 7-4 Total bio-based production and primary biomass demand in the EU27 (see chapter 5)

	2010[a]	2020				
		BAU	BAU-bsc	SNP	SNP-bsc	NREAP
Bio-based production (PJ final energy)						
Electricity	379	707	708	945	946	834
Heat	2711	3290	3290	3700	3682	3763
Transport fuels, of which:	616	838	838	1062	1062	1245
First generation	491	460	460	431	430	673
Second generation	0	91	91	152	152	110
Imported	125	287	287	479	479	462
Total bio-based production	**3706**	**4835**	**4836**	**5706**	**5690**	**5843**
Total renewable energy	5936	7820	7821	9754	9772	10256
Primary biomass demand (PJ primary bioenergy)						
Domestic[b]	4596	5750	5772	6755	6806	
Import EU	14	102	106	117	122	
Import non-EU	61	349	266	389	319	
Total	**4671**	**6200**	**6145**	**7262**	**7246**	
Renewable energy share of gross final energy consumption (%)						
Bio-based RES share	7.4%	9.1%	9.1%	11.6%	11.6%	11.7%
Total RES share	11.9%	14.8%	14.8%	19.8%	19.8%	20.6%

a) Based on Green-X database
b) Including gaseous biomass and organic waste

The role of bioenergy at the Dutch national level to meet the renewable energy targets

To assess the future prospects of bioenergy at the national level, we zoom in on the Netherlands, currently one of the key importing regions of biomass in the EU27 [30, 31]. Table 7-5 compares the expected deployment of renewable energy in the NREAP of the Netherlands [32] with the projections of Green-X for the BAU-bsc and SNP-bsc scenario in 2020 (Chapter 5) and the projections of the combined bottom-up –LEITAP approach in 2020 and 2030 for the GlobLowTech and GlobHighTech scenarios (Chapter 3).

According to the NREAP of the Netherlands , the Netherlands will exceed the national binding renewable energy target of 14 % in 2020 slightly (14.1 %) [32]. Wind is expected to become the main source of renewable electricity in 2020 (64 % of total renewable electricity generation) followed by electricity from biomass (33 % of total electricity generation). Total electricity generation from co-firing is expected to increase from 11 PJ in 2010 to 30 PJ in 2020 which is more than 50 % of total renewable electricity generation from biomass, which is in turn represents 17 % of total renewable electricity generation in the Netherlands in 2020. However, in the recently published Energy Agreement [33], a maximum contribution of co-firing to 25 PJ electricity in 2020 is reported.

According to the model based Green-X projections for the Netherlands, a small increase from 3.8 % in 2010 to 4.3 % in 2020 is projected if no changes are made to the currently implemented renewable energy policies (BAU-bsc scenario). The SNP-bsc scenario, in which the RES 2020 target for the EU27 will be met (Table 7-4), the share of renewable energy is projected to increase to 10.1 %. According to the Green-X model, the Netherlands will use renewable energy certificate trading (cooperation mechanisms) to meet the binding target of 14 % renewable energy in 2020 thus implying that part of renewable energy can be generated more cost effectively outside the Netherlands. Also the contribution of bioenergy is substantially lower (111 PJ final bioenergy in 2020) compared to the NREAP of the Netherlands (134 PJ final bioenergy in 2020).

The role of bioenergy at the national level in a bio-based economy

The scenario projections in Chapter 3 are not aimed at meeting the binding RES target in 2020, but are backcasting exercises that explore different roadmaps of bioenergy deployment up to high ambition levels. These high ambitions are in line with the energy transition platform 'Bio-based Green Materials' to replace 30% of fossil primary resources with biomass in 2030 [34]. The scenarios assess bio-based substitution of fossil fuels (non-energy use) in chemical industries which are not considered in the Green-X SNP scenarios and NREAPs aimed to meet the EU renewable energy targets. Furthermore, the scenarios in Chapter 3 focus on the bio-based substitution of fossil energy carriers and do not consider other renewable energy sources (e.g. wind, solar) The LowTech scenarios assume conservative shares of co-firing in existing coal fired power plants (10 % of final electricity generation) compared to the NREAP (20 %). The NREAP, on the other hand, does not include co-generation of electricity with 2nd generation biofuel production and syngas based chemical production resulting in higher electricity generation in the High-tech scenarios. The reason that biofuels are substantially higher in the LowTech scenarios compared to the NREAP and the SNP-bsc scenario is that LEITAP projects substantial increases in transport fuel demand (44 % to 47 % increase compared to 2006 in all scenarios). In the NREAP of the Netherlands, gross final energy consumption in transport is projected to decrease with 6 % in 2020 compared to 2005. For 2030, the expected role of renewable energy generation and bioenergy is uncertain. In the GlobLowTech and GlobHighTech scenarios, total bio-based production is projected to increase to 214 PJ and 653 PJ final energy respectively. The bio-based shares in final supply (including bioenergy and bio-based chemicals) is projected to increase to 12 % in the GlobLowTech to 38 % in the GlobHighTech scenarios in 2030. These scenarios demonstrate the potential importance of the possibly growing role of bio-based chemicals. Especially in the HighTech scenarios, the production of syngas based chemicals with co-generation of electricity contributes substantially to the total output in these sectors.

Primary bioenergy demand and trade (NL)

In the NREAP of the Netherlands, the role of imported biomass is not quantified. Sectors that are likely to import in 2020 are co-firing (total demand: 69 PJ primary biomass), and biofuels (total demand: 35 PJ final fuel) [32]. In 2011, the Netherlands imported 1.4 Tg in 2011 (25 PJ) [31] which implies that solid biomass imports will more than double towards 2020. The Green-X projections to 2020 are conservative with respect to bioenergy deployment in the Netherlands when compared to the expectations in the NREAP, in turn resulting in conservative estimates on imports of biomass. In the SNP-bsc scenario, total imports of solid biomass remain similar to 2011 imports of wood pellets (25 PJ primary biomass). The ranges in the GlobLowTech and GlobHighTech scenarios are substantially larger. The main difference between the NREAP and the GlobLowTech scenario are imports of ethanol from South America for the production of chemicals and the higher demand of transport fuels resulting from the LEITAP projections.

The GlobHighTech scenario describes a development pathway in which bioenergy will become cost competitive with fossil based production of energy and chemicals. Currently, bio-based production of modern bioenergy is only cost effective to fossil based production with support (e.g. subsidies). For example, wood pellets used for electricity generation are currently available to the Netherlands for about 130 € Mg^{-1} (7.4 € GJ^{-1}) (CIF ARA) and cannot compete with coal prices (currently about 3.3 € GJ^{-1}) [35] without support. Ambitious targets, such as aimed for in the GlobHighTech scenarios, can therefore only be achieved when bio-energy becomes cost competitive with fossil based production. This requires strong changes in technological development of production (e.g. yield improvements by management and organization, crop types), efficient logistic chains and commercial deployment of advanced conversion technologies as well as changes in fossil fuel prices and carbon taxes. In total, primary imports of biomass are projected to increase to 1.4 EJ in 2030 which is equivalent to 20 % of the total primary biomass demand for bioenergy in the total EU27 for the SNP-bsc scenario in 2020. These scenarios are assessed in LEITAP assuming that biomass demand in other countries will also grow, but more moderately than the highly ambitious GlobHighTech scenario for the Netherlands. For example, other EU member states aim to meet the EU renewable energy targets in all scenarios. These results do show that if the Netherlands will pursue a strong bio-based economy, a strong growth in the demand for (imported) biomass resources has to be anticipated in Europe and beyond.

We used the composition of total biomass crops (M€ in 2030) of Figure 3-6 (p. 67) as a proxy to roughly estimate extra-EU and intra-EU imports of solid biomass in the GlobLowTech and GlobHightech scenario. According to the LEITAP model, about 93 % of total crop imports are projected to be imported from outside the EU, 60 % from South America. Although a substantial part can be met by domestic residues ranging from 16 % in the GlobHighTech scenario to almost 70 % in the RegLowTech scenario, imports of biomass originating from dedicated energy crops or residues are required in all scenarios to meet the demand for bioenergy in the Netherlands.

Table 7-5 Bio-based production of renewable energy and chemicals in the NREAP of the Netherlands, Green-X (Chapter 5) and the combined BU - LEITAP approach (Chapter 3).

		NREAP		Chapter 5 (Green-X)		Chapter 3 (Bottom-up/LEITAP)[c]		
			2020		2020		2030	
	2010[a]	2020[b]	BAU-bsc	SNP-bsc	Glob-LowTech	Glob-HighTech	Glob-LowTech	Glob-HighTech
Bio-based production (PJ final energy)								
Electricity	19	60	23	32	26	110	32	141
Heat	29	39	39	54	20	20	22	22
Transport fuels, of which:	10	35	2	25	55	138	125	380
First generation	5	7	2	6	55	27	122	233
Second generation	0	6	0	2	0	111	3	147
Imported	5	22	0	18	37	21	141	0
Bio-based chemicals					15	49	34	111
Total bio-based production	**57**	**134**	**64**	**111**	**116**	**318**	**214**	**653**
Total renewable energy	81	307	92	199				
Primary biomass demand (PJ primary bioenergy)								
Domestic[d]	89		103	131	93	168	103	238
Import EU[e]	0		3	8	5	38	7	106
Import non-EU[e]	7		8	17	32	392	48	1084
Total	**96**	**349**	**113**	**156**	**130**	**599**	**158**	**1428**
Renewable energy share of gross final energy and non-energy (chemicals) demand (%)								
Bio-based RES share	2.7%	6.1%	3.0%	5.7%	4.4%	11.2%	7.9%	20.8%
Bio-based share (with chemicals)					7.5%	20.5%	12.4%	37.8%
Total RES share	3.8%	14.1%	4.3%	10.1%				

a) Based on Green-X database
b) ECN and NREAP of the Netherlands
c) Calculated with the BU Spreadsheet tool
d) Including gaseous biomass and organic waste
e) GlobLowTech and GlobHighTech: rough estimation of Intra-EU and Extra-EU imports based on the composition of biomass crops imported in the scenarios in 2030 (Chapter 3).

These scenarios show that the potential bioenergy deployment in the Netherlands depends to a large extent on the development of ecologic and economic sustainable biomass potentials in exporting countries, efficient supply chains to mobilize biomass resources and commercialization of advanced conversion technologies. The land availability per region and the yield levels of energy crops are very important factors in the economic potential of biomass production. To capture the changes in land use and land use intensity levels, the LEITAP model has been linked to the bio-physical model IMAGE to introduce a land supply curve, representing the process of land conversion and an endogenous change in yield level. As a consequence, in land-abundant regions like South America, an increase in demand results in a large increase in land use, a modest increase in rental rates and only a small increase in land intensity level. Land scarce regions experience a small increase in land use, a large increase in the rental rate, and a movement towards an increased intensity level of land use, if land demand increases. These model outcomes used, as an input to LEITAP, are highly uncertain and land supply curves are dynamic under different scenarios. For example, at the European level, the economic supply potential of biomass can vary widely under different land use scenarios, types of management applied and crop types cultivated [36, 37].

7.4 Key messages and recommendations

There is a strong need for improved insights in the potential impacts with respect to GHG mitigation impact and economics of bio-based substitution of fossil energy carriers. It depends on the purpose and application which method is appropriate. At the single production level, the intricacies of single bioenergy production chains can be captured using system analyses / bottom-up approaches. To assess the potential role of bioenergy in the context of the transition towards a sustainable energy system requires complex interdisciplinary models that take into account the direct and indirect impacts of future bioenergy deployment. This thesis has contributed to the improved representation of bioenergy in (established) models that are used for renewable energy and bioenergy impact assessments, including:

- Insights in methodological choices and input assumptions on the GHG mitigation performance of biofuel production systems;
- Quantification of possible economic impacts of bioenergy deployment at the national level;
- The economic potential of alternative wood sources available for wood pellet production in the Southeast of the U.S.;
- Geographic explicit assessments of biomass logistics;
- The potential role of intra-EU and extra-EU bioenergy trade.

7.4.1 Policy makers

The impact of policy decisions on bioenergy can be divers because bioenergy deployment is intermixed with different policy areas (climate, energy, agriculture, forestry, economy, environment), different sectors of the economy and across borders as a result of trade. Models can support policy makers to assess the possible impacts of decisions.

Lifecycle GHG emission tools have become critically important in renewable energy policies. Their main purpose in renewable energy support policy instruments is to set minimum GHG saving requirements relative to the reference system. Such insights can help to design biomass energy systems and mechanism to avoid deployment poorly performing bioenergy systems. For example, the RED requires minimum GHG savings for liquid biofuels in order to count for meeting the renewable energy targets [12]. Although not implemented yet, the European Commission recommended to use similar methods for solid and gaseous biofuels used for electricity generation, heating and cooling [38] as well as biomaterials. However, the GHG saving criteria for biofuels in the EU RED[16] might be too low to initiate efficiency improvements in solid biofuels used for electricity and heat generation. Unless land use change emissions are included (worst cases), bioenergy production is not affected by minimum GHG saving criteria of 60 %. Bottom-up

[16] Minimum GHG savings compared to fossil fuels: 35 % currently increasing to 50 % in 2017 and 60 % for plants that start production in 2017 [12].

assessment tools can inform policy makers on the consequences of methodological choices as well as input assumptions. These tools should therefore explicate the impact of input assumptions and different accounting procedures (e.g. energy allocation versus system expansion) and ranges of uncertainties that result from possible system changes.

To assess the possible impacts of minimum GHG saving criteria for solid biomass next to renewable energy policies in the EU, the Green-X model can be used. The bioenergy trade extension in Green-X of this thesis enables insights in the role of bioenergy from domestic and imported resources and the renewable energy deployment pathways, GHG emission reduction potentials, implied cost and required resources. Furthermore, the model enables the identification of possible weak spots or opportunities in sustainable use of domestic and imported biomass resources. Because minimum GHG saving restrictions can be specified in each country and each conversion technology and size, it is possible to assess the possible risks, but also opportunities of shifts in biomass uses. One example is the possible shift of uncertified biomass supply from extra-EU resources to sectors that do not have to comply with binding sustainability criteria. It would be relevant for policy makers and researchers to assess more strict sustainability regulations with the modeling framework. It should be noted however, that there is a major lack of understanding on the possible impact of sustainability criteria and regulations on the economic supply potential of international resources. More research is therefore required to improve the input assumptions on extra-EU biomass supply, as well as opportunities for intra-EU biomass supply to the modeling framework.

This thesis has shown that combination of bottom-up input and output accounting, including physical material and energy flows, with the top-down economic model LEITAP provides improved insights in environmental and economic impacts of bioenergy deployment. Policy makers should however be aware that these scenario assessments are explorations and not forecasts. Nevertheless, the scenarios demonstrate that large scale substitution of fossil energy carriers with biomass can result in substantial reductions in GHG emissions and dependency on fossil resources. However, the magnitude of these positive impacts depends strongly on the rate of technological development and mobilization of international, sustainable biomass resources and the price of biomass sources relative to the price of fossil energy carriers. This implies that consistent research, development and demonstration efforts are required to further develop and commercialize the desired advanced technologies. Technological development is essential to achieve the more beneficial results.

Furthermore, if the Netherlands would pursue for a bio-based economy, it would have domestic and international economy-wide effects. This implies that efforts over the whole production chain are required to safeguard sustainable and reliable biomass supply chains, including imports from Extra-EU and Intra-EU resources. Effective sustainability frameworks (including certification) are a key instrument to achieve that.

7.4.2 Investors and industrial stakeholders

To initiate further deployment of bioenergy will require private and public strategic investments that may, on short term, not be profitable, but which are likely to become more sustainable on longer term, for example due to increases in fossil fuel prices. The scenarios assessed for the Netherlands in this thesis show that major efforts are needed in public and private sectors, targeted at further internationalization of sustainable bioenergy trade, supporting logistic infrastructure and investments in advanced bioenergy technologies. The long term net economic benefits can be substantial. These scenarios also demonstrate that bioenergy trade will become increasingly important for Europe (Chapter 5) and especially for open economies such as the Netherlands (Chapter 3). Wood pellets have become the largest traded source of solid biomass today and this growing trend is likely to continue. In this thesis, wood pellet imports to the EU from extra-EU sources are projected to grow from 4.6 Tg y^{-1} in 2012 to 15 Tg y^{-1} to 22 Tg^{-1} in 2020. For investors and industrial stakeholders, the results can be used to identify possible business opportunities and identify investment risks in biomass supply (forestry and agriculture), logistic facilities (e.g. storage and handling facilities in sea or inland waterway ports) and bioenergy conversion systems.

Markets for lignocellusic bioenergy commodities, e.g. pellets, but in the future also other intermediates such as torrefied biomass or pyrolysis oil are expected to become increasingly large as a result of bioenergy demand for electricity and heat, but also 2nd generation biofuels and chemicals. This will create a need for additional and alternative sources of lignocellulosic biomass beyond the conventional sources (e.g. sawdust) and opportunities for farmers (agriculture residues and perennial crops), logistics (e.g. port terminals) and suppliers of intermediates (e.g. pellet producers). For example, wood pellet exporting regions, such as the Southeast of the U.S., are becoming more dependent on primary wood sources such as low grade pulp wood. However, as shown in this thesis, there are also wood sources available that are currently used as furnace fuel or disposed as waste that could be used for wood pellet production if collected properly. Although many of these wood sources have unfavorable characteristics compared to primary wood sources or sawdust, if properly collected, these wood sources could add substantially to a sustainable wood pellet supply. Test batches produced from un-merchantable forest residues and pole peelings demonstrate that it is possible to produce qualified pellets [39]. With the tools developed in this thesis, opportunities can be assessed, but also possible risks for resource competition. For example, the geographic dispersed supply of wood residues limits the optimal pellet production capacity in Georgia to 125 Gg y^{-1}. In this location, pellets are could be produced from low-value wood resources for 85 \$ Mg^{-1} according to the assessment. Furthermore, the logistic tool developed in Chapter 6 demonstrates that, despite the required transport via inland waterways to a sea shipping port, pellets from agriculture biomass cultivated in the U.S. Midwest, could be supplied in Europe for competitive costs compared to wood pellets from the U.S. Southeast because of lower preprocessing requirements and related dry matter losses. Last but not least, it is quite possible that the demand for lignocellulosic biomass for energy will increase in the

US (e.g. as lignocellulosic biofuels become commercially availability), which stresses the need to further develop and diversify sustainable biomass supply.

7.4.3 Recommendations for further research

At the national level for the Netherlands, it has been demonstrated that a spreadsheet accounting tool can be used to improve the representation of bioenergy in CGE models such as LEITAP. The combined approach also revealed important shortcomings that need further research. First, capital expenditures of bioenergy technologies are a critical component of the bioenergy production system. This is of main importance for capital-intensive technologies that use relatively low price feedstock which might be used for second generation biofuel production (Chapter 3, Chapter 6). The implicit modeling of bioenergy, as applied in LEITAP does not cover these effects properly. The latent technologies approach or disaggregation of the Social Accounting Matrices (SAMs) [21] with relevant sub-sectors would enable an improved representation of sector specific technology characteristics. Furthermore, the SAMs used in this thesis are derived from the GTAP 6 database for 2001, when modern bioenergy deployment started to accelerate. Newer versions should be used when available to cover the recent activities and relations in and around bio-based sectors. Biomass trade and modern bioenergy capacities that increased significantly since the last update of the SAMs are needed to assess the impact of bioenergy more accurately.

To quantify indirect effects of bioenergy deployment, consequential LCA methods are dependent on economic CGE or partial equilibrium models. However, further model collaboration is required to improve the representation of biomass flows, possible multiple energy and co-product outputs, for example from the multiple outputs of biorefineries (e.g. chemicals and energy). Furthermore, Chapter 2 shows that the location and type of land used for bioenergy production has a major impact on the GHG balance and thus the need for improved model collaboration between CGE models and bio-physical land use models. This is also true for scenarios that explicitly include measures to avoid unsustainable land use and indirect land use change, such as improved agricultural production efficiency, zoning of land use to protect carbon stocks and deployment of effective certification [15]. Lastly, energy system models, such as Green-X at the EU level, could be used to improve the technical representation of bioenergy energy and competing renewable energy sources in the CGE modeling framework. These linkages could also improve insights in trade flows using the bottom-up approach available in Green-X combined with the top-down market approach in the CGE model. Such a model collaboration could improve the representation of the renewable energy system and trade of biomass (Green-X) whereas a CGE model, such as LEITAP, could address for effects of (bioenergy) commodity prices, shifts in markets in agriculture and forestry sector and possible consequences on energy and material demands.

The extension of Green-X with bioenergy trade using the GIS based BIT-UU model, as described in Chapter 5, is mainly focused on the improved representation of cost and GHG emissions related to bioenergy transport logistics between European supply and demand regions. In Chapter 6, the BIT-UU model has been linked to the logistic operations model BLM to cover all logistic operations (harvest and collection, queuing and storage, pretreatment and transportation) and extended with ocean shipping. The current modeling framework available now enables detailed calculations of intercontinental logistic chains between the U.S. and Europe. The developed link between the BLM and BIT-UU model also enables extension of similar assessments to other regions within Europe as well as key supply regions outside Europe (e.g. from North America, South America, Africa and Russia).

Further research can be done using the linked BLM BIT-UU model for optimal location selection of supply regions, locations of preprocessing (depots), shipping terminals and end users as well as the impact of competitive uses. Lastly, the extension of the tool with the addition of liquid biomass intermediates (e.g. pyrolysis oil) and biofuels logistics.

Furthermore, according to the scenarios in Chapter 3 for the Netherlands, bio-based chemicals might become increasingly important. For medium term projections beyond 2020, the inclusion of bio-based chemicals, as a competing sector for bioenergy resources is likely to become more important. Another key need for improvement of the modeling framework for demand sectors is the advanced representation of end use facilities in the model. Domestic heat markets (e.g. pellet stoves in households) require different supply chains from industrial uses of biomass, e.g. bulk supply of wood pellets for co-firing. The BIT-UU model allows for specific modeling of end use facilities, their geographic locations and the logistic operations required. These sector supply chains could be used as input to the biomass trade module in Green-X, but this requires major efforts to incorporate in the current modeling framework, but can be very worthwhile to provide more detailed economic and risk analyses (e.g. underpinning investment opportunities and risks and planning logistic capacity).

Finally, this thesis has combined several modeling approaches to improve insights in the role of bioenergy and bioenergy trade in transition to a sustainable energy system. The core focus of this thesis was on improving the representation of bioenergy trade and implied logistic cost and GHG emissions. The collaborations between the models used in this thesis provide synergetic advantages and insights that cannot be provided by the individual models. There are still many shortcomings and limitations regarding the combination of a) LEITAP with a bottom-up spreadsheet accounting tool and b) combinations of the GIS based biomass transport model with the energy model Green-X and the logistic operations model BLM. Still, linking these models provides advanced insights in (macro-) economic impacts, technological details of the developing bio-based sectors, the role of domestic and traded biomass in electricity, heat and transport sectors in Europe, and possible cost and GHG emissions from long distance intercontinental supply chains.

The key missing link in the model assessments in this thesis is the dynamic characteristics and wide variety of biomass supply potentials [40]. The future economic and sustainable supply of biomass resources within the EU and available for import to the EU are subject to a complex and dynamic environment, dependent on policy choices and technological developments and therefore highly uncertain. The static approach used in LEITAP (based on IMAGE model outcomes) and Green-X (based on economic-implementation potentials) do not take into account the key aspects that determine the supply potential of bioenergy resources . The most important factors that impact biomass potentials are [41]:

- Improvements in agriculture management;
- Choice of crops;
- Food demand and human diet;
- Use of degraded land;
- Competition for water.

The relevance to include these factors within the assessment framework becomes larger for medium and long term projections (beyond 2020) when the share of dedicated energy crops in primary bioenergy supply is expected to become substantial. For short term projections, it is relevant to improve the logistic supply chains of biomass residues and identify possible options to reallocate uses of biomass. For example, low grade biomass sources can replace clean sawdust used as furnace fuel. To assess the potential role of bioenergy therefore requires an improved representation of determining factors that increase the potential (see above) and safeguard sustainability (e.g. zoning of land use, deployment of sustainability frameworks and certification) that could increase or decrease the supply potentials and cost and related interactions between domestic supply versus imports from extra-EU and intra-EU resources. Examples of these factors are changes in forest practices and agriculture management that could increase the biomass supply potential substantially. Strict sustainability criteria and increased international competition could reduce the availability of especially extra-EU resources, but could also improve management practices and learning that could ultimately increase the sustainable supply potential. These factors play a key role in future biomass deployment and trade and warrant substantial research and development efforts in the coming decade.

References Chapter 7

[1] International Energy Agency (IEA). Key World Energy statistics. 2013th.Paris; OECD/IEA. 2013. 81 p.

[2] Chum H, Faaij A, Moreira J, Berndes G, Dhamija P, Dong H, et al. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation. Cambridge, United Kingdom and New York, NY, USA.; Cambridge University Press. 2011.

[3] IEA. World Energy Outlook 2012. Paris; International Energy Agency (IEA). 2012.

[4] Lamers P, Marchal D, Heinimö J, Steierer F. Chapter 3: Global Woody Biomass Trade for Energy. In: Martin J, Goh CS, Faaij A, editors. International Bioenergy Trade: Springer; 2013.

[5] Lamers P, Junginger M, Hamelinck C, Faaij A. Developments in international solid biofuel trade - An analysis of volumes, policies, and market factors. Renew Sust Energ Rev 2012; 16(5): 3176-99.

[6] Lamers P, Hamelinck C, Junginger M, Faaij A. International bioenergy trade - A review of past developments in the liquid biofuel market. Renewable and Sustainable Energy Reviews 2011; 15(6): 2655-2676.

[7] Scarlat N, Dallemand J, Banja M. Possible impact of 2020 bioenergy targets on European Union land use. A scenario-based assessment from national renewable energy action plans proposals. Renew Sust Energ Rev 2013; 18(0): 595-606.

[8] van Stralen JNP, Uslu A, Dalla Longa F, Panoutsou C. The role of biomass in heat, electricity, and transport markets in the EU27 under different scenarios. Biofuel Bioprod Bior 2013; 7(2): 147-63.

[9] Faaij APC. Bio-energy in Europe: changing technology choices. Energy Policy 2006; 34(3): 322-42.

[10] Wicke B, Hilst F, Daioglou V, Banse M, Beringer T, Gerssen-Gondelach S, et al. Opportunities and limitations of model collaboration for the assessment of biomass supplies and impacts Submitted.

[11] Kendall A, Yuan J. Comparing life cycle assessments of different biofuel options. Curr Opin Chem Biol 2013; 17(3): 439-43.

[12] European Commission. Directive 2009/28/EC of the European Parliament and of the Council - on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC. Brussels, Belgium; European Commission. 2009. 62 p.

[13] Tipper R, Hutchison C, Brander M. A Practical Approach for Policies to Address GHG Emissions from Indirect Land Use Change Associated with Biofuels. Greenenergy 2009; Technical Paper - TP-080212-A.

[14] Wicke B, Dornburg V, Junginger M, Faaij A. Different palm oil production systems for energy purposes and their greenhouse gas implications. Biomass Bioenergy 2008; 32(12): 1322-37.

[15] Wicke B, Verweij P, Meijl Hv, Vuuren Dv, Faaij A. Indirect land use change: Review of existing models and strategies for mitigation. Biofuels 2012; 3.

[16] Creutzig F, Popp A, Plevin R, Luderer G, Minx J, Edenhofer O. Reconciling top-down and bottom-up modelling on future bioenergy deployment. Nature Clim.Change; advance online publication.

[17] Edwards R, Mulligan D, Marelli L. Indirect Land Use Change from increased biofuels demand - Comparison of models and results for marginal biofuels production from different feedstocks. Ispra, Italy; European Commission Joint Research Centre (JRC). 2010.

[18] Lefevre J. Building Input-Output tables in physical units and in money value to calibrate hybrid energy-economy CGE models: application to the Brazilian economy. 15th Annual Conference on Global Economic Analysis 2012.

[19] Böhringer C, Rutherford TF. Combining bottom-up and top-down. Energy Econ 2008; 30(2): 574-96.

[20] Messner S, Schrattenholzer L. MESSAGE-MACRO: linking an energy supply model with a macroeconomic module and solving it iteratively. Energy 2000; 25(3): 267-82.

[21] Kretschmer B, Peterson S. Integrating bioenergy into computable general equilibrium models -- A survey. Energy Econ 2010; 32(3): 673-86.

[22] Haarlemmer G, Boissonnet G, Imbach J, Setier P, Peduzzi E. Second generation BtL type biofuels - a production cost analysis. Energy Environ Sci 2012; 5(9): 8445-56.

[23] Lamers P, Hoefnagels R, Junginger M, Hamelinck C, Faaij A. Global solid biomass trade for energy under different sustainability constraints by 2020: an assessment of potential import streams and supply costs to North-West Europe. GCB BIOENERGY 2013.

[24] Hess JR, Wright CT, Kenney KL. Cellulosic biomass feedstocks and logistics for ethanol production. Biofuel Bioprod Bior 2007; 1(3): 181-90.

[25] Searcy EM, Hess JR. Uniform-Format Feedstock Supply System: A Commodity-Scale Design to Produce an Infrastructure-Compatible Biocrude from Lignocellulosic Biomass. 2010. INL/EXT-10-20372.

[26] Cafferty KG, Searcy EM, Jacobson JJ. Biomass Logistics Model: Analyzing biomass supply systems. Submitted.

[27] Cafferty KG, Jacobson JJ, Muth DJ, Bryden KM. Model based biomass system design of feedstock supply systems for bioenergy production. IDETC/CIE 2013 2013; DETC2013-13556.

[28] Ragwitz M, Steinhilber S, Breitschopf B, Resch G, Panzer C, Ortner A, et al. D23 Final Report: RE-Shaping: Shaping an effective and efficient European renewable energy market. Karlsruhe, Germany; 2012. 112 p.

[29] European Commission. Energy Roadmap 2050. Brussels; EUROPEAN COMMISSION. 2011. COM(2011) 885/2.

[30] Goh CS, Junginger M, Cocchi M, Marchal D, Thrän D, Hennig C, et al. Wood pellet market and trade: a global perspective. Biofuel Bioprod Bior 2013; 7(1): 24-42.

[31] Goh CS, Junginger M, Junginger M, Faaij A. Monitoring sustainable biomass flows in a bio-based economy: General methodology development. Submitted to Biofuels, Bioproducts & Biorefining 2013.

[32] Government of the Netherlands. National renewable energy action plan of the Netherlands - Directive 2009/28/EC. the Netherlands; 2011. 118 p.

[33] Social and Economic Council (SER). Energy agreement (Energieakkoord). 2013, September.

[34] Rabou LPLM, Deurwaarder EP, Elbersen HW, Scott EL. Biomass in the Dutch Energy Infrastructure in 2030. ECN and WUR. 2006.

[35] CBS. CBS-Statline: Import price of steam coal 1990 2012 (in Compendium voor de Leefomgeving) [internet]. CBS (Centraal Bureau voor de Statistiek); 2012. [cited 2012 november]. Available at: statline.cbs.nl.

[36] Fischer G, Prieler S, van Velthuizen H, Berndes G, Faaij A, Londo M, et al. Biofuel production potentials in Europe: Sustainable use of cultivated land and pastures, Part II: Land use scenarios. Biomass Bioenerg 2010; 34(2): 173-87.

[37] de Wit M, Junginger M, Lensink S, Londo M, Faaij A. Competition between biofuels: Modeling technological learning and cost reductions over time. Biomass Bioenerg 2010; 34(2): 203-17.

[38] European Commission. On sustainability requirements for the use of solid and gaseous biomass sources in electricity, heating and cooling - Report from the Commission to the Council and European Parliament. Brussels, Belgium; 2010, February. COM(2010)11 final.

[39] Sikkema R, Meyers S, Schipper E. Sustainable import of pellets from the United States (Inbio A project). Zwolle, the Netherlands; Control Union. 2012. 28 p.

[40] Batidzirai B, Smeets EMW, Faaij APC. Harmonising bioenergy resource potentials-Methodological lessons from review of state of the art bioenergy potential assessments. Renew Sust Energ Rev 2012; 16(9): 6598-630.

[41] Dornburg V, Van Vuuren D, Ven VD, Langeveld H, Meeusen M, Banse M, et al. Bioenergy revisited: Key factors in global potentials of bioenergy. Energy and Environmental Science 2010; 3(3): 258-67.

Hoofdstuk 7

Samenvatting en conclusies

De transitie naar een duurzaam energiesysteem is een forse uitdaging waarvoor fossiele brandstoffen op grote schaal vervangen moeten worden door hernieuwbare energiebronnen, de energie-efficiëntie substantieel verbeterd moet worden en aanzienlijke reducties nodig zijn in de uitstoot van broeikasgassen. De vervanging van fossiele brandstoffen door biomassa in energiesectoren (bio-energie) en materialen (niet-energetisch verbruik, bijvoorbeeld voor de productie van plastics) wordt gezien als een van de belangrijkste opties in deze transitie. Het huidige primaire aanbod van bio-energie is jaarlijks ongeveer 50 EJ, wat overeenkomt met 10 % van het wereldwijde primaire energieverbruik (549 EJ in 2011). In hetzelfde jaar was de bijdrage van fossiele brandstoffen aan het totale primaire verbruik van energie 82 % [1]. Bio-energie wordt op dit moment nog hoofdzakelijk gebruikt voor traditionele toepassingen (37 tot 43 EJ jr^{-1}) [2]. Deze traditionele toepassingen bestaan hoofdzakelijk uit het lokaal verbruik van biomassa voor verwarming en koken in ontwikkelingslanden met beperkte toegang tot moderne energiebronnen. In het afgelopen decennium is het gebruik van biomassa voor moderne energietoepassingen sterk toegenomen. Voorbeelden van moderne toepassingen van bio-energie zijn elektriciteit, warmte-krachtkoppeling (WKK), efficiënte verwarming en biobrandstoffen. De sterke stijging van moderne toepassingen van bio-energie zijn voor het grootste deel toe te schrijven aan beleid gericht op de vermindering van broeikasgasemissies en gericht op de verbetering van de energiezekerheid alsmede de recente stijgingen en de volatiliteit van fossiele energieprijzen. Naar verwachting zullen dezelfde drijfveren ook sterk bepalend blijven voor de inzet van bio-energie in de toekomst. Volgens het "Nieuw Beleid" scenario van het Internationaal Energie Agentschap (IEA), waarin beleid wordt toegepast om de mondiale temperatuurstijging te beperken tot 3,6 °C ten opzichte van pre-industrieel niveau, zal in 2035 de mondiale inzet van moderne bio-energie toepassingen meer dan verdubbelen ten opzichte van de huidige situatie. Op de langere termijn, tot 2050, wordt een toename van bio-energieverbruik verwacht tot gemiddeld 80 tot 190 EJ jr^{-1} en maximaal 265 tot 300 EJ jr^{-1}, afhankelijk van de gekozen maximale broeikasgasconcentraties in de scenario's [2].

In tegenstelling tot traditionele vormen van bio-energie, vindt de vraag naar moderne bio-energie voornamelijk plaats in regio's met sterke industriële activiteiten waar beleid wordt gevoerd op de ontwikkeling van hernieuwbare energie. Vaak zijn deze regio's geografisch ver verwijderd van de regio's met grote economische biomassapotentiëlen. De stijging van de moderne toepassingen van bio-energie heeft daarom ook geleid tot een stijging in de internationale en intercontinentale handel van biomassa voor energiedoeleinden. Zo is de handel in vaste biobrandstoffen gestegen tot 302 PJ jr^{-1} in 2010 [4, 5] en is de handel in vloeibare biobrandstoffen vanaf 2000 exponentieel gegroeid tot tussen de 119 en 129 EJ jr^{-1} in 2009 [6]. In deze periode is de Europese Unie (EU) uitgegroeid tot de grootse handel- en importregio van biobrandstoffen ter wereld en er wordt verwacht dat de rol van biomassahandel in de EU verder zal groeien voor het behalen van de doelstelling van 20 % hernieuwbare energie in 2020. Volgens de Nationale Actieplannen voor Hernieuwbare Energie (NREAPs) zal bio-energie met 54 % de grootste bijdrage leveren aan de totale mix van hernieuwbare energie in de EU in 2020. Op de lange termijn, na 2020, zal de inzet van hernieuwbare energie voor een groot deel worden bepaald door ambities om broeikasgasemissies te reduceren. Wanneer serieus wordt ingezet op het nastreven van klimaatdoelstellingen, zal naar verwachting het aandeel van hernieuwbare energie, bio-energie en handel in biomassa ook na 2020 sterk blijven toenemen.

Door deze ontwikkelingen groeit de behoefte naar betere inzichten in de kansen, risico's en onzekerheden omtrent de bijdrage van bio-energie aan de transitie naar een duurzaam energiesysteem. Beleidsmakers en andere belanghebbenden moeten rekening houden met verschillende beleidsthema's die relevant zijn voor bio-energie (klimaat, energie, landbouw, bosbeheer, economie en milieu) en de manier waarop bio-energie is verweven met verschillende sectoren van de economie (energie, industrie, transport, landbouw, bosbouw, etc.) op nationaal, regionaal en mondiaal niveau [9]. Door deze complexiteit wordt rol van bio-energie in de verduurzaming van het energiesysteem gekenmerkt door onzekerheden en belangrijke kennishiaten. Modellen uit verschillende wetenschappelijke disciplines worden gebruikt om inzicht te verschaffen in de huidige en toekomstige effecten van het gebruik van bio-energie. Zo worden economische algemene evenwichtsmodellen (CGE) en gedeeltelijke evenwichtsmodellen (PE) gebruikt om de mogelijke effecten van het gebruik van bio-energie in onderling verbonden sectoren van de economie in te schatten. Energiesysteemmodellen worden gebruikt om de rol van bio-energie te berekenen in een dynamisch energiesysteem (elektriciteit, warmte, transportbrandstoffen). De verschillende modellen zijn over het algemeen zeer gedetailleerd in een specifiek gebied, maar afhankelijk van kentallen voor variabelen die niet of alleen sterk geaggregeerd meegenomen kunnen worden in de modelberekeningen. Deze benadering is noodzakelijk voor efficiënte analyses en om te voorkomen dat modellen te complex worden en daardoor hun geloofwaardigheid verliezen. Dit betekent echter ook dat deze modellen tot nu toe geen consistent, compleet en tegelijk voldoende gedetailleerd inzicht kunnen verschaffen in de mogelijke effecten van het gebruik van bio-energie waarbij rekening wordt gehouden met de dynamische- en situatie-afhankelijke aspecten van bio-energie productiesystemen en de manier waarop bio-energie is verweven met verschillende economische sectoren.

Zeer relevant voor dit onderzoek zijn de grote variabiliteit van kosten en broeikasgasbalansen van bio-energie productiesystemen. Deze kunnen het resultaat zijn van methodologische keuzes, maar zijn ook afhankelijk van de geografische situatie en de prestaties van de productieketen met de productie van biomassa, het ontwerp van de logistieke keten, de conversie naar finale energiedragers en de fossiele referentiesystemen.

7.5 Doelstelling en onderzoeksvragen

Dit proefschrift is gericht op het overbruggen van een aantal belangrijke hiaten in kennis over de inzet van bio-energie op nationaal en Europees niveau met inbegrip van internationale biomassahandel. Het hoofddoel van dit proefschrift is de vertegenwoordiging van bio-energie productieketens in economische, milieu en energie evaluatie-modellen te verbeteren naast modelleringsbenaderingen die een verbeterd inzicht verschaffen in de potentiële directe en indirecte mitigatie en economische gevolgen van de vervanging van fossiele energiedragers met biomassa. Daartoe zijn in dit proefschrift de volgende onderzoeksvragen geformuleerd:

i. Wat zijn de huidige en toekomstige kosten en broeikasgasbalansen van binnenlandse en internationale bio-energie productieketens?
ii. Hoe kan systeemanalyse bijdragen aan de verbeterde beschrijving en analyse van binnenlandse en internationale bio-energie productieketens in (gevestigde) energie en economische evaluatiemodellen en tot welke mate kunnen de verschillende modelbenaderingen elkaar aanvullen?
iii. Wat zijn de vooruitzichten van bio-energie in het vervullen van de nationale en Europese doelstellingen voor hernieuwbare energie, wat is de rol van internationale biomassahandel, wat zijn belangrijke handelsregio's en soorten biomassa en welke factoren zijn van invloed op de handel en de inzet van biomassa?

Deze onderzoeksvragen worden behandeld in hoofdstuk 2 tot en met 6 zoals weergegeven in Tabel 7-1. Hoofdstuk 2 geeft inzicht in de mogelijke variaties in broeikasgas- en energiebalansen die het resultaat zijn van methodologische keuzes en aannames over de keten. In hoofdstuk 3 zijn scenario's met de substitutie van fossiele grondstoffen door biomassa voor Nederland doorgerekend met het CGE model LEITAP. In hoofdstuk 4 wordt het economisch potentieel van laagwaardige houtstromen en houtafval voor de productie van houtpellets geraamd. Hierbij wordt rekening gehouden met de geografische distributie van deze houtachtige stromen. In Hoofdstuk 5 is de mogelijke rol van bio-energie onderzocht op Europees niveau met het energiemodel Green-X. In hoofdstuk 5 en 6 wordt beschrijving gegeven van een geografisch expliciete manier om internationale logistieke biomassa aanvoerketens te berekenen.

Tabel 7-1 Matrix van de onderzoeksvragen behandeld per hoofdstuk

Hoofdstuk		**Onderzoeksvragen**		
		I	**II**	**III**
2	Broeikasgas-voetafdruk van verschillende biobrandstof productiesystemen	●		
3	Macro-economische effecten van de grootschalige inzet van biomassa voor energie en materialen op nationaal niveau – een gecombineerde aanpak voor Nederland	●	●	●
4	Het economisch potentieel van houtpellet productie uit alternatieve, laagwaardige houtstromen in het Zuidoosten van de VS	●		
5	Internationaal en binnenlands gebruik van vaste biomassa in verschillende scenario's voor stimulering van hernieuwbare energie in de Europese Unie	●	●	●
6	Aanvoerketens van lignocellulose biomassa met intermodaal transport en transport over zee	●	●	

7.6 Samenvatting van de resultaten

In **hoofdstuk 2** worden de broeikasgas- en energiebalansen van verschillende productiesystemen van biobrandstoffen met behulp van levenscyclusanalyse (LCA) geanalyseerd. De inbegrepen biobrandstoffen zijn ethanol van de eerste generatie (uit maïs, tarwe, suikerbiet, suikerriet en zoete sorghum), biodiesel van de eerste generatie (uit palmolie, koolzaadolie, sojaolie, jatropha-olie) en biobrandstoffen van de tweede generatie (uit lignocellulose biomassa) waaronder ethanol en Fischer-Tropsch diesel uit grassen (vingergras, miscanthus) en geteeld hout (eucalyptus). Van deze biobrandstofproductieketens zijn de resultaten op consistente basis met elkaar vergeleken waarbij belangrijke parameters zijn gevarieerd. Deze omvatten de allocatiemethode en de verschillende toepassingsmogelijkheden van bijproducten, N_2O-emissies door teelt, type conversiesystemen en emissies door directe veranderingen in landgebruik.

De broeikasbalansen van biobrandstoffen van de tweede generatie in hoofdstuk 2 variëren van -2 g. CO_2eq MJ^{-1} tot 25 g. CO_2eq MJ^{-1} waarbij rekening is gehouden met de variatie die ontstaat door het type productiesysteem en de LCA methode. Daarmee presteren biobrandstoffen van de tweede generatie over het algemeen beter dan biobrandstoffen van de eerste generatie onafhankelijk van de gekozen allocatiemethode voor bijproducten. Redenen hiervoor zijn de hogere opbrengsten van lignocellulose gewassen, het lagere gebruik van meststoffen in vergelijking met gewassen voor de productie van eerste generatie biobrandstoffen en de emissiereductie door cogeneratie van elektriciteit wanneer systeemuitbreiding wordt toegepast in plaats van allocatie.

Voor biobrandstoffen van de eerste generatie (zetmeel, suiker, oliehoudende zaden), is de variabiliteit door de gekozen methode (bijv. de allocatiemethode) en echte systeemverschillen (bijv. de locatie van productie), aanzienlijk groter. Wanneer emissies door veranderingen in landgebruik worden uitgesloten, dan zijn de locaties van productie en gerelateerde gewasopbrengsten, de toepassing van meststoffen en N_2O emissies uit landbouwbodems bepalende factoren van de broeikasgasprestaties van biobrandstoffen. Zo kunnen de broeikasgasemissies van koolzaaddiesel bijna twee keer zo hoog zijn (140 g. CO_2eq MJ^{-1}) dan fossiele diesel indien koolzaad wordt geteeld in Oost Europa, met de huidige gewasopbrengsten en zonder N_2O emissies van het referentieland. Indien koolzaad wordt geteeld in West Europa en de bijproducten (perskoek en glycerine) worden gebruikt voor de opwekking van energie, dan zijn voor dezelfde biobrandstof de broeikasgasemissies berekend op 17 g. CO_2eq MJ^{-1}.

Wanneer emissies door veranderingen in landgebruik worden meegenomen in de broeikasgasbalans, dan hangt het sterk af van het type land dat wordt omgezet of de koolstofvoorraden in de bodem of vegetatie groter of kleiner is na deze wijziging. Wanneer gewassen worden geteeld op gedegradeerde gronden, dan kan er potentieel meer koolstof in de bodem worden opgeslagen door de veranderingen in landgebruik wat resulteert in een positief effect op de broeikasgasbalans. Bijvoorbeeld, wanneer gedegradeerd land wordt gebruikt voor een oliepalmplantage in Zuidoost-Azië, dan kan dit resulteren in een netto verandering in de koolstofvoorraad van -90 Mg CO_2 ha^{-1} (netto opslag). Wanneer daarentegen gemanaged bos in dezelfde regio wordt omgezet naar een oliepalmplantage, dan zijn de emissies van deze veranderingen netto 433 Mg CO_2 ha^{-1} en tot 1580 Mg CO_2 ha^{-1} wanneer tropisch regenwoud op veenbodems wordt omgezet naar oliepalmplantages [14]. De effecten op de broeikasgasbalans hangen af van de verspreiding van deze missies. Wanneer deze over 20 jaar worden verspreid, dan zijn de totale emissies van biodiesel uit palmolie 25 g. CO_2eq MJ^{-1} (gedegradeerd land) tot 541 g CO_2eq MJ^{-1} (tropisch regenwoud op veenbodems).

De gekozen LCA methode om broeikasgasemissies te berekenen (GHG-LCA) in richtlijn hernieuwbare energie (EU RED) [12] is grotendeels in overeenstemming met de 'attributionele' LCA methode. Allocatie op basis van energie-inhoud wordt gebruikt voor bijproducten, maar voor de co-generatie van elektriciteit wordt een beperkte vorm van systeemgrensuitbreiding gebruikt ('consequentiële' LCA methode) [13]. Bijvoorbeeld, de productie van graanethanol met stro als procesbrandstof in een WKK-installatie met extra elektriciteit dat geleverd wordt aan het net, krijgt volgens de EU RED-methode emissiereducties toegekend op basis van elektriciteit opgewekt in een elektriciteitscentrale met stro als brandstof. Het verschil tussen allocatie op basis van energie-inhoud (totale broeikasgasemissies: 23 g. CO_2eq. MJ^{-1}) en de EU RED methode (totale broeikasgasemissies: 27 g. CO_2eq. MJ^{-1}) blijven klein. Het verschil wordt groter wanneer extra emissiereducties worden toegekend op basis van de gemiddelde elektriciteitsmix (totale broeikasgasemissies: 15 g. CO_2eq. MJ^{-1}). Soortgelijke variabiliteit is ook zichtbaar in de resultaten van biobrandstoffen van de tweede generatie.

In **hoofdstuk 3** worden de mogelijke economische gevolgen van de grootschalige vervanging van fossiele grondstoffen door biomassa in Nederland geanalyseerd. Het gaat hierbij om de toegevoegde waarde in de betreffende sectoren, aandelen in werkgelegenheid en de handelsbalans naast de vermeden fossiele emissies in verschillende scenario's. De scenario's verschillen van elkaar in de snelheid van technologische ontwikkeling en de mate van openheid in wereldhandel. Voor het ontwikkelen van strategische routekaarten en beleid gericht op het faciliteren van een economisch en ecologisch efficiënte inzet van bio-energie uit binnenlandse en geïmporteerde bronnen is inzicht nodig in de relevante potentiële voordelen, risico's en onzekerheden. In dit hoofdstuk is het macro-economische CGE model LEITAP gebruikt in combinatie met een spreadsheet tool voor het analyseren van de directe en indirecte economische effecten en mitigatie van emissies en fossiele brandstoffen van de toekomstige inzet van biomassa in Nederland. De spreadsheet tool is gebruikt voor een verbeterde detailweergave van technologieën voor warmte, elektriciteit, transportbrandstoffen en chemicaliën uit biomassa en voor het berekenen van fysieke stromen. De scenario's laten zien dat, wanneer ambitieuze doelstellingen worden nagestreefd voor een bio-based economie, dit positieve effecten kan hebben op de toegevoegde waarde in de sectoren landbouw, energie en chemie en op de handelsbalans van Nederland, hoofdzakelijk door de vermeden import van ruwe olie. Hiervoor moet echter wel aan een aantal belangrijke voorwaarden worden voldaan, waaronder een versnelling van technologische ontwikkeling en grootschalige beschikbaarheid van duurzaam geproduceerde biomassa voor export vanuit EU en niet-EU landen naar Nederland.

Volgens de scenarioprojecties met het LEITAP model, zal in 2030 de meeste biomassa naar Nederland worden geïmporteerd vanuit Zuid-Amerika, gevolgd door Noord-Amerika. Op dit moment is Noord-Amerika de grootste exporteur van vaste biomassa (houtpellets). Met name in het zuidoosten van de Verenigde Staten (VS) is de productie van houtpellets in de afgelopen jaren door de export naar Europa sterk gestegen. Door de toenemende vraag naar houtpellets en de huidige krimp van andere markten, wordt steeds meer hout van pulp kwaliteit gebruikt voor de productie van houtpellets. Het gebruik van deze bosbouwproducten voor energie staat ter discussie door de mogelijke negatieve ecologische effecten en de tijdelijke onbalans tussen houtkap en aangroei. In de betreffende regio's zijn mogelijk ook grote hoeveelheden houtresiduen en afvalhout beschikbaar.

In **hoofdstuk 4** wordt het economisch potentieel van alternatieve, laagwaardige houtstromen geraamd die beschikbaar zijn voor de productie van houtpellets in het Zuidoosten van de VS (Florida, Georgia, North Carolina en South Carolina). Voor drie geschikte houtstromen is een potentieelstudie uitgevoerd. Dit zijn primaire bosbouwresiduen van onverkoopbaar hout uit dunningen en houtkap van land dat geschikt wordt gemaakt voor andere doeleinden, secondaire bosbouwresiduen uit de houtverwerkingsindustrie (productie van palen) en tertiaire houtresiduen van afgedankte transport pallets. Deze houtstromen worden op dit moment niet gebruikt of alleen gebruikt voor laagwaardige, inefficiënte toepassingen zoals lage temperatuur warmteproductie. Het totale potentieel van deze drie houtstromen is geraamd op 1,9 Tg jr^{-1} (droog) beschikbaar aan de bron (exclusief transport) voor 22 US$ Mg^{-1} (droog) en in totaal 5,1 Tg jr^{-1} (droog), wanneer ook houtresiduen beschikbaar voor 33 US$ Mg^{-1} (droog) worden ingezet. Hier zouden theoretisch gezien jaarlijks 4,1 Tg houtpellets uit kunnen worden geproduceerd. Echter, door de geografische distributie van deze houtstromen kunnen de kosten voor transport snel oplopen wanneer de vraag toeneemt. Het is daarom onwaarschijnlijk dat het gehele potentieel benut kan worden voor de productie van pellets tegen concurrerende productiekosten van conventionele houtpellets. Op locaties van bestaande houtpelletfabrieken in het zuidoosten van de VS varieert de optimale schaalgrootte van houtpelletproductie van 55 Gg jr^{-1} tot 315 Gg jr^{-1} afhankelijk van de gekozen locatie en aangenomen beschikbaarheid van houtstromen. De productiekosten van pellets op deze locaties worden geraamd van 82 US$ Mg^{-1} tot 100 US$ Mg^{-1}.

In **hoofdstuk 5** wordt de methodiek beschreven van een verbeterde weergave van logistiek en handel in biomassa in het Europese hernieuwbare energiemodel Green-X. Hiervoor is gebruik gemaakt van het op GIS (Geografische Informatie Systemen) gebaseerde biomassa transport model (BIT-UU). Met dit model zijn de kosten en gerelateerde broeikasgasemissies van mogelijke transportroutes van biomassa in de EU berekend waarbij gebruik kan worden gemaakt van intermodale transportketens (weg, spoor, binnenvaart en zee). De resultaten hiervan zijn gebruikt als invoer voor de module van biomassahandel in Green-X. De uitbreiding van Green-X met EU en niet-EU import van biomassa maakt scenarioprojecties en evaluaties mogelijk van de toekomstige inzet van hernieuwbare energie, waarbij de rol van biomassa en biomassahandel expliciet kan worden geanalyseerd. Daarnaast geeft het model inzicht in de concurrentie van bio-energie uit binnenlandse bronnen met import van biomassa en alternatieve vormen van hernieuwbare energie (bijvoorbeeld wind en zon). Het ontwikkelde modelraamwerk is in dit hoofdstuk gedemonstreerd aan de hand van scenarioprojecties tot 2020. Deze projecties laten zien dat tot 2020 de vraag naar bio-energie voor het grootste deel uit biomassa van binnenlandse bronnen kan blijven voorzien (91 % tot 93 % in 2020). Echter, door de toenemende vraag naar biomassa in de toekomst, wordt ook de rol van biomassahandel steeds belangrijker. Wanneer er niets verandert aan het huidige hernieuwbare energiebeleid en geen duurzaamheidscriteria worden geïmplementeerd, dan zullen de doelstellingen van duurzame energie in de EU niet worden gehaald. In dit 'Business-as-Usual' scenario zal de handel in biomassa groeien tot 451 PJ in 2020 volgens de modelprojecties. In een scenario waarin het beleid wordt aangepast om de hernieuwbare energie doelstelling the realiseren in 2020, maar geen duurzaamheidscriteria worden geïmplementeerd, zal de handel in biomassa toenemen tot 506 PJ in 2020. In een scenario met dezelfde doelstelling, maar met duurzaamheidscriteria wordt de totale handel in vaste biomassa geraamd op 440 PJ in 2020.

De resultaten van hoofdstuk 5 laten zien dat import van buiten de EU groter kan worden dan de handel van biomassa tussen lidstaten in de EU. Dit geeft het belang van een verbeterde modellering van biomassa aanvoerketens van buiten de EU aan.

In **hoofdstuk 6** wordt een methode beschreven om internationale aanvoerketens van lignocellulose biomassa te evalueren op het detailniveau van individuele logistieke processen. Hiervoor is het bestaande Biomassa Logistiek Model (BLM) gekoppeld aan het op GIS gebaseerde BIT-UU model dat voor deze studie is uitgebreid met netwerkdata voor intercontinentaal transport. Ketens van stro en geteeld gras geproduceerd in het middenwesten en houtachtige biomassa geproduceerd in het zuidoosten van de VS die getransporteerd worden naar Europa voor conversie naar Fischer-Tropsch (FT) diesel zijn geanalyseerd met het ontwikkelde modelraamwerk. Deze ketens laten zien hoe intermodaal transport en in het bijzonder transport over zee integreert met aanvoerketens van vaste biomassa. Voor de berekende ketens in dit hoofdstuk kan biomassa uit de VS worden aangeboden in een Europese haven voor 99 € Mg^{-1} (droog) tot 117 € Mg^{-1} (droog) en worden omgezet in FT-diesel voor 19 € GJ^{-1} tot 24 € GJ^{-1} afhankelijk van de gekozen locatie, de tussenproducten (chips of pellets) en de schaal van de FT-diesel fabriek.

7.7 Antwoorden op de onderzoeksvragen

Vraag I. Wat zijn de huidige en toekomstige kosten en broeikasgasbalansen van binnenlandse en internationale bio-energie productieketens?

De gebruikte aannames en de methodes voor het berekenen van broeikasgasemissies en kosten van bio-energie productiesystemen kunnen resulteren in uiteenlopende resultaten. Tabel 7-2 vat de belangrijke factoren samen en geeft de aspecten die zijn behandeld in de afzonderlijke hoofdstukken van dit proefschrift. In dit proefschrift ligt de focus hoofdzakelijk op het verbeteren van inzichten in bio-energie productieketens en logistiek. De modelramingen met LEITAP (hoofdstuk 3) maken gebruik van een gevestigd CGE modelraamwerk voor het berekenen van biomassaprijzen. In hoofdstuk 3 is beschreven hoe dit model is gecombineerd met bottom-up spreadsheet berekeningen van productiekosten en broeikasgasbalansen. Het Green-X model, gebruikt in hoofdstuk 5, maakt ook gebruik van een bestaande database van de economisch potentiëlen van biomassa in de EU.

Tabel 7-2 Aspecten van kosten- en broeikasgasbalansen van bio-energieproductieketens behandeld in de hoofdstukken van dit proefschrift met gebruik van verschillende benaderingen en de belangrijke factoren voor kosten [2] en broeikasgasemissies.

Hoofd-stuk	Stap in de bio-energie productieketen					
	Teelt/productie		Logistiek		Omzetting	
	Kosten/prijzen	Broeikasgasbalans	Kosten	Broeikasgasbalans	Kosten	Broeikasgasbalans
2		√		√		√
3	○[a] ●[b]	√	√	√	√	√
4	√		√			
5	●	√	√	√	●	●
6	○	√	√	√	●	●
Belang-rijke factoren	· Gewasproductie · Land · Arbeid · Gewasopbrengst · Materiaalprijzen · Cultuurmethode · Productie van agro-chemicaliën, kunstmest. · Emissies door toepassing van meststoffen (in het bijzonder N_2O). · Emissies door veranderingen in landgebruik.		· Ruimtelijke distributie van biomassa · Verzamelen, verwerking, opslag · Beschikbaarheid van (bestaande) infrastructuur · Gebruikte transportwijzen en afstand · Locatie, schaalgrootte en type voorbehandeling		· De geproduceerde energiedrager · Energie-efficiëntie · Het verbruik van materialen (bijv. chemicaliën) · Schaalgrootte · Financieringsmechanismen · Productiviteitsfactor · Productie, waarde en bestemde markt van nevenproducten · Kapitaal-en operationele uitgaven	
Legenda: √ Berekend in dit proefschrift m.b.v. systeemanalyse. ● Zoals beschikbaar in de gebruikte modellen. ○ Uit literatuur.						

a) De kosten van bio-energiegewassen en -residuen in de bottom-up spreadsheet tool zijn gebaseerd op beschikbare literatuur.
b) Prijzen van biomassa zijn met het LEITAP model berekend met behulp van aanbodcurven van land op basis van beschikbare resultaten van het bio-fysische model IMAGE. Deze zijn niet aangepast voor het onderzoek in dit proefschrift.

Broeikasgasbalans

De analyse van scenario's met grootschalige vervanging van fossiele grondstoffen door biomassa in de context van een bio-based economy in hoofdstuk 3, laten zien dat in 2030 grote reducties in de uitstoot van broeikasgasemissies mogelijk zijn (tot 54 Tg CO_2eq jr^{-1}) door het vermeden gebruik van fossiele brandstoffen (tot 790 PJ jr^{-1} vermeden primaire energie). Daarnaast heeft de vervanging van fossiele brandstoffen door biomassa ook een netto positief effect op de handelsbalans van Nederland en verbetert de economische activiteiten binnen de sectoren landbouw, chemie en energie. De omvang van deze positieve effecten zijn echter sterk afhankelijk van de snelheid van technologische ontwikkeling en de beschikbaarheid internationale, duurzame bronnen van biomassa en de prijs ten opzichte van fossiel brandstoffen (vooral ruwe olie). Een sleutelrol in het bereiken van deze doelstellingen is de commercialisatie van bio-energieconversiesystemen op basis van lignocellulose biomassa zoals aangenomen in hoofdstuk 3. Deze systemen kunnen gebruik maken van gewassen met hoge opbrengsten, residuen (bosbouw en landbouw), en organisch afval voor de productie van synthese gas (chemicaliën), elektriciteit en transportbrandstoffen (ethanol en FT-diesel).

De opbrengsten van biobrandstofproductiesystemen varieert aanzienlijk tussen de verschillende soorten gewassen. De hoogste opbrengst van de verschillende type biobrandstoffen in hoofdstuk 2 is gevonden voor ethanol geproduceerd uit eucalyptus in

Brazilië (246 GJ ha^{-1} jr^{-1}) op basis van 22 Mg ha^{-1} jr^{-1} (droog) eucalyptushout. De laagste opbrengst is gevonden voor biodiesel uit koolzaad wanneer dit nu zou worden geteeld in Oost-Europa (9,4 GJ ha^{-1} jr^{-1}). In West-Europa is de opbrengst van biodiesel met de huidige productiesystemen aanzienlijk hoger geraamd (40,6 GJ ha^{-1} jr^{-1}).; Dit illustreert het verbeterpotentieel voor Oost-Europa. Wanneer lignocellulose gewassen worden geteeld (miscanthus, vingergras en eucalyptus), dan zijn de gewasopbrengsten hoger dan olie-, zetmeel- en suikergewassen. Het grootste verbeterpotentieel kan daarom worden bereikt met verbeterde landbouwmanagementsystemen en de teelt van lignocellulose gewassen.

Het dient echter te worden opgemerkt dat de broeikasgasprestaties van bio-energieproductiesystemen aanzienlijk varieert afhankelijk van de LCA methode, het gekozen productiesysteem en het type referentieland waarop wordt aangenomen dat biomassa wordt gecultiveerd en de toepassing van bijproducten.

Een belangrijke beperking van de combineerde aanpak van het top-down LEITAP model met de spreadsheet tool in hoofdstuk 3, is dat ondanks dat systeemvergroting is toegepast voor het toerekenen van bijproducten, de aangenomen toepassingen gebaseerd zijn op vooraf gedefinieerde aannames en daarmee statisch in de scenario's. Idealiter zou de broeikasgasbalansen endogeen in het LEITAP berekend moeten worden waardoor marginale systeemveranderingen en markten voor bijproducten consistent kunnen worden meegenomen in de berekeningen. Dit geldt ook voor de emissies van veranderingen in landgebruik, de selectie van land en de variabiliteit van emissies die het resultaat zijn van de locatie specifieke milieuaspecten, het type gewas en het landbouwmanagementsysteem. Ook wanneer dit niet endogeen kan worden meegenomen, blijft systeemvergroting de beste methode om de effecten van het gebruik van bijproducten inzichtelijk te maken. Dit is echter niet altijd haalbaar. Bijvoorbeeld, wanneer het referentiesysteem niet kan worden geïdentificeerd of bij referentiesystemen met meerdere productstromen.

Kosten van bio-energie

De bottom-up kostenberekeningen van bio-energie en bio-based chemicaliën in hoofdstuk 3 laten zien dat bij een hoge prijs voor ruwe olie in de toekomst (112 US$ per vat), de productiekosten van bio-energie en bio-based chemicaliën lager kunnen worden dan die van conventionele (fossiele) productiesystemen. Hierdoor zijn de mitigatiekosten in 2030 negatief in alle scenario's tot -51 € Mg^{-1} CO_2 in het GlobHighTech scenario. De top-down projecties met het LEITAP model laten zien dat, met dezelfde prijs voor ruwe olie in 2030, er nog steeds een lage subsidie nodig is om het verschil tussen biobrandstoffen en de fossiele referentie te overbruggen (0,015 € L^{-1}). Dit betekent dat oftewel het LEITAP model conservatief is voor mogelijke kostenbesparingen in de toekomst en de gerelateerde prijzen voor de productie van biobrandstoffen of dat de bottom-up productiekosten in hoofdstuk 3 te optimistisch zijn.

Een van de belangrijkste kostenfactoren van de productieketens van vaste biomassa met transport over grote afstanden zijn de kosten voor logistiek. Zo zijn er bijvoorbeeld in het zuidoosten van de VS laagwaardige houtstromen beschikbaar voor 17 € Mg^{-1} (droog)[17]. Wanneer de kosten voor transport en productie van houtpellets worden inbegrepen, dan kunnen van deze houtstromen pellets worden geproduceerd voor minimaal 69 € Mg^{-1} (droog), verondersteld dat deze op de optimale locatie en schaalgrootte (laagste kosten) van bestaande locaties van houtpelletfabrieken in de staat Georgia worden geproduceerd. De logistieke kosten voor het vervoer naar een exporthaven zijn in hoofdstuk 4 niet inbegrepen. Wanneer vaste biomassa wordt geëxporteerd naar een bioraffinaderij in Nederland (zie hoofdstuk 6), dan zijn de totale leveringskosten voor biomassa geraamd op 99 tot 104 € Mg^{-1} (droog) (5,7 tot 6,4 € GJ^{-1})[18] voor pellets geproduceerd uit stro en vingergras in het middenwesten van de VS en 103 tot 117 € Mg^{-1} (droog) (5,5 tot 5,7 € GJ^{-1}) voor houtpellets uit het zuidoosten van de VS. De totale leveringskosten stijgen tot 105 tot 117 € Mg^{-1} (droog) (6,1 tot 6,8 € GJ^{-1}) wanneer houtchips niet worden gepelletiseerd voordat ze naar Nederland wordt geëxporteerd. In deze aanbodketens zijn de kosten voor alle logistieke processen die noodzakelijk zijn om biomassa vanaf het veld of vanuit het bos in de VS te leveren tot in een raffinaderij in Nederland inbegrepen. Volgens deze resultaten kan met de CIF-ARA prijzen (levering, inclusief vervoer en verzekering in de regio Antwerpen, Rotterdam, Amsterdam) van houtpellets in 2012, een bruto winstmarge van 20 % tot 26 % worden behaald. Hierbij is geen rekening gehouden met de mogelijke variatie en onzekerheid en van alternatieve aanvoerketens. Deze kunnen door middel van gevoeligheids- en onzekerheidsanalyse met behulp van de gelinkte modellen (BLM en BIT-UU) geanalyseerd worden. Voor de aanvoerketens die zijn berekend in hoofdstuk 6 zijn voorbewerking (waaronder pelletiseren) en transport over lange afstand de belangrijkste kostenposten over de gehele aanvoerketen. Voor ketens met transport van houtchips, is het aandeel van transport 50 % van de totale aanvoerkosten van vaste biomassa. Voor aanvoerketens van pellets, is het aandeel van voorbewerking geraamd op 38 % en het aandeel van transport op 34 % van de totale leveringskosten.

Voorbewerking van houtachtige biomassa in houtpellets voor transport over lange afstand kan de totale leveringskosten met 11 % verminderen ten opzichte van transport van houtchips doordat pellets een hogere bulk dichtheid hebben. Daarnaast is er in de bioraffinaderij minder voorbewerking nodig voor houtpellets dan voor houtchips (drogen, vermalen). Verdere kostreducties zijn mogelijk door gebruik te maken van schaalvoordelen. Zo kan het gebruik van grotere oceaanschepen (Panamax in plaats van Supramax) de totale leveringskosten met 2 % tot 4 % reduceren voor de ketens in hoofdstuk 6. Echter, niet alle zeehavens zijn geschikt voor deze schepen door beperkingen in diepgang en lengte en de benodigde havenfaciliteiten. De ketens met pellets van stro en vingergras uit het middenwesten van de VS maken gebruik van binnenvaart voor transport naar een zeehaven in de staat Alabama en zijn daarmee al deels

[17] Wisselkoers: 1,0 € = 1,32 US$

[18] Netto calorische waarde van pellets uit gras en stro: 15-16 MJ kg^{-1} (5 % - 10 % vocht). Houtpellets en houtchips: 17 MJ kg^{-1} (vochtgehalte: 9 % - 10 %).

geoptimaliseerd. Op dit moment vindt er nog geen export van biomassa voor bio-energiedoeleinden plaats vanuit het middenwesten van de VS. Deze aanvoerketens kunnen daarom alleen worden opgezet wanneer er grootschalige investeringen worden gedaan in de benodigde logistieke faciliteiten. Soortgelijke logistieke aanvoerketens bestaan echter wel voor de export van voedergranen. Voor verdere reducties in de logistieke kosten, moeten meer geavanceerde ketens worden opgezet met goedkope aanvoer van biomassa, optimale locaties en schaalgroottes en technieken van voorbewerking (bijvoorbeeld torrefactie of pyrolyse) en 'hub and spokes' concepten.

De aanvoer van biomassa uit bronnen binnen de EU is voor de meeste soorten biomassa en de meeste lidstaten goedkoper dan import van buiten de EU. Zo zijn houtpellets van buiten de EU beschikbaar voor 6,3 € GJ^{-1} tot 6,5 € GJ^{-1} in hoofdstuk 5 en zijn bijvoorbeeld bosbouwresiduen (houtchips) beschikbaar voor gemiddeld 5,5 € GJ^{-1} tot 6,0 € GJ^{-1} afhankelijk van de regio's van vraag en aanbod binnen de EU. Pelletiseren is voor Europese biomassa niet kosteneffectief, maar het kan noodzakelijk zijn om opslag en hanteerbaarheid te vergroten, bijvoorbeeld voor houtzaagsel uit zagerijen.

Vraag II. Hoe kan systeemanalyse bijdragen aan de verbeterde beschrijving en analyse van binnenlandse en internationale bio-energie productieketens in (gevestigde) energie en economische evaluatiemodellen en tot welke mate kunnen de verschillende modelbenaderingen elkaar aanvullen?

Biomassa is op een complexe manier ingebed in een onderling verweven en dynamische omgeving. Voor een voldoende uitgebreid en gedetailleerd inzicht in de mogelijke effecten van bio-energie, is samenwerking nodig tussen bottom-up en top-down modelbenaderingen [15, 16]. Er zijn verschillende manieren van samenwerking tussen modellen [10]: harmonisatie en afstemming van invoergegevens en scenario's (bijvoorbeeld in Edwards et al. [17]), het onderling vergelijken van resultaten en de integratie van modellen. De meest geschikte manier van samenwerking tussen modellen hangt af van het doel, de reikwijdte en de tekortkomingen van de individuele modellen. In dit proefschrift zijn verschillende benaderingen van modelsamenwerking onderzocht voor een verbeterd inzicht in bio-energieproductiesystemen. Deze zijn samengevat in Tabel 7-3. In de volgende secties worden de gemaakte verbeteringen en resterende tekortkomingen van de drie modelkoppelingen in dit proefschrift verder toegelicht.

Tabel 7-3 Overzicht van de verschillende manieren van samenwerking tussen modellen in dit proefschrift

Hoofdstuk[a]	3	5	6
Naam model	LEITAP	Green-X	BLM
Instituut	LEI-WUR	TU Wien - EEG	Idaho National Laboratory
Type model	Algemeen evenwichtsmodel	(Hernieuwbaar) energiesysteem partieel evenwichtsmodel	Bottom-up, logistiek procesmodel
Schaal	Wereld	Europa	Regionaal (VS)
Tijdshorizon	2006 - 2030	2006 - 2030	2015
Model aanpassingen	Scheiding van chemische sectoren, impliciete representatie van bio-energie	Biomassahandel module	GIS module
Bottom-up samenwerking			
Naam model	Spreadsheet	BIT-UU	BIT-UU
Type	Statisch, BU karakterisatie van technologieën	GIS - Excel	GIS
Type samenwerking	Kalibratie en harmonisatie van invoergegevens en resultaten	Invoergegevens voor BLM	Integratie (hard-link)
Hoofddoel	Het verbeteren van details per sector (elektriciteit, transport, chemicaliën) en technologie. Het berekenen van fysieke stromen.	Land-tot-land specifieke details van biomassa transportkosten en broeikasgas emissies	Analyse van lange afstand aanvoerketens met ruimtelijke kenmerken van intercontinentaal en intermodaal transport.
Belangrijkste beperkingen	Sector- en technologiedetails zijn alleen toegevoegd voor Nederland. Geen details voor (hernieuwbare) warmteproductie.	Gedetailleerde logistieke ketens zijn alleen toegevoegd voor Europa. Geaggregeerde representatie van niet-Europese ketens. Transport van vloeibare biobrandstoffen niet gemodelleerd.	Beperkt tot de V.S. (aanbod) en Europa (vraag). Transport van vloeibare biobrandstoffen niet gemodelleerd.

a) Hoofdstuk 2 en hoofdstuk 4 beschrijven bottom-up benaderingen van respectievelijk de LCA van biobrandstoffen en potentieelramingen van biomassa, maar zijn niet gelinkt aan andere modellen in dit proefschrift.

LEITAP en Bottom-up spreadsheet rekentool

Voor het berekenen van marginale veranderingen in productie en consumptie die kunnen ontstaan door de vervanging van fossiele brandstoffen door biomassa, worden economische modellen zoals LEITAP gebruikt. Echter, een van de belangrijkste concessies van deze top-down modellen is het gebrek aan details binnen sectoren, technologieën en technologisch leren en fysieke stromen van materialen en energie [10, 18]. Verschillende studies hebben een link gemaakt tussen top-down modellen en bottom-up energiesysteemmodellen om dit probleem te adresseren [19, 20]. Daarnaast zijn CGE modellen in verscheidene studies uitgebreid met bio-energie. De focus van deze studies ligt echter hoofdzakelijk op de transportsector (biobrandstoffen), om de mogelijke consequenties van biobrandstofproductie op landgebruiksveranderingen, voedselmarkten en handel te onderzoeken [15, 21]. Voor de overige sectoren waarin biomassa kan worden gebruikt, blijft het detailniveau laag [10].

Verbeteringen: in dit proefschrift is het CGE model LEITAP gecombineerd met een spreadsheet rekentool. Deze gecombineerde aanpak maakt het mogelijk om ramingen te maken van de economische en milieueffecten van de grootschalige vervanging van fossiele brandstoffen door biomassa in de sectoren elektriciteit, transport en chemie op nationaal niveau voor Nederland. De scenario's laten zien dat het nastreven van een bio-based economie, de afhankelijkheid van fossiele energie en de uitstoot van broeikasgassen flink kan verlagen in de toekomst. Daarnaast kunnen de verschuivingen tussen sectoren van de economie ook een positief effect hebben op de handelsbalans van Nederland en de toegevoegde waarde in de bio-based sectoren.

Resterende uitdagingen: de gecombineerde aanpak van het LEITAP model en de bottom-up spreadsheet rekentool heeft inzicht verschaft in de beperkte mate van de technologische details die kunnen worden toegevoegd aan het LEITAP model zonder aanpassing van de bestaande modelstructuur. Een van de bepalende, maar onzekere factoren voor het potentieel van bio-energie is de snelheid van technologische ontwikkeling en de diffusie van geavanceerde conversiesystemen van bio-energie. De HighTech scenario's in hoofdstuk 3 laten zien dat, wanneer de technologie zich voldoende snel ontwikkelt, de productiekosten van bio-energie en chemicaliën uit biomassa sterk kunnen reduceren door technologisch leren en daarmee concurrerend kunnen worden met fossiele productiesystemen. Het gaat hierbij om de teelt van gewassen met hoge opbrengsten, geavanceerde conversiesystemen zoals thermochemische en biochemische conversie van lignocellulose biomassa naar transportbrandstoffen en geavanceerde bioraffinage concepten met mogelijk cascadering [2]. Deze systemen zijn echter nog niet commercieel beschikbaar en de kostenramingen zijn onzeker, bijvoorbeeld van FT-diesel productie [22]. De diffusiesnelheid van geavanceerde productiesystemen in LEITAP is belangrijk, maar is in het gebruikte model nog niet voldoende onderbouwd. Verdere samenwerking tussen bottom-up en top-down benaderingen is daarom noodzakelijk om de diffusiesnelheid en leersnelheid van technologieën en onderliggende factoren inzichtelijk te maken.

De scenario resultaten van het LEITAP model voor het aanbod, de vraag en handel in bio-energie konden met het gebruikte model niet worden berekend in absolute, fysieke hoeveelheden van materialen (bijvoorbeeld Mg hout) door de hoge aggregatie van de resultaten van LEITAP (in geldstromen en relatieve veranderingen). Deze fysieke hoeveelheden zijn belangrijk voor het vergelijken van de top-down resultaten met bottom-up productiekosten, feitelijke grondstofprijzen, oogstopbrengsten en de efficiëntie van bio-energie productiesystemen.

Green-X en Biomassa Intermodaal Transport Model (BIT-UU)

Green-X is een dynamische tool met een gedetailleerde weergave van de sectoren elektriciteit, warmte en transport waar scenario's mee kunnen worden doorgerekend over de inzet van hernieuwbare energie in de EU met het huidige en toekomstige hernieuwbare energiebeleid. Het model berekent de inzet van bio-energie per land en per technologie, geoptimaliseerd voor de laagste kosten en geeft de bijbehorende investeringen en kosten en vermeden fossiele brandstoffen en broeikasgasemissies ten opzichte van de referentiescenario's per jaar tot 2030. In deze scenario's wordt het belang van biomassahandel steeds groter, met name voor scenarioprojecties na 2020 [23].

In dit proefschrift is het op GIS gebaseerde biomassa transport model BIT-UU model ontwikkeld. Dit model is gebruikt om mogelijke transportroutes van biomassa te identificeren en de gerelateerde kosten en broeikasgasemissies te berekenen. Hierbij kan gebruik worden gemaakt van intermodaal transport (weg, spoor, binnenvaart en zee) waarbij de routes zijn geoptimaliseerd voor de laagste transportkosten inclusief de kosten voor overslag tussen de verschillende transportmogelijkheden. De resultaten zijn gebruikt voor de module voor biomassahandel in Green-X. Met deze module worden de potentiëlen en kosten van vaste biomassa uit de bestaande Green-X database gecombineerd met de kosten en broeikasgasemissies voor alle mogelijke transportketens van biomassa tussen EU lidstaten voor de verschillende projectiejaren. Met het Green-X model worden de kosten en baten van elke mogelijke combinatie van biomassa grondstof, transport en conversie berekend in het veronderstelde beleidsraamwerk.

Verbeteringen: de combinatie van Green-X met het BIT-UU model maakt twee belangrijke verbeteringen mogelijk.

- Het maakt gedetailleerde ramingen mogelijk van kosten en broeikasgasemissies van optimale transportroutes (laagste kosten) waarbij rekening wordt gehouden met de ruimtelijke aspecten van bestaande transportnetwerken die beschikbaar zijn in Europa. Hiervoor worden consistente aannames gebruikt voor de berekeningen van transportkosten met de scenario's in Green-X (prijzen van elektriciteit, diesel etc.). Daarnaast biedt de tool flexibiliteit voor het invoeren of wijzigen van vraag- en aanbodlocaties en gerelateerde kosten en emissies. In Green-X wordt de optimale distributie van biomassa tussen lidstaten en sectoren op basis van deze gegevens endogeen berekend.
- Met de handelsmodule voor biomassa in Green-X kunnen duurzaamheidscriteria worden gespecificeerd. Voor elk type biomassa en soort eindconversie (bijvoorbeeld kleinschalige verwarming versus elektriciteitsopwekking) kunnen minimale broeikasgasemissie besparingseisen en additionele kosten voor certificering worden ingevoerd.

Resterende uitdagingen: met het Green-X model kunnen mogelijke vraag- en aanbodregio's van biomassa worden geïdentificeerd. Echter, omdat het model geen module bevat voor landgebruik en bosbouw, is het niet mogelijk om de effecten te berekenen van beleid dat het aanbod van biomassa beïnvloedt. Daarnaast is de benodigde data en informatie om de effecten van duurzame biomassaproductie te kwantificeren nog niet voldoende beschikbaar en onzeker. Om deze redenen is er meer onderzoek nodig om dit te verbeteren.

Biomassa Logistiek model (BLM) en BIT-UU

Met de groei in vraag naar biomassa voor grootschalige, centrale industriële conversie zoals elektriciteitsopwekking, WKK, stadsverwarming en bio-chemicaliën, is ook de complexiteit van de logistieke aanvoerketens groter geworden met lange afstand en internationaal transport. Voor het berekenen van complexe logistieke ketens is een model vereist dat alle logistieke processen omvat met inbegrip van de oogst, verzameling, verwerking, opslag, voorbehandeling en transport zoals mogelijk is met het Biomassa Logistiek Model (BLM) ontwikkeld door Idaho National Laboratory (INL) [24-27]. Dit model kan voor verschillende biomassagrondstoffen, vanaf het veld tot in de bioraffinaderij, de logistieke keten simuleren. Transport wordt echter relatief eenvoudig berekend in het model, gebaseerd op vooraf gedefinieerde aannames. In dit proefschrift is het BLM gekoppeld aan het geografisch expliciete intermodale transport model BIT-UU en is het

BIT-UU model uitgebreid met intercontinentaal zee transport en transportnetwerken (weg, spoor, binnenvaart en zee) in Noord-Amerika.

Verbeteringen: de combinatie van gedetailleerde logistieke processen in BLM en de geografisch expliciete optimalisatie van intermodaal transport met het BIT-UU model, vormen samen een flexibel modelraamwerk dat gebruikt kan worden voor de analyse van biomassa aanvoerketens met transport over lange afstand. Belangrijke verbeteringen van deze studie zijn het toevoegen van ruimtelijke functies in BLM en de mogelijkheid om optimale (laagste kosten) intermodale transportroutes te berekenen met inbegrip van verschillende transportnetwerken en gerelateerde data (kosten, afstanden, restricties) en mogelijkheden voor overslag (bijvoorbeeld tussen weg en spoor). Dergelijke geïntegreerde analyse tools zijn belangrijk voor het evalueren van verschillende biomassa aanvoerketens met inbegrip van de onzekerheden en mogelijke variaties in aanbodregio's van biomassa, soorten biomassa en eigenschappen, type management en potentiele veranderingen in beleid en technologie. De tool is flexibel in het aanpassen van de eigenschappen van biomassagrondstoffen, invoergegevens (fossiele brandstofprijzen, loonkosten, vrachttarieven) alsmede het toevoegen, weglaten of veranderen van de locaties van voorbewerking (bijvoorbeeld drogen, vermalen en pelletiseren).

Resterende uitdagingen:

- Op dit moment wordt in GIS alleen het transport tussen export terminals en bioraffinaderijen met het BIT-UU model berekend. Verdere integratie tussen het BLM en BIT-UU model zou meerdere analyses mogelijk maken, waaronder de optimalisatie van biomassa aanbodregio's, locaties van voorbewerking (depots), terminals en concurrerende toepassingen. Verdere integratie tussen de modellen is ook noodzakelijk voor het mogelijk maken van uitgebreide gevoeligheidsanalyses. Een voorbeeld hiervan zijn Monte-Carlosimulaties om het effect van externe variabelen, zoals seizoenvariaties, inzichtelijk te maken.
- De uitbreiding van het model met vloeibare biomassa (tussen-)producten zoals pyrolyse-olie en logistiek van vloeibare biobrandstoffen en uitbreiding van het model naar andere regio's (bijvoorbeeld Brazilië, Canada, Rusland) is belangrijk voor een volledige analyse van (toekomstige) internationale handel in biomassa en concurrentie tussen technologieën en verschillende (tussen-) producten.
- Het geïntegreerde modelraamwerk kan worden gekoppeld aan modules van biomassa in bijvoorbeeld energiemodellen voor een verbeterde weergave van kosten, energie en broeikasgasemissies van logistieke processen voor een breed scala van mogelijke variaties in vraag en aanbodlocaties van verschillende soorten biomassa, tussenproducten en eindconversie.

Vraag III. Wat zijn de vooruitzichten van bio-energie in het vervullen van de nationale- en Europese hernieuwbare energie doelstellingen, wat is de rol van internationale biomassahandel, wat zijn belangrijke handelsregio's en soorten biomassa en welke factoren hebben een belangrijk effect op handel en toepassing van biomassa?

De rol van bio-energie (EU)

Met een voortzetting van het huidige hernieuwbare energiebeleid tot 2020, zoals het is aangenomen in het Green-X 'Business as Usual' (BAU) scenario in hoofdstuk 5, zal de totale productie van hernieuwbare energie in de EU naar verwachting stijgen van 5,9 EJ jr^{-1} in 2010 naar 7,8 EJ jr^{-1} in 2020. Hiermee zal het aandeel van hernieuwbare energie in het totale bruto eindverbruik stijgen van 11,9 % in 2010 tot 15 % in 2020 (Tabel 7-4). Voor het behalen van de hernieuwbare energie doelstelling zullen extra maatregelen moeten worden in alle sectoren (warmte, elektriciteit, transport), zoals het is aangenomen in de SNP en SNP-bsc scenario's. In de SNP(-bsc) scenario's wordt de totale opwekking van hernieuwbare energie geraamd op 9,7 EJ jr^{-1} in 2020 en daarmee 0,5 EJ jr^{-1} lager geschat dan de individuele EU-lidstaten in de NREAPs (10,2 EJ jr^{-1} in 2020). Bio-energie heeft een sleutelrol in het behalen van de hernieuwbare energiedoelstelling in de EU. Green-X projecties van de BAU en BAU-bsc scenario's laten tussen 2010 en 2020 een stijging van de totale opwekking van bio-energie zien van meer dan 30 % tot 4,8 EJ in 2020. In de SNP en SNP-bsc scenario's is de verwachte stijging meer dan 64 % tot 5,7 EJ in 2020. Deze scenarioprojecties bevestigen de verwachtingen van EU-lidstaten in de NREAPs dat bio-energie de belangrijkste bron van hernieuwbare energie zal blijven tot 2020.

Voor biomassahandel is het meest relevante verschil tussen de NREAPs en de Green-X SNP(-bsc) scenario's is de verwachte groei van elektriciteitsopwekking in de grotere lidstaten. Zo wordt in het NREAP van Duitsland tussen 2010 en 2020 een groei van 21 % voorzien in de opwekking van hernieuwbare elektriciteit uit vaste biomassa ten opzichte van 41 % in de SNP(-bsc) scenario's. In Frankrijk en het Verenigd Koninkrijk wordt in de NREAPs echter een grotere bijdrage voorzien van elektriciteit uit vaste biomassa (40 % in Frankrijk, 86 % in het Verenigd Koninkrijk) in vergelijking met de Green-X SNP scenarioprojecties (29 % in Frankrijk en 68 % in het Verenigd Koninkrijk).

Primaire vraag naar bio-energie en biomassahandel (EU)

De scenarioprojecties laten zien dat de totale primaire vraag naar bio-energie in de EU tot 2020 met 26 % kan stijgen van 3,98 EJ jr^{-1} in 2010 tot 5,01 EJ jr^{-1} in het BAU-bsc scenario in 2020 en tot maximaal 5,78 EJ jr^{-1} in het SNP-bsc scenario in 2020. Het overgrote deel van de totale primaire vraag naar bio-energie kan worden voorzien uit binnenlandse herkomst in alle scenario's, maar door de toenemende vraag naar bio-energie wordt de rol van internationaal verhandelde biomassa naar verwachting groter. In totaal wordt de handel tussen EU landen en import van buiten de EU geraamd op 373 EJ jr^{-1} in het BAU-bsc scenario tot 506 EJ jr^{-1} in het SNP scenario in 2020. Dit is equivalent aan 21 tot 28 Tg jr^{-1} houtpellets. Volgens de projecties groeit de import van vaste biomassa van buiten de EU sneller dan handel tussen EU landen. Vergeleken met de huidige import van houtpellets in de EU (4,6 Tg in 2012), zal de import van houtpellets in 2020 3,2 keer groter worden (15 Tg pellet eq.) in het BAU-bsc scenario en tot 4,7 keer groter (22 Tg pellet eq.) in het SNP scenario. De verwachte handel in vaste biomassa tussen EU lidstaten wordt geraamd op maximaal 122 PJ jr^{-1} (7 Tg pellet eq.) in 2020 in het SNP-bsc scenario, maar tot 2020 blijven de verschillen tussen de scenario's klein. Belangrijke exportregio's van vaste biomassa in 2020 zijn voornamelijk Centraal- en Oost-Europese landen (Bulgarije, Tsjechië, Hongarije, Polen, Slowakije, Slovenië) waar relatief goedkope biomassa (bijvoorbeeld stro) beschikbaar is en bosrijke landen, zoals de Baltische Staten (Estland, Letland). Volgens de scenarioprojecties worden Duitsland en Oostenrijk belangrijke importlanden van Europese biomassa met respectievelijk import uit Polen en Tsjechië (hoofdzakelijk landbouwresiduen) en Slovenië en Hongarije (bosbouwproducten en teelt van energiegewassen).

De vooruitzichten van bio-energie na 2020 zijn in Europa voor een groot deel afhankelijk van de beleidsambities voor het verhogen van de opwekking van energie uit hernieuwbare bronnen en mitigatie van broeikasgasemissies. Wanneer ambitieuze doelstellingen worden nagestreefd om klimaatsverandering tegen te gaan, dan zal naar verwachting het aandeel van hernieuwbare energie sterk groeien na 2020. Volgens projecties van het SNP scenario met het Green-X model, zal het aandeel van hernieuwbare energie in de EU groeien van 20 % in 2020 tot 31 % in 2030 [28]. Dit aandeel wordt in 2030 ook bereikt in het PRIMES 'High Renewables' scenario, ondanks dat de onderliggende data en aannames sterk verschillen met de Green-X scenario's [28, 29].

Tabel 7-4 Totale bio-based productie en primaire biomassavraag in de EU (zie hoofdstuk 5).

	2010[a]	2020				
		BAU	BAU-bsc	SNP	SNP-bsc	NREAPs
Bio-based productie (PJ finale energie)						
Elektriciteit	379	707	708	945	946	834
Warmte	2711	3290	3290	3700	3682	3763
Transportbrandstoffen, waarvan:	616	838	838	1062	1062	1245
Eerste generatie	491	460	460	431	430	673
Tweede generatie	0	91	91	152	152	110
Import	125	287	287	479	479	462
Totaal bio-based productie	**3706**	**4835**	**4836**	**5706**	**5690**	**5843**
Totaal hernieuwbare energie	5936	7820	7821	9754	9772	10256
Biomassa vraag (PJ primaire energie)						
Binnenland[b]	4596	5750	5772	6755	6806	
Import EU	14	102	106	117	122	
Import niet-EU	61	349	266	389	319	
Totaal	**4671**	**6200**	**6145**	**7262**	**7246**	
Aandeel hernieuwbare energie in het totale bruto eindverbruik (%)						
Aandeel bio-energie	7,4%	9,1%	9,1%	11,6%	11,6%	11,7%
Aandeel hernieuwbare energie	11,9%	14,8%	14,8%	19,8%	19,8%	20,6%

a) Gebaseerd op de bestaande Green-X database.
b) Inclusief gasvormige biomassa en organisch afval.

De rol van bio-energie voor het behalen van de hernieuwbare energie doelstellingen in Nederland

In dit proefschrift is Nederland geselecteerd voor een analyse van de rol van bio-energie op nationaal niveau. Nederland is op dit moment een van de belangrijkste importerende regio's van biomassa in de EU [30, 31]. In Tabel 7-5 wordt de verwachte inzet van hernieuwbare energie in het NREAP van Nederland [32] vergeleken met de ramingen van het Green-X model voor de BAU-bsc en SNP-bsc scenario's uit hoofdstuk 5 en de GlobLowTech en GlobHighTech scenarioprojecties met de gecombineerde bottom-up en LEITAP aanpak uit hoofdstuk 3.

Volgens het hernieuwbare actieplan van Nederland, zal het aandeel van hernieuwbare energie in Nederland in 2020 enigszins hoger zijn (14,1 %) dan de vereiste energiedoelstelling van 14 % [32]. In Nederland wordt verwacht dat in 2020 wind met een aandeel van 64 % de belangrijkste bron van hernieuwbare elektriciteitsopwekking wordt van Nederland, gevolgd door elektriciteitsopwekking uit biomassa (33 %). Elektriciteitsopwekking uit bij- en meestook wordt verwacht te stijgen van 11 PJ in 2010 tot 30 PJ in 2020, wat gelijk is aan 50 % van de totale elektriciteitsopwekking uit biomassa en 17 % van de totale opwekking van hernieuwbare elektriciteit in 2020. In het recentelijk gepubliceerde energieakkoord [33], wordt echter een maximum gesteld aan elektriciteit uit bij- en meestook van 25 PJ jr^{-1}.

Volgens de scenarioprojecties met het Green-X model voor Nederland, zal het aandeel van hernieuwbare energie stijgen van 3,8 % in 2010 tot 4,3 % in 2020 wanneer het beleid niet wordt aangepast (BAU-bsc scenario). Wanneer het beleid wordt aangepast om de EU hernieuwbare energie doelstelling te behalen in 2020, dan zal het aandeel van hernieuwbare energie stijgen tot 10,1 % in 2020 (SNP-bsc scenario). Nederland zal volgens het Green-X model gebruik maken van hernieuwbare energiecertificaten (samenwerkingsmechanismen) voor het behalen van de doelstelling van 14 % hernieuwbare energie in 2020. Dit impliceert dat hernieuwbare energie buiten Nederland voor een deel goedkoper kan worden opgewekt dan in Nederland zelf. Ook de totale bijdrage van bio-energie in de Green-X scenario's is substantieel lager (111 PJ finale energie in 2020) dan in het NREAP van Nederland (134 PJ finale energie in 2020).

De rol van bio-energie in Nederland in een bio-based economie

De scenarioprojecties voor Nederland in hoofdstuk 3 (RegLowTech, GlobLowTech, RegHighTech, GlobHighTech(AC)) zijn zogenaamde 'backcasting' exercities waarin verschillende ontwikkelingspaden tot een hoog ambitieniveau van de inzet van bio-energie worden verkend. Deze ambities zijn niet consistent met de Europese hernieuwbare energiedoelstelling, maar zijn in lijn met de doelstelling van het Platform Groene Grondstoffen (PGG) om in 2030, 30 % primaire fossiele energie te vervangen door groene grondstoffen (biomassa) in Nederland [34]. In tegenstelling tot de Green-X scenario's en NREAPs, is in deze scenario's ook het niet-energetisch gebruik van fossiele brandstoffen inbegrepen. Daarnaast ligt de focus van hoofdstuk 3 op de bio-based economie en zijn concurrerende hernieuwbare energiebronnen (bijvoorbeeld wind en zon) niet inbegrepen. In de LowTech scenario's in hoofdstuk 3 worden conservatieve aannames gemaakt voor bij- en meestook in bestaande kolencentrales (10 % van elektriciteitsopwekking) in vergelijking met het NREAP van Nederland (20 % van elektriciteitsopwekking). In de HighTech scenario's in hoofdstuk 3 wordt een aanzienlijk deel van de elektriciteit uit biomassa opgewekt met cogeneratie tijdens de productie van biobrandstoffen van de tweede generatie en chemicaliën uit synthesegas. Deze zijn in het NREAP van Nederland niet inbegrepen. Daarnaast groeit de vraag naar transportbrandstoffen substantieel (44 % tot 47 % ten opzichte van 2006) volgens de LEITAP projecties. In het NREAP wordt verwacht dat de bruto finale energievraag in de transportsector juist daalt met 6 % in 2020 ten opzichte van 2005. Op de middellange termijn tot 2030 neemt de onzekerheid over de rol van hernieuwbare energie en bio-energie verder toe. In de GlobLowTech en GlobHighTech scenario, is de totale bio-based productie geraamd op respectievelijk 214 PJ jr^{-1} tot 653 PJ^{-1} finale energie in 2030. Het aandeel van biomassa in het finale aanbod (inclusief bio-energie en bio-chemicaliën) is geraamd op 12 % in het GlobLowTech scenario en 38 % in het GlobHighTech scenario in 2030. Deze scenario's onderstrepen het belang van groene grondstoffen in de chemie. In de HighTech scenario's draagt de productie van chemicaliën uit synthesegas en de gerelateerde cogeneratie van elektriciteit substantieel bij aan de totale productie in deze sectoren.

Primaire vraag naar bio-energie en biomassahandel (NL)

In het NREAP van Nederland is de rol van de import van biomassa niet gekwantificeerd. Sectoren die waarschijnlijk biomassa zullen importeren zijn volgens het NREAP bij- en meestook (totale primaire vraag: 69 PJ in 2020) en biobrandstoffen (totale finale vraag: 35 PJ in 2020) [32]. In 2011 heeft Nederland 1,4 Tg houtpellets geïmporteerd (25 PJ) [31]. Volgens het NREAP van Nederland kan de import van biomassa dus meer dan verdubbelen in 2020 ten opzichte van 2011. De projecties met het Green-X model (hoofdstuk 5) zijn een stuk conservatiever met betrekking tot de inzet van bio-energie in Nederland. In het SNP-bsc scenario blijft de totale invoer van vaste biomassa in 2020 gelijk aan 2011 (25 PJ primaire bio-energie). De scenarioprojecties uit hoofdstuk 3 laten grotere variaties zien. Het grootste verschil tussen het NREAP en het GlobLowTech scenario uit hoofdstuk 3 is dat in de GlobLowTech en GlobHighTech scenario's grootschalige invoer van ethanol uit Zuid-Amerika wordt verwacht voor de productie van chemicaliën en om in de hogere vraag naar biobrandstoffen te voorzien zoals geprojecteerd met het LEITAP model.

Het GlobHighTech scenario uit hoofdstuk 3 beschrijft een toekomstbeeld waarin bio-based productie van energie en chemicaliën concurrerend wordt met productie van energie en chemicaliën op basis van fossiele brandstoffen. Op dit moment zijn de meeste bio-energie productiesystemen ten opzichte van fossiele productiesystemen alleen rendabel met ondersteuning (bijvoorbeeld subsidies). Houtpellets zijn bijvoorbeeld beschikbaar in Nederland voor 130 € Mg^{-1} (7,4 € GJ^{-1}) (CIF ARA) en kunnen daarom niet concurreren met de huidige prijs van kolen (ongeveer 3,3 € GJ^{-1}) [35] zonder ondersteuning of beleid.

Ambitieuze doelstellingen, zoals aangenomen in de GlobHighTech scenario's, zijn daarom alleen haalbaar wanneer bio-energie concurrerend worden met productie op basis van fossiele brandstoffen. Om dit te bereiken is sterke verandering nodig in de ontwikkeling van productie (bijvoorbeeld hogere landbouwopbrengsten door verbeterd management en organisatie en type gewas), efficiënte logistieke ketens, de commerciële beschikbaarheid van geavanceerde conversietechnologieën, stijgende fossiele energieprijzen en CO_2 belastingen. In het GlobHighTech scenario, stijgt de totale invoer van biomassa naar Nederland (bio-energie en chemicaliën) tot 1,4 EJ jr^{-1} in 2030. Dit komt overeen met 20 % van de totale vraag naar biomassa voor bio-energie in het SNP-bsc scenario in de EU in 2020. In zowel de LowTech en HighTech scenario's in hoofdstuk 3 wordt buiten Nederland alleen gematigde groei verondersteld in de vraag naar biomassa volgens de hernieuwbare energiedoelstelling van de EU in de overige EU lidstaten. Deze resultaten laten zien dat, wanneer in een open economie zoals Nederland, een bio-based economie wordt nagestreefd, in en buiten Europa rekening gehouden moet worden met een sterke groei naar vraag en import van biomassa.

Om in te schatten waar biomassa vandaan zal komen (EU en niet-EU) in het GlobLowTech en GlobHighTech scenario in Tabel 7-5, is de totale samenstelling van handel in gewassen naar Nederland (in M€ in 2030) uit het LEITAP uit Figuur 3-6 (p. 67) gebruikt. Volgens de scenarioprojecties met het LEITAP model, zal ongeveer 93 % van de totale invoer van gewassen naar Nederland van buiten de EU komen en 60 % uit Zuid-Amerika. Volgens de Bottom-Up projecties kan het binnenlands aanbod van biomassaresiduen substantieel bijdragen aan de totale vraag naar biomassa (16 % in het GlobHighTech scenario tot 70 % in het RegLowTech scenario). Toch kan in geen enkel scenario worden volstaan met biomassa uit binnenlands aanbod en blijft Nederland afhankelijk van biomassa import.

Tabel 7-5 Bio-based productie van hernieuwbare energie en chemicaliën in het NREAP van Nederland, Green-X (hoofdstuk 5) en de gecombineerde BU – LEITAP aanpak in hoofdstuk 3.

	NREAP		Hoofdstuk 5 (Green-X)		Hoofdstuk 3 (Bottom-up/LEITAP)[c]			
			2020		2020		2030	
	2010[a]	2020[b]	BAU-bsc	SNP-bsc	Glob-LowTech	Glob-HighTech	Glon-LowTech	Glob-HighTech
Bio-based productie (PJ finale energie)								
Elektriciteit	19	60	23	32	26	110	32	141
Warmte	29	39	39	54	20	20	22	22
Transportbrandstoffen, waarvan:	10	35	2	25	55	138	125	380
Eerste generatie	5	7	2	6	55	27	122	233
Tweede generatie	0	6	0	2	0	111	3	147
Import	5	22	0	18	37	21	141	0
Bio-based chemicaliën					15	49	34	111
Totaal bio-based productie	**57**	**134**	**64**	**111**	**116**	**318**	**214**	**653**
Totaal hernieuwbare energie	81	307	92	199				
Biomassa vraag (PJ primaire energie)								
Binnenland[d]	89		103	131	93	168	103	238
Import EU[e]	0		3	8	5	38	7	106
Import niet-EU[e]	7		8	17	32	392	48	1084
Totaal	**96**	**349**	**113**	**156**	**130**	**599**	**158**	**1428**
Aandeel hernieuwbare energie in het totale bruto energiegebruik (%)								
Aandeel bio-energie	2,7%	6,1%	3,0%	5,7%	4,4%	11,2%	7,9%	20,8%
Aandeel bio-energie met chemicaliën					7,5%	20,5%	12,4%	37,8%
Aandeel hernieuwbare energie	3,8%	14,1%	4,3%	10,1%				

a) Gebaseerd op de Green-X database.
b) ECN en NREAP van Nederland.
c) Berekend met de BU Spreadsheet tool.
d) Inclusief gasvormige biomassa en organisch afval.
e) Ruwe schatting van Intra-EU and Extra-EU importen gebaseerd op de samenstelling van de import van alle gewassen in de LEITAP scenarioprojecties van 2030 (hoofdstuk 3).

De scenario's laten zien dat de inzet van bio-energie in Nederland in grote mate afhankelijk is van de ontwikkeling en beschikbaarheid van ecologisch en economisch duurzame biomassa potentiëlen in exporterende landen, efficiënte aanvoerketens en de commerciële beschikbaarheid van geavanceerde conversietechnologieën. De beschikbaarheid van landbouwgrond per regio en gewasopbrengsten van de teelt van energiegewassen zijn belangrijke factoren in de kosten en beschikbaarheid van biomassa. Voor het modelleren van veranderingen en de intensiteit van landgebruik op basis van beschikbaarheidscurves van land, is het LEITAP model gekoppeld aan het biofysische model IMAGE. Met deze beschikbaarheidscurves berekent het LEITAP model landconversie en veranderingen in gewasopbrengsten. Wanneer de vraag naar energiegewassen toeneemt, zal hierdoor in regio's waar relatief veel land beschikbaar is, zoals in Zuid-Amerika, het landgebruik sterk toenemen en zal dit een gering effect hebben op de landprijzen en landbouwintensiteit. In gebieden waar land relatief schaars is, zoals in West-Europa, zal het landgebruik beperkt toenemen, maar zullen bij een groeiende vraag de prijs van landgebruik en de intensiteit sterk toenemen. Deze modelresultaten, die in het LEITAP model worden gebruikt, zijn erg onzeker en de landbeschikbaarheidscurves zijn dynamisch afhankelijk van de scenario-ontwikkelingen. Zo is voor Europa aangetoond dat het economisch potentieel van biomassa sterk kan variëren in verschillende scenario's, het type management en het type gewas dat wordt verbouwd [36, 37].

7.8 Slotopmerkingen en aanbevelingen

Er is een sterke behoefte aan verbeterde inzichten in de mogelijke gevolgen van de vervanging van fossiele energiedragers met betrekking tot de reductie van broeikasgasemissies en economische aspecten. Het hangt van het doel en de toepassing af wat hiervoor de meest geschikte benadering is. Op het niveau van de productieketen, kunnen systeemanalyses en bottom-up benaderingen inzicht verschaffen. Voor het analyseren van de mogelijke rol van bio-energie in de context van de transitie naar een duurzaam energiesysteem, zijn complexe interdisciplinaire modellen nodig die de directe en indirecte consequenties van de toekomstige inzet van bio-energie kunnen berekenen. Dit proefschrift heeft bijgedragen aan de verbeterde weergave van bio-energie in de (gevestigde) modellen die gebruikt worden voor het analyseren van ontwikkelingspaden van hernieuwbare energie en bio-energie:

- Inzicht in de effecten van methodologische keuzes en aannames op het broeikasgas mitigatiepotentieel van productiesystemen van biobrandstoffen;
- Kwantificering van de mogelijke economische effecten van de inzet van bio-energie op nationaal niveau;
- Het economisch potentieel van alternatieve houtbronnen die beschikbaar zijn voor de productie van houtpellets in het zuidoosten van de VS;
- Geografisch expliciete analyses van biomassa logistiek;
- De potentiële rol van intra- en extra EU handel van bio-energie.

7.8.1 Beleidsmakers

De mogelijke consequenties van beleidsbeslissingen met betrekking tot bio-energie kunnen divers zijn omdat bio-energie op verschillende manieren gelieerd is aan verschillende beleidsterreinen (klimaat, energie, landbouw, bosbouw, economie en milieu), verschillende sectoren van de economie en reikt over landsgrenzen heen het gevolg van internationale biomassahandel. Modellen kunnen beleidsmakers helpen bij het maken van strategische beslissingen.

Modellen voor levenscyclusanalyse zijn van cruciaal belang geworden in het beleid voor hernieuwbare energie. Het hoofddoel van deze modellen is het vaststellen van minimale eisen voor de reductie van broeikasgasemissies ten opzichte van de fossiele referentie. Dergelijke inzichten kunnen helpen bij het ontwerpen van efficiënte productiesystemen en beleidsmechanismen ter voorkoming van de inzet van slecht presterende bio-energie productiesystemen. Zo worden in de richtlijn hernieuwbare energie van de EU (RED) [12] minimale eisen gesteld aan vloeibare biobrandstoffen. Hoewel soortgelijke criteria niet geïmplementeerd zijn voor vaste- en gasvormige biomassa die worden ingezet voor de opwekking van elektriciteit, warmte en koeling [38], evenals de productie van materialen, worden dezelfde criteria aangeraden door de Europese Commissie[19]. Deze criteria zijn mogelijk niet strikt genoeg voor vaste biomassa gebruikt voor de opwekking van warmte en elektriciteit. Met uitzondering van productiesystemen waarbij de emissies van landgebruiksverandering worden inbegrepen, hebben minimale broeikasgasreductie-eisen van 60 % geen significante invloed op de efficiëntieverbetering van deze systemen. Bottom-up tools kunnen beleidsmakers informeren over de gevolgen van methodologische keuzes en de invloed van belangrijke aannames. De effecten van methodologische keuzes en onzekerheden van aannames, bijvoorbeeld de allocatieprocedure voor nevenproducten, die in deze tools worden gemaakt moeten daarom expliciet en transparant worden gemaakt.

Het Green-X model kan worden gebruikt voor het analyseren van de mogelijke effecten van minimale broeikasgasreductie-eisen in de context van het hernieuwbaar energiebeleid in de EU. De uitbreiding van Green-X met handel in biomassa, zoals beschreven in dit proefschrift, biedt inzicht in de mogelijke rol van binnenlandse en geïmporteerd biomassa in de context van ontwikkelingspaden van hernieuwbare energie, het besparingspotentieel van broeikasgasemissies, de kosten en benodigde middelen. Bovendien helpt het model bij het identificeren van kansen of mogelijke zwakke punten van het duurzaam gebruik van binnenlandse en geïmporteerd biomassa. Omdat de minimale eisen voor broeikasgasreductie kunnen worden gespecificeerd per land, per conversietechnologie en per schaalgrootte, kunnen ook de kansen en risico's van verschuivingen in gebruik naar eindgebruikers waarvoor duurzaamheidseisen niet van toepassing zijn worden geïdentificeerd. Ook is het relevant voor beleidsmakers om de mogelijke effecten van strengere duurzaamheidseisen te analyseren met het Green-X model. Er dient echter te worden opgemerkt dat het inzicht in de effecten van duurzaamheidseisen op het economisch potentieel van biomassa nog zeer beperkt is. Meer onderzoek is daarom noodzakelijk om de huidige aannames aangaande het aanbod van niet-Europese biomassa en de kansen voor duurzame biomassaproductie in Europa zelf in het model te verbeteren.

Dit proefschrift heeft aangetoond dat een gecombineerde aanpak van een bottom-up tool met fysische stromen van energie en materialen en het top-down economische model LEITAP, inzicht geeft in de ecologische en economische effecten van de inzet van bio-energie. Beleidsmakers moeten er echter bewust van zijn dat dit verkenningen zijn en geen prognoses. Niettemin laten de scenario's zien dat een grootschalige vervanging van fossiele energiedragers door biomassa de uitstoot van broeikasgassen en afhankelijkheid van fossiele brandstoffen sterk kan verminderen. Echter, de omvang van deze positieve effecten is sterk afhankelijk van de snelheid van de technologische ontwikkeling, de mobilisatie en beschikbaarheid van duurzame, internationale biomassa en de prijs van biomassa ten opzichte van de fossiele referenties. Grote inspanningen en investeringen in onderzoek en demonstrering zijn daarom nodig voor de verdere ontwikkeling en de

[19] Minimale broeikasgasemissiereductie ten opzichte van fossiele referenties: 35 %, oplopend naar 50 % in 2017 en 60 % voor systemen waarvan de productie gestart is in of na 2017 [12].

commercialisatie van de gewenste geavanceerde technologieën, omdat technologische ontwikkeling essentieel is voor gunstigere resultaten vanuit een economisch en ecologisch perspectief.

Het nastreven van een bio-based economie in Nederland werkt sterk door in de nationale economie en heeft ook internationale impact. Het waarborgen van een duurzaam aanbod van biomassa vergt daarom inspanningen over de gehele productieketen met inbegrip van de invoer van biomassa uit EU en niet-EU landen. Effectieve duurzaamheidskaders (inclusief certificering) zijn een belangrijk instrument om dat te bereiken.

7.8.2 Investeerders en industriële stakeholders

Voor het initiëren van verdere ontwikkelingen in bio-energie, zijn private en publieke strategische investeringen vereist. Zo laten de scenario's voor Nederland in dit proefschrift zien dat grote inspanningen gericht op de verdere internationalisering van duurzame handel in bio-energie, het ondersteunen van logistieke infrastructuur en investeringen in geavanceerde bio-energietechnologieën nodig zijn. Op de korte termijn zijn deze investeringen niet altijd rendabel, maar op de lange termijn kunnen deze investeringen duurzamer uitpakken, bijvoorbeeld door stijgende prijzen van fossiele brandstoffen. Ook laten de scenario's zien dat de rol van internationale handel in biomassa steeds belangrijker wordt voor de EU (hoofdstuk 5), met name in lidstaten met een open economie zoals Nederland (hoofdstuk 3). Houtpellets zijn uitgegroeid tot de belangrijkste vorm van verhandelde vaste biomassa en deze trend zal waarschijnlijk doorzetten. Zo laten de scenario's voor de EU in dit proefschrift groei in de handel van vaste biomassa zien van 4,6 Tg jr^{-1} hout pellets in 2012 naar 15 tot 22 Tg jr^{-1} in 2020. De resultaten van deze scenario's kunnen worden gebruikt voor het identificeren van kansen en beleggingsrisico's in aanbod van biomassa (bos- en landbouw), logistieke faciliteiten (bijvoorbeeld op- en overslag in havens) en bio-energie conversiesystemen.

De markten voor lignocellulose grondstoffen voor de productie van bio-energie, zoals houtpellets, maar in de toekomst ook andere tussenproducten, zoals getorreficeerde biomassa of pyrolyse-olie, worden naar verwachting steeds groter door de toenemende vraag naar grondstoffen voor elektriciteit, warmte, maar ook 2^{e} generatie biobrandstoffen en chemicaliën. Hierdoor wordt de vraag naar aanvullende en alternatieve bronnen van lignocellulose biomassa groter en biedt daarmee kansen voor landbouw (landbouwresiduen en meerjarige gewassen), logistiek (bijvoorbeeld zeehavens) en leveranciers van tussenproducten (bijvoorbeeld producenten van houtpellets). Zo worden in het zuidoosten van de VS steeds meer pellets geproduceerd uit primaire houtstromen zoals hout van pulpkwaliteit. In deze regio zijn echter ook alternatieve houtstromen beschikbaar die op dit moment alleen worden gebruikt voor laagwaardige toepassingen, zoals brandstof in inefficiënte ovens, of worden afgevoerd als afval. Deze houtstromen kunnen ook worden gebruikt voor de productie van houtpellets mits ze goed worden ingezameld. Testpartijen, geproduceerd uit niet-verkoopbare bosresiduen en de productie van houten palen, laten zien dat het mogelijk is om gekwalificeerde pellets te produceren uit deze alternatieve houtstromen [39]. Met de tools die ontwikkeld zijn in dit proefschrift kunnen mogelijke kansen, risico's en concurrenten voor houtpellets uit alternatieve houtstromen worden onderzocht. Zo kunnen ondanks de geografische spreiding van alternatieve houtstromen in Georgia, houtpellets worden geproduceerd voor gemiddeld 85 US$ Mg^{-1} uit laagwaardige houtstromen. De optimale productiecapaciteit met de onderzochte alternatieve houtstromen in de staat Georgia (hoofdstuk 4) is 125 Gg jr^{-1}. Daarnaast laten de resultaten uit hoofdstuk 6 zien dat, ondanks het vereiste transport via binnenwateren naar een zeehaven, pellets geproduceerd uit landbouwresiduen (maïsstro) en gewassen (gras) in het middenwesten van de VS kunnen worden geleverd in Europa voor concurrerende kosten ten opzichte van houtpellets geproduceerd in het zuidoosten van de VS door de lagere kosten van voorbewerking (drogen). Ten laatste is het goed mogelijk dat de vraag naar lignocellulose biomassa voor energie ook zal toenemen in de VS, bijvoorbeeld door de ontwikkeling van lignocellulose biobrandstoffen. Dit benadrukt de noodzaak om markten van duurzame biomassa verder te ontwikkelen en te diversifiëren.

7.9 Aanbevelingen voor verder onderzoek

In dit proefschrift is voor Nederland aangetoond dat een spreadsheet accounting tool kan worden gebruikt om de analyses van bio-energie op nationaal niveau met CGE modellen, zoals LEITAP, te verbeteren. De gecombineerde aanpak laat ook een aantal belangrijke tekortkomingen zien waarvoor verder onderzoek nodig is. Ten eerste, kapitaalinvesteringen van bio-energietechnologieën zijn een essentieel onderdeel van de totale kosten van bio-energieproductie. Met name voor kapitaalintensieve technologieën met relatief lage grondstofkosten, zoals tweede generatie biobrandstoffen (hoofdstuk 3, hoofdstuk 6). De impliciete methode voor het modelleren van bio-energie in LEITAP (hoofdstuk 3) is hiervoor niet goed geschikt. Alternatieve benaderingen om bio-energie en gerelateerde kapitaalinvesteringen beter te verwerken in CGE modellen zijn de 'latente technologieën' methode of het opsplitsen van de 'Social Accounting Matrices' (SAM's) [21] voor relevante subsectoren. Bovendien zijn de SAM's die in het LEITAP model in dit proefschrift zijn gebruikt afgeleid uit de GTAP 6 database voor 2001. Sinds 2001 is de totale inzet van bio-energie substantieel gegroeid. Wanneer beschikbaar, dienen nieuwe versies van de SAM's gebruikt te worden waarin de recente ontwikkelingen van bio-energie gerelateerde activiteiten zijn verwerkt. De recente ontwikkelingen in handel van biomassa en de capaciteitsgroei van moderne bio-energie zijn nodig voor meer accurate ramingen van de inzet van bio-energie in de toekomst.

Voor het kwantificeren van de indirect effecten van bio-energie, zijn consequentiële LCA studies afhankelijk van de resultaten van economische CGE of partiële equilibrium modellen. Er is echter meer samenwerking nodig tussen modellen en om de vertegenwoordiging van biomassa, bio-energie, nevenproducten en mogelijk meerdere hoofdproducten in bio-raffinaderijen (bijvoorbeeld chemicaliën en elektriciteit) te verbeteren in deze top-down modellen. Daarnaast is in hoofdstuk 2 aangetoond dat de locatie en het type land dat wordt gebruikt voor de productie van biomassa een grote invloed heeft op de broeikasgasbalans en daarmee het belang aangetoond van modelsamenwerking tussen CGE modellen en biofysische landgebruik modellen. Dit geldt ook voor de scenario's die maatregelen bevatten voor het vermijden van niet duurzaam gebruik van land en bodem en het voorkomen van indirecte veranderingen in landgebruik. Voorbeelden van zulke maatregelen zijn verbeteringen in agrarische productie-efficiëntie, zonering van landgebruik voor het beschermen van koolstofvoorraden en de implementatie van effectieve certificeringssystemen [15]. Tenslotte kunnen energiesysteemmodellen, zoals het Europese Green-X model, gebruikt worden voor een betere weergave van bio-energie en concurrerende hernieuwbare energiebronnen in top-down CGE modellen. Deze marktbenadering in CGE modellen kan ook leiden tot betere inzichten in biomassahandel in bottom-up modellen. Een dergelijke modelsamenwerking kan de vertegenwoordiging van hernieuwbare energie en handel in biomassa (Green- X) verbeteren, terwijl een CGE-model, zoals LEITAP, kan worden ingezet voor het beoordelen van de effecten van (bio-energie) grondstofprijzen, verschuivingen in markten in de sectoren land- en bosbouw en de mogelijke gevolgen op vraag en aanbod van (bio-)energie en materialen.

De uitbreiding van het Green-X model met handel in biomassa met behulp van het op GIS gebaseerde BIT-UU model, zoals beschreven in hoofdstuk 5, is voornamelijk gericht op de verbeterde weergave van kosten en uitstoot van broeikasgassen met betrekking tot logistiek transport tussen vraag- en aanbodregio's van bio-energie in Europa. Het BIT-UU model is in hoofdstuk 6 gekoppeld aan het logistieke model BLM voor een verbeterde modellering van alle logistieke activiteiten in de aanvoerketens van bio-energie vanuit de VS (oogsten en verzamelen, opslag, voorbehandeling en transport). Het BIT-UU model is in hoofdstuk 6 uitgebreid met zeescheepvaart. Het ontwikkelde modelraamwerk maakt gedetailleerde analyses mogelijk van intercontinentale logistieke ketens tussen de VS en Europa. Met deze gekoppelde modellen is het ook mogelijk om soortgelijke analyses uit te voeren voor andere regio's buiten Europa (bijvoorbeeld Noord-Amerika, Zuid-Amerika, Afrika en Rusland).

Verder kan met behulp van de gekoppelde BLM en BIT - UU modellen onderzoek worden gedaan naar optimale locatie selecties van aanbodgebieden van biomassa, locaties van voorbewerking (depots), logistieke terminals en eindgebruikers, evenals de impact van concurrentie in vraag en aanbod. Tenslotte kunnen ook producten worden toegevoegd aan het modelraamwerk, zoals logistieke ketens met vloeibare biomassa tussenproducten (bijvoorbeeld pyrolyse-olie) en biobrandstoffen.

Uit hoofdstuk 3 blijkt bovendien dat chemicaliën uit biomassa op de lange termijn mogelijk steeds belangrijker worden. Voor scenario's na 2020 is het daarom belangrijk dat, naast de energiesectoren warmte, elektriciteit en transport, deze concurrerende sectoren in de modellen worden opgenomen. Ook is er in de gebruikte modellen een belangrijk potentieel in het verbeteren van de gedetailleerde weergave van biomassasectoren en de specifieke logistieke ketens. Het gebruik van houtpellets voor warmte in huishoudens vereist een andere logistieke aanvoerketen dan industrieel gebruik van houtpellets, bijvoorbeeld voor het bijstoken van houtpellets (bulk) in kolencentrales. Met het BIT-UU model kunnen de sectorspecifieke aanvoerketens, de geografische locaties en de benodigde logistieke processen worden berekend. De resultaten kunnen worden gebruikt in de biomassahandel module in het Green-X model, maar het vereist additionele activiteiten om dit mogelijk te maken in het huidige modelraamwerk. Deze inspanningen kunnen interessant zijn voor meer gedetailleerde economische en risicoanalyses, bijvoorbeeld voor het bieden van een onderbouwing voor investeringsmogelijkheden en het in kaart brengen van risico's en het plannen van logistieke capaciteiten.

In dit proefschrift zijn verschillende modelmatige benaderingen gecombineerd om inzicht te krijgen in de rol van bio-energie en bio-energiehandel in de transitie naar een duurzame energiehuishouding. De hoofdfocus van dit proefschrift lag op het verbeteren van inzichten in handel in bio-energie en de kosten en emissies van logistieke processen aan de hand van (bestaande) modellen. Dit proefschrift laat zien dat, ondanks de beperkingen en tekortkomingen in de samenwerking tussen de verschillende modellen, uit deze samenwerking synergievoordelen en nieuwe inzichten te verkrijgen zijn die deze modellen afzonderlijk niet kunnen leveren. Dit zijn onder andere: (macro-) economische effecten en technologische details van de ontwikkeling van bio-based sectoren, de rol van de binnenlandse en verhandelde biomassa in elektriciteit, warmte en transport in Europa en de mogelijke kosten en de uitstoot van broeikasgassen van intercontinentale biomassa aanvoerketens.

De belangrijkste ontbrekende schakel in dit proefschrift is het aanbod van biomassa en de gerelateerde dynamische eigenschappen en het brede scala van biomassa-aanbodpotentiëlen [41]. De toekomstige economische en duurzame potentiëlen van biomassa binnen de EU en de potentiële beschikbare aanvoer van buiten de EU zijn afhankelijk van een complexe en dynamische omgeving, afhankelijk van beleidskeuzes en technologische ontwikkelingen en daarmee dus zeer onzeker. Met de statische benadering die gebruikt is in LEITAP (gebaseerd op IMAGE modeluitkomsten) en Green-X (op basis van de economische-implementatie potentiëlen van biomassa), wordt geen rekening gehouden met de belangrijkste aspecten die het potentieel van bio-energie bepalen. De belangrijkste factoren die van invloed zijn op potentiëlen van biomassa, zijn [41]:

- Verbeteringen in landbouwbeheer;
- Keuze van gewassen;
- Vraag naar voedsel en dieet;
- Het gebruik van gedegradeerd land;
- Concurrentie voor water.

De relevantie om deze factoren te verwerken in het toetsingskader wordt groter voor middellange en lange termijn projecties na 2020, omdat naar verwachting het aandeel van gewasteelt voor bio-energie in het totale aanbod van biomassa aanzienlijk zal toenemen. Voor korte termijn projecties is het relevant om de logistieke ketens van biomassaresiduen te verbeteren en mogelijkheden te identificeren voor het herverdelen van biomassa over verschillende sectoren. Zo kan schoon zaagsel, dat nu wordt ingezet voor laagwaardige toepassingen in ovens, mogelijk worden vervangen door laagwaardige biomassa waarmee het zaagsel beschikbaar komt voor de productie van houtpellets. Om de potentiële rol van bio-energie te beoordelen, moeten daarom de doorslaggevende factoren die het potentieel van biomassa bepalen en de duurzaamheid waarborgen (zonering van landgebruik, de inzet van duurzaamheidskaders en certificering) beter worden opgenomen in de gebruikte modellen. Deze factoren kunnen het potentieel van bio-energie verhogen en verlagen, de kosten en de interactie tussen binnenlands aanbod en invoer van binnen en buiten de EU beïnvloeden. Voorbeelden van deze factoren zijn veranderingen in bosbeheer en landbouwmanagement, strenge duurzaamheidseisen en de mogelijke internationale concurrentie in vraag. Strikte duurzaamheidscriteria en de toegenomen internationale concurrentie strikte duurzaamheidscriteria en groei in internationale concurrentie kunnen de beschikbaarheid van, in het bijzonder, biomassa bronnen van buiten de EU reduceren, maar kunnen ook leiden tot verbeterde managementpraktijken en technologisch leren welken het duurzame potentieel van biomassa uiteindelijk kunnen verhogen. Deze factoren spelen een sleutelrol in de toekomstige inzet van bio-energie en biomassahandel en vergen in het komende decennium aanzienlijke inspanningen in onderzoek en ontwikkeling.

Dankwoord

Utrecht, januari 2014

Nu mijn proefschrift af is, vormt het schrijven van het dankwoord een mooi moment om terug te kijken op ruim acht jaar Universiteit Utrecht waarvan bijna zes jaar als onderzoeker. Het schrijven van dit boekje en het gerelateerde onderzoek is gelukkig geen eenzaam proces geweest. Met velen heb ik samengewerkt en velen hebben mij direct of indirect geholpen. Hiervoor wil ik iedereen bedanken en een aantal van hen wil ik in het bijzonder noemen.

Allereerst wil ik mijn promotor André bedanken. Ook al is het al vaak gezegd in een dankwoord, dat maakt het niet minder waar: je vertrouwen, enthousiasme en onuitputtelijke optimistisme werken buitengewoon inspirerend. Je scherpe visie en doelgerichtheid hebben mij geholpen het einddoel in zicht te houden en waar nodig het juiste spoor weer op te pakken wanneer ik verdwaald dreigde te raken in eindeloze details of de complexiteit van sommige vraagstukken. Juist over Groningen zou je kunnen zeggen dat er behoefte is aan een nieuwe ‘beweging’ en ongetwijfeld zal je ook daar een positieve draai kunnen geven aan de noodzakelijke energietransitie. Ik wens je daarin veel succes.

Martin, zijdelings was je betrokken bij mijn afstudeeronderzoek over technologisch leren en ik ben erg blij dat je uiteindelijk mijn copromotor bent geworden. Dank voor de zeer goede samenwerking, je begeleiding en feedback vanuit diverse plekken op de wereld. Dankzij je inzicht, vertrouwen en dankzij de ruimte en mogelijkheden die je hebt gecreëerd, hebben we veel kunnen oogsten uit diverse projecten waarin we hebben samengewerkt. Jij en André wisten elkaar goed aan te vullen. Dat heb ik altijd zeer gewaardeerd.

Tijdens het onderzoek en het schrijven van de artikelen in de hoofdstukken van dit proefschrift heb ik meerdere dagelijkse begeleiders versleten en in meerdere consortia samengewerkt. Roni, dank voor de begeleiding van het onderzoek naar bio-energie en bio-chemicaliën in hoofdstuk 3. Martin Banse, I would like to thank you for your help with the macro-economic projections, providing a peek in the engine room of the LEITAP model, the many Skype calls and your contributions to the article in chapter 3. Edward, ik wil je bedanken voor je begeleiding en de samenwerking aan de broeikasgasbalansen van biobrandstoffen in hoofdstuk 2. Je inzichten in biomassapotentiëlen en transport zijn in later onderzoek nog vaak van pas gekomen.

I would like the people involved in the Re-Shaping, Biobench and Dia-Core consortia and in particular Gustav and Christian from TU Wien. Gustav, thanks for helping me out with the Green-X model and outcomes, sharing ideas on renewable energy and bioenergy trade and your contributions to the article in chapter 5.

Richard, thank you for creating the opportunity for me to work shortly at INL and the kind welcome. Jake, Kara, Erin and all other colleagues of INL, thanks for helping me out, showing me some of the many great surroundings of Idaho Falls as well as the 'beer on the street' and your help with the BLM model and contributions to the article in chapter 6.

Pjotr, Tjipke, Erik en Richard, dank voor de samenwerking in het Inbio project. Steven, thanks for the nice field trip in Georgia, the pellet mill in Baxley and sharing your experience on wood fiber procurement and pelletization. I would also like to thank the people from the USDA Forest Service, Southern research station and the University of Georgia for their help and time to share ideas during my field trip in the southeast of the U.S..

Verder wil ik alle collega's en oud collega's van NW&S, nu Energy & Resources, bedanken voor de mooie tijd, de bizarre wendingen en uiteenlopende onderwerpen van lunchdiscussies, de borrels, uitjes en hardloopwedstrijdjes. In het bijzonder mijn kamergenoten. Edward, dank voor de leuke discussies. Birka, dank voor de introductie in GIS en je hulpvaardigheid. Gert-Jan en Anne-Sjoerd, het is mooi om met jullie samen het Bio-CCS team te vormen. Verder wil ik de bio-energie en biomaterialengroepen bedanken voor alle hulp en inzichten: Floor, Bothwell, Chung Shen, Marnix, Judith, Sanne, Michiel, Vasileios, Sarah, Li, John, Yannis, Berthe en Loek. Krishna, Akshay, thanks for bringing Indian food to our offices. Rosalien en Carina, de Gütenbergkoffie tijdens de drukke dagen kwam als geroepen. Marc, dank voor je hulp met de REFUEL resultaten. De PV-groep, Atse en Boudewijn, dank voor de coördinatie van de lunch. De CCS-groep en in het bijzonder Machteld voor de goede samenwerking in het Fenco-Era Net project en de begeleiding van Thijs. Andrea, I am grateful for our joint work on the Fenco-Era Net project which also turned out be a very useful experience for my research on bio-energy. Hans, Niels, dank voor de UMC dinertjes wanneer het werk weer langer was dan de dag en de hulp met technische vragen. Deger, Martin Weiss and Janske, thanks for the organization of the vakgroepuitjes. I think that our colleagues are still grateful for the offshore adventure. Patrick, although our work on bioenergy trade is not part of this thesis, I enjoyed working with you on the Rabobank project.

Wim, je bent niet direct betrokken geweest bij mijn onderzoek, maar ik heb veel van je kunnen leren en waardeer je visie. Ik wil jou, Jos en Jeroen ook bedanken voor de samenwerking tijdens de MT-vergaderingen. Aisha, dank ook voor het oplossen van bureaucratische problemen.

Siham en Petra, het is een luxe dat het secretariaat altijd klaar staat om te helpen. Hiervoor wil ik jullie hartelijk bedanken.

De master studenten die ik begeleid heb. Berry, dank voor je hulp bij het inschatten van potentiëlen in Polen en de Baltische staten, dat een stuk complexer bleek dan we in hadden geschat. Thijs, de vaardigheid waarmee jij je modellen en software eigen maakt en problemen oplost zijn bijzonder. Dankzij jouw hulp hebben we een echte link kunnen maken tussen de modellen van Utrecht en INL. Daarnaast heb je mooi werk verzet bij het havenbedrijf Rotterdam.

Lieve vrienden, met uitzondering van wat afwezige aanwezige momenten, heb ik in jullie omgeving juist niet aan de inhoud van dit boekje gedacht en daarvoor wil ik jullie bedanken. Een mooi voorbeeld hiervan zijn de halfjaarlijkse resetmomenten tijdens wintersport en festivals met de 'usual suspects' Nilse, Aline, Peter, Anne, Merle, Roos, Thijs, Marian, Ber, Eric, en alle anderen. Koos, Liard, Ies, Mathijs, onze reizen zijn kleiner geworden in afstand, grootte en duur, maar het blijft leuk. Ike en Willem, jullie kijken kritisch naar het werk van onze vakgroep en zeker ook naar mijn werk; blijf dat doen. Chris, Yuki, Jules, Joseph and all others, thanks for the nice concerts and other events. Timon, samen met ons houd je het lang vol in de Buys Ballotstraat en beiden hebben we ons proefschrift hier 'overleefd'. De etentjes, borreltjes en voetbalwedstrijden hebben hier zeker positief aan bijgedragen. Heren4 en GUC, het is een slecht excuus, maar de gemiste wedstrijden zitten voor een deel in dit boekje.

In Lierop is het altijd heerlijk tot rust komen in de chaos en gezelligheid. Pap en mam, Vera en Rob, Erica en Bram, Jan en Rachel, Mara, Patrick, Floor en Lara, dank voor alles.

De familie Diek, Mirjam, Frits, Sanne, Wim en Goutje, Gé en Ineke, dank voor de morele support bij het schrijven van dit boekje.

Renske, met jou is alles gewoon veel leuker. Ik kijk uit naar onze toekomst.

Curriculum Vitae

Ric Hoefnagels was born on February 14th 1982 in Geldrop. In 2001, Ric started his higher education in Environmental studies at Avans Hogeschool in Breda and he obtained his degree as Bachelor of Applied Sciences in 2005. His BSc thesis dealt with the role of a regional environmental NGO (Brabantse Milieufederatie) in stimulating corporate social responsibility in small and medium enterprises. Ric started the master's program in Sustainable development (track Energy and Resources) at Utrecht University in September 2005. He was a visiting scholar at Carnegie Mellon University during his research on technological learning in power plants with and without carbon capture which is presented in his MSc thesis and in a scientific article. In March 2008, Ric received his Master of Science degree. From April 2008 Ric has been working as a junior researcher at the Energy and Resources group of the Copernicus Institute of Sustainable Development at Utrecht University. He has been involved in many bioenergy projects, including macro-economic effects of bioenergy and bio-based materials on a national level in the Netherlands and European and international projects on biomass potentials, trade and sustainability criteria of solid biomass. Furthermore, he has experience with greenhouse gas balances of biofuels, technological learning and CO_2 capture and storage. He has frequently worked for IEA Bioenergy Task 40, amongst others on the development of a comprehensive GIS-based logistic model to analyze intra-European biomass trade, in cooperation with Vienna University of Technology and intercontinental biomass logistics in cooperation with Idaho National Laboratory (INL). He has also been a member of multiple EU funded projects including Re-Shaping and Biobench. The results of several of these projects are presented in this thesis. After completing his doctoral work, Ric will continue to work at the Energy and Resources group as a postdoctoral researcher.

Peer-reviewed articles and contributions:

1. van den Broek, M., R. Hoefnagels, E. Rubin et al. (2009), Effects of technological learning on future cost and performance of power plants with CO2 capture. Progress in Energy and Combustion Science 35(6), pp.457-480.
2. Hoefnagels, R., E. Smeets & A. Faaij. (2010), Greenhouse gas footprints of different biofuel production systems. Renewable and Sustainable Energy Reviews 14(7), pp.1661-1694.
3. Strachan, N., R. Hoefnagels, A. Ramírez et al. (2011), CCS in the North Sea region: A comparison on the cost-effectiveness of storing CO2 in the Utsira formation at regional and national scales. International Journal of Greenhouse Gas Control 5(6), pp.1517-1532.
4. Hoefnagels, R., M. Banse, V. Dornburg et al. (2013), Macro-economic impact of large-scale deployment of biomass resources for energy and materials on a national level-A combined approach for the Netherlands. Energy Policy 59, pp.727-744.

(3 more articles are forthcoming, see chapters 4, 5 and 6)