APPENDIX I
BOTTOM-UP SCENARIOS

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PREFACE

The Bio-based Raw Materials Platform (known as PGG), which is part of the Energy Transition programme in the Netherlands, commissioned the Agricultural Economics Research Institute (LEI) and the Copernicus Institute at Utrecht University to conduct a study on the macro-economic impact of the large-scale deployment of biomass for energy and materials in the Netherlands. Two model approaches were applied based on a consistent set of scenario assumptions: a bottom-up study (part I) including techno-economic projections of fossil and bio-based conversion technologies and a top-down study (part II) including macro-economic modelling of the (global) trade of biomass and fossil resources.

This report (part I) presents scenarios for future biomass use for energy and materials, and analyses the consequences on energy supply, chemical productions, costs and greenhouse gas (GHG) emissions with a bottom-up approach. The bottom-up projections, as presented in this report, form the basis for modelling work using the top-down macro-economic model (LEITAP) to assess the economic impact of substituting fossil-based energy carriers with biomass in the Netherlands. The results of the macro-economic modelling work, and the linkage between the results of the bottom-up and top-down work, will be presented in the top-down economic part and synthesis report of this study.

1 EXECUTIVE SUMMARY

To quantify the potential macro-economic impact of the large-scale deployment of biomass in the Netherlands, four scenarios were developed with future projections focused on biomass for electricity generation, biofuel production and bio-based production of chemicals in the Netherlands. These scenarios were based on the WLO (Welfare and Environment) scenarios, but differ with respect to the deployment of biomass for bioenergy and bio-based materials and the related conversion technologies. The current use and techno-economic performance of conversion technologies in the baseline situation (2006), the future improvement potential as a result of technological change (learning), which differs per scenario, and the results of the scenario projections, will be used as input data for the top-down Computable General Equilibrium (CGE) model LEITAP, in order to quantify the impact of substituting fossil energy and fossil-based chemicals with bioenergy and bio-based chemicals.

Biomass use in the baseline situation

The production of bio-based electricity in the baseline year of this study (2006) amounted to 4.7 TWh, a share of 3.9% of the total electricity demand in the Netherlands. Electricity was mainly generated from biomass co-firing in Pulverised Coal (PC) plants, but also liquid biomass was used (palm oil) in gas-fired steam turbine plants (conventional gas). Note that electricity generation from palm oil was discontinued in 2007 due to sustainability issues, and was therefore excluded from this study. Biomass digestion and incineration of municipal solid organic waste also contributed to the share of bio-based electricity. The share of biofuels in the transport sector was marginal in 2006. On an energy basis, the bio-based share was 0.55% for petrol, by blending petrol with ETBE (ethyl tertiary butyl ether) and 0.35% for diesel. Their shares increased rapidly in 2007, to 2.74% and 3.24% respectively.

Although biomass is already a common feedstock for the production of chemicals, used for example in pharmaceuticals, but also in bulky products such as lactic acid or citric acid, it was not possible to quantify the current bio-based production share of chemicals in the Netherlands. In contrast to fossil-based energy carriers, biomass is not reported in statistics and quantitative data is often confidential.

Scenarios

In order to make future projections of biomass for bioenergy and bio-based materials to 2030 for the Netherlands, this study includes four scenarios. Emphasis in these scenarios is on technological development of (biomass) conversion technologies and international cooperation, including international trade of biomass. The two national scenarios include limited sources of biomass available from EU27+[1] countries. The two international scenarios include global biomass sources available for the Netherlands, such as palm oil and sugar cane. Other than

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[1] EU27 + Norway, Switzerland and Ukraine.

international cooperation, the two national and international scenarios include one scenario with low technological development and one with high technological development. For the low-tech scenarios (NatLowTech and IntLowTech) we assumed biomass conversion technologies to be used until 2030 that are already commercially available, while for the high-tech scenarios (NatHighTech and IntHighTech), we assumed that advanced (2nd-generation) technologies substitute current technologies from 2010 onwards. For the IntHighTech scenario, two projections are made. One is limited to replacing fossil-based synthesis gas with biomass, and one where all chemicals are replaced with a bio-based blending share of 25% as targeted by the PGG (IntHighTech AC).

Projections of socio-economic change and final energy demands were derived from the WLO scenarios. The amount of fossil energy that can be substituted by biomass depends mainly on costs and the supply of biomass, plus the techno-economic performance of biomass conversion technologies. The blending targets, i.e. the fossil energy fractions of fossil resources that can be replaced by biomass differ per scenario, and are limited by the combined performance of biomass conversion technologies and international resources of biomass feedstocks as shown in Table 1.

Table 1 Blending shares of biomass per scenario and sector (energy basis)

	NatLowTech		IntLowTech		NatHighTech		IntHighTech		IntHighTech AC	
Electricity (% energy output)										
2010	4%		4%		5%		5%		5%	
2020	6%		5%		9%		24%		20%	
2030	7%		6%		9%		29%		21%	
Transport fuels (% energy output)										
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 chemicals (% energy for raw materials in the chemical industry)										
	Bulk[a]	**Specialty[a]**	**Bulk[b]**	**Specialty**	**Bulk**	**Specialty[c]**	**Bulk[d]**	**Specialty[d]**	**Bulk[e]**	**Specialty[f]**
2010	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2020	N/A	N/A	4%	N/A	N/A	4%	9%	9%	13%	13%
2030	N/A	N/A	7%	N/A	N/A	7%	19%	19%	25%	25%

a) No bio-based chemicals in the NatLowTech 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).

For electricity generation, the share of biomass was estimated by taking into account the structure of the Dutch electricity sector. In the low-tech scenarios, retired PC plants and new required capacities are met by new PC plants with a higher biomass co-firing share (20%). In the High-Tech scenario, retired PC and

NGCC plants and new required capacities are met by NGCC plants with co-gasification of biomass. Blending shares of biomass for transport fuels in the IntLowTech and NatHighTech scenario were based on the EU's 2003 Biofuel Directive. The blending share of biomass in the NatLowTech scenario was assumed to be more conservative, with limited biomass sources and low production efficiencies. The shares in the IntHighTech scenario were based on the PGG targets for biomass in the transport sector, including global biomass resources and high production efficiencies. In this study, shares for biomass in the chemical industry were based on the substitution of chemical representatives, i.e. replacement of individual fossil-based chemical production routes per scenario. The IntLowTech scenario includes bio-based ethylene, the NatHighTech scenario includes bio-based caprolactam and the IntHighTech scenario includes bio-based synthesis gas. Please note that, although 100% of caprolactam was assumed to be replaced by biomass, the total share of bio-based production in the chemical industry will remain limited due to the production share of caprolactam in the chemical industry. In reality, a variety of chemicals will be substituted by biomass, instead of substitution of one single product completely, as assumed in the scenarios. In contrast to the IntHighTech scenario, the IntHighTech AC scenario includes all three chemical representative routes in order to substitute 25% of fossil raw materials in the chemical industry, as targeted by the PGG.

Conversion technologies

A selection of biomass conversion technologies was projected to be deployed in the scenarios in order to substitute fossil energy and fossil-based chemicals. The biomass conversion technologies in the scenarios differ on biomass feedstock types (availability of non-EU biomass in the international scenarios), technological development and availability. In all scenarios, wet organic waste and solid organic waste were assumed to be used for electricity generation by anaerobic digestion and incineration respectively.

The low-tech scenarios included technologies that are already used on a commercial scale. For electricity generation, biomass was assumed to be co-fired in PC plants, biopetrol and biodiesel were assumed to be produced from fermented sugar and starch crops, and transesterification of oil and fat residues and vegetable oils respectively. In the NatLowTech scenario, biodiesel and biopetrol were assumed to be made from EU rapeseed and EU starch respectively. In the IntLowTech scenario, imported sugar -cane-derived ethanol was assumed to be used for transport fuels and for ethylene production via ethanol dehydration. Imported palm oil and jatropha oil were the major feedstock for biodiesel production in this scenario. In the high-tech scenarios, advanced conversion options were assumed to be commercially available from 2010 onwards. Included were ethanol production from lignocellulosic biomass and synthesis gas production from biomass gasification. Synthesis gas was used for electricity generation (co-combustion in gas turbine combined cycle plants), biodiesel production via Fischer-Tropsch synthesis and for substitution of fossil-based synthesis gas in the chemical industry. The latter option was only assumed to be available in the IntHighTech scenario. In the NatHighTech scenario, bio-based caprolactam, a precursor for the production of nylon-6, was assumed to substitute fossil-based caprolactam from 2020 onwards.

Available biomass

In order to substitute the targeted shares of biomass in the different scenarios, large quantities of biomass are required. The total demand for biomass ranges from 150 PJ (NatLowTech), 300 PJ (IntLowTech), 400 PJ (NatHighTech), 1450 PJ (IntHighTech) and 1460 PJ (IntHighTech AC) in 2030. The national scenarios were restricted to EU27+ resources, while in the international scenarios, global biomass sources were assumed to be available.

Domestic biomass resources included primary residues (e.g. agricultural residues), secondary residues (e.g. sawdust) and tertiary residues (e.g. municipal solid waste) as well as dedicated energy crops. The total domestic availability of biomass for non-food purposes was estimated to be 390 PJ in 2030, of which 283 PJ were residues. Although this was sufficient to meet the total demand in the NatLowTech scenario and IntLowTech scenario, a large fraction of these residues are difficult to process or require extensive pre-treatment. Furthermore, a fraction of these residues is (and will be) used for processes not included in this study, such as heat production or material production other than chemicals (e.g. chipboard). We excluded solid organic waste streams in all scenarios and excluded the availability of agricultural residues in the low-tech scenarios. The total supply of biomass from domestic residues was therefore estimated to be ~100 PJ in the low-tech scenarios and ~225 PJ (including production grasses) in the high-tech scenarios. Estimated imports of biomass in 2030 range from 0-48 PJ (NatLowTech), to 1176-1230 PJ (IntHighTech AC), depending on whether domestic dedicated energy crop production is taken into account (max. 54 PJ in 2030).

Results and conclusions

The projected production of bio-based electricity, transport fuels and chemicals range from 74 PJ in the NatLowTech scenario to 680 PJ in the IntHighTech scenario (Figure 1). The avoided primary fossil energy ranges from 113 PJ in the NatLowTech scenario to 833 PJ in the IntHighTech scenario, as displayed in Figure 2. Note that the avoided primary energy is lower in the IntHighTech AC scenario, although more bio-based chemicals are produced. This can be explained by the higher share of bio-based electricity co-produced from synthesis gas production in the IntHighTech scenario.

Figure 1 Bioenergy and bio-based chemicals in the scenarios in 2030

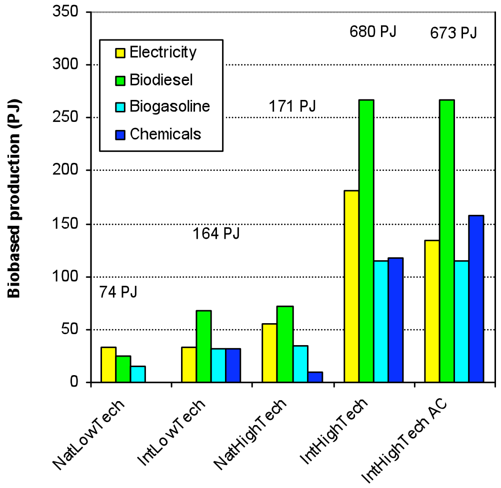
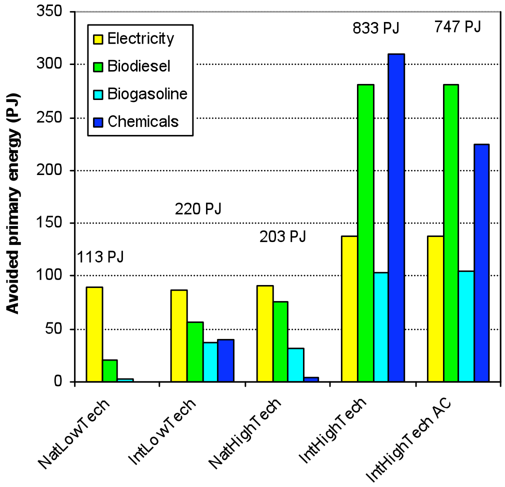


Figure 2 Avoided non-renewable primary energy by biomass in the scenarios in 2030



The greenhouse gas (GHG) emission reduction from substituting fossil energy with biomass ranges from 9 Mton CO_2 eq. in 2030 for the NatLowTech scenario to 56 Mton CO_2 eq. in the IntLowTech scenario. The total avoided GHG emissions in the IntLowTech scenario and NatHighTech scenario were almost identical (Figure 3), whereas the avoided GHG emissions in the IntHighTech AC scenario are slightly lower than in the IntHighTech scenario as a result of the better environmental performance of bio-based synthesis gas in combination with co-generated electricity rather than the replacement of petroleum products. Although advanced biodiesel production (FT-synthesis) improved the mitigation potential of transport fuels, there was little difference in the GHG mitigation performance of ethanol from sugar cane and lignocellulosic biomass[2]. Despite the use of more efficient electricity generation technologies (co-gasification), the difference in avoided GHG emissions for the IntLowTech and NatHighTech scenario was limited, because biomass replaced mainly carbon-intensive coal in the low-tech scenarios while (for the high-tech scenarios), relatively clean gas technologies were assumed to be replaced by biomass.

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[2] It should be noted though that the effect of indirect land-use change was not taken into account.

Figure 3 GHG emissions avoided per scenario in 2030

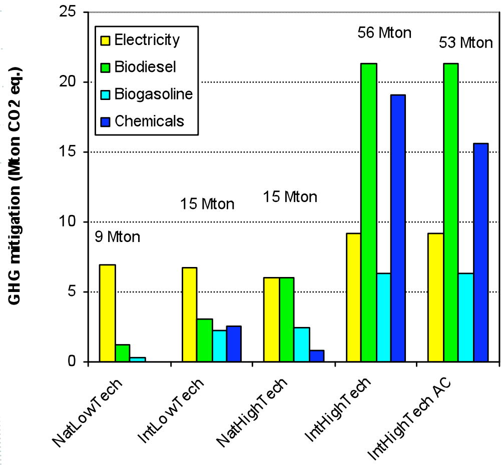
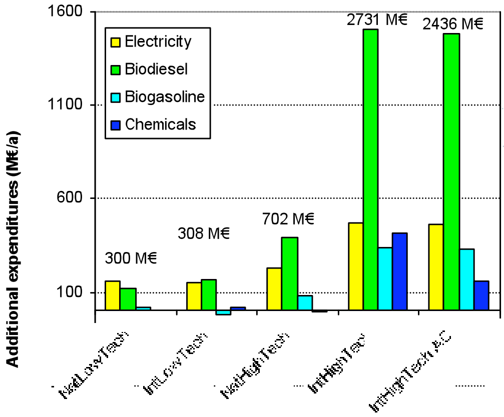


Figure 4 Additional cost for bio-based substitution in the scenarios in 2030. Oil price = 50 US\$/bbl, coal = 2 €/GJ, natural gas = 6 €/GJ



The total expenditures for bioenergy and bio-based chemicals range from 1,073 M€ in the NatLowTech scenario to 9,655 M€ in the IntHighTech AC scenario in 2030. Costs for biofuel production from vegetable oil and sugar/starch crops are dominated by feedstock costs as, especially for biodiesel from vegetable oil, few conversion processes are required to produce biodiesel. The additional costs for substituting fossil fuels with biomass depend on the difference between the fossil reference[3] technologies and the biomass substitutes and ranged from 300 M€ in the NatLowTech scenario to 2,731 M€ in the IntHighTech scenario (Figure 4).

GHG mitigation costs differ per scenario as a result of the different biomass conversion technologies used and their techno-economic performance. Mitigation costs are estimated to be 19 €/tonne $CO_{2\ eq.}$ In 2006, and increase to 35 €/tonne $CO_{2\ eq.}$ in the NatLowTech scenario in 2030. This increase is mainly the result of the poor mitigation performance of biodiesel from rapeseed and starch crops. Lower feedstock prices and the better GHG mitigation performances of biodiesel from palm oil and jatropha oil and ethanol from sugar cane result in mitigation costs of 21€/tonne $CO_{2\ eq.}$ in the IntLowTech scenario in 2030. The mitigation costs are highest in the high-tech scenarios, with 46 €/tonne $CO_{2\ eq.}$ for the NatHighTech and IntHighTech AC scenarios and 49 €/tonne $CO_{2\ e}$ for the IntHighTech scenario. The main reasons for the higher mitigation costs in the high-tech scenarios are better environmental performances of the reference technologies for electricity generation[4] and the use of advanced and capital-intensive conversion technologies.

[3] Oil price = 50 $US\$_{2006}$/bbl, Natural gas price = 6 €/GJ and coal price = 2 €/GJ.

[4] Biomass co-gasified in NGCC plants replaces natural gas with relatively low GHG emissions, while biomass replaces carbon-intensive coal in the low-tech scenarios.

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ABBREVIATIONS

BIG/CC	Biomass Integrated Gasification Combined Cycle plant
BTX	Benzene – Toluene – Xylenes
Capex	Capital Expenditures
CH4	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO2	Carbon Dioxide
ETBE	Ethyl-Tertiary-Butyl Ether
EtOH	Ethanol
EU27	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxemburg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden and the United Kingdom.
EU27+	EU27 + Norway, Switzerland and Ukraine
FAME	Fatty Acid Methyl Esther (biodiesel made from vegetable oil and methanol)
FCF	Fixed Charge Factor
FT	Fischer-Tropsch (synthesis of syngas to hydrocarbon chains like FT-diesel)
GDP	Gross Domestic Product
GJ	Giga Joule (10^^{9} Joule)
GHG	Greenhouse Gas
GTAP	Global Trade Analysis Project
GTCC	Gas Turbine Combined Cycle
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle plant
IPCC	Intergovernmental Panel on Climate Change
kWh	Kilowatt Hours
LA	Latin America
LCA	Life Cycle Assessment
MJ	Mega Joule (10^^{6} Joule)
MSW	Municipal Solid Waste
MWe	Megawatt electrical
MWh	Megawatt Hours
MWth	Megawatt thermal
N2O	Nitrous Oxide (laughing gas)
NGCC	Natural Gas Combined Cycle plant
NOx	Nitrogen Oxides
O&M	Operation & Maintenance
Opex	Operational Expenditures
RD&D	Research, Development and Demonstration
RME	Rapeseed Methyl Ester
PC	Pulverised Coal (plant)
PGG	Bio-based Raw Materials Platform
PJ	Peta Joule (10^^{15} Joule)
RDF	Refuse Derived Fuel
SRES	Special Report on Emissions Scenarios
TCR	Total Capital Requirement
TJ	Tera Joule (10^^{12} Joule)
TWh	Terawatt Hours
WLO	Welfare and Environment (Welvaart en Leefomgeving)
WOW	Wet Organic Waste

2 INTRODUCTION

The transition to a more sustainable energy system leading to a strongly reduced dependency on fossil fuels and significant greenhouse gas emission reductions is an unsurpassed challenge. In the Netherlands, this challenge is addressed by the ‘Energy Transition’ programme, in which stakeholder platforms have formulated strategies and pathways for different key themes in order to realise the required changes. One of the platforms deals with ‘Bio-based Raw Materials’ (Platform Groene Grondstoffen), which tackles the large-scale and sustainable use of biomass for energy and material applications. As a longer term vision, the platform has targeted 30% replacement of fossil fuels by biomass resources (assuming a stabilised energy use), divided over: 17% of the heating demand, 25% of electricity demand, 25% of feedstock use for chemicals and 60% of transport fuels.

Such proposed changes will require considerable investments in infrastructure and conversion capacity. In addition, the technologies that may facilitate such large-scale use of biomass partly require further development (including biomass production and supplies), which will need financial support. Another major implication is that such a strategy means a considerable shift in the use and production of primary energy carriers. Imported (coal, oil, natural gas) or indigenous (natural gas) fossil fuels are to be replaced by either imported biomass (e.g. as pre-treated material or biofuel) as well as indigenous biomass resources which are available (e.g. residues and waste streams) or can be produced (agriculture, algae). As a consequence, economic activity will shift to different sectors of the economy.

At the moment, actively produced biomass (especially via agricultural crops) is generally more expensive than the use of fossil fuels for producing energy. However, fossil fuel prices on the international markets are expected to continue increasing [IEA 2007], while there is substantial potential for reducing production and supply costs of biomass cropping systems.

Besides investments in infrastructure and technology development, a ‘bio-based strategy’ will also generate new economic activity. This is particularly true when biomass is produced within the Netherlands (compared to imports of fossil fuels). But also imported biomass, which is further processed in the Netherlands, may generate a higher added value to the national economy when compared to imported oil and natural gas. The latter require limited further processing compared to biorefineries, for example. If this could be realised, this can have very significant (positive) impacts on the trade balance of the country, given the large annual expenditures on imported energy (see also the Roadmap on Sustainable Biomass Import prepared for the PGG, [Faaij, 2006]. In addition, fossil energy prices are likely to continue rising in the medium to longer term [IEA 2006b; IEA 2007].

If the Netherlands can build and maintain a leading position in the relevant areas, other benefits include export opportunities for technology and knowledge, and reduced GHG emissions (with an equivalent value that may be determined by the international carbon market). The latter is inherently significant, given the projected role of biomass in replacing fossil fuels (30% of total fossil fuels replaced). Furthermore, developing biomass as a new key pillar of the (national) energy and material supply will increase diversity in the energy supply mix and could therefore contribute substantially to improved energy security. A more stable energy supply (in particular compared to international supplies of oil and natural gas) also has a positive impact on (macro-) economic development.

With respect to the use of biomaterials, new biochemicals in particular may also lead to considerable (energy) savings in the production chain, as highlighted by [Sanders et al., 2006] and [Bruggink, 2006], as outlined for the Bio-based Raw Materials Platform. Such indirect savings and potentially higher value chemicals, will contribute positively to economic growth. Another opportunity for the Netherlands may lay in a strengthened role as a logistic hub for Europe in the bio-based arena, as such developments will also take place throughout the rest of Europe.

However, the real (net) impact of building a large bio-based industry in the Netherlands over the coming 3-4 decades will largely depend on the cost developments of key biomass conversion technologies (such as biorefinery concepts, 2nd-generation biofuel production technology and advanced power generation) and the prices at which biomass resources can be made available. These costs will then be evaluated against the (relative) future costs of fossil fuels (most notably oil and gas), which are also uncertain (although likely to follow an upward trend for the coming decades). Other economic factors, such as growth rate, sectoral change in the (national) economy, prices for CO_2 and agricultural policies (subsidies and prices) are also variables. Determining the economic value of a bio-based strategy for the Netherlands must therefore also keep these uncertainties in mind. With improved understanding of the mechanisms and uncertainties, more targeted policies and implementation strategies can be devised, which are fundamentally important for both the market and the government. Such information allows for optimising the (economic) benefits and minimising the risks (costs) of implementation and development of a bio-based infrastructure and relevant sectors. This justifies a full-blown analysis of these matters. Remarkably, to date, such analyses are very rare.

2.1 Objective

The overall objective of this study is therefore:
To provide quantitative insights into the macro-economic impacts of the large-scale deployment of biomass-based resources and related infrastructure and production capacity for the energy and material supply.

Part I of this report includes the following sub-objectives:

- Quantitative descriptions of scenarios for biomass use in the Netherlands in 2010 to 2030, under different premises of technological development and biomass trade. These descriptions include biomass resource availability, production and costs, main conversion options for energy and materials and are relative to a baseline scenario.
- A description of the impact of biomass use in the scenarios with regard to biomass use for energy and materials, fossil primary energy saving, total costs and net costs, and GHG emission reduction. These impacts are calculated using bottom-up information on technologies for biomass production and use, while taking future technological learning into account.

These results are used in part II of the study to estimate the macro-economic impact of the large-scale deployment of biomass in the Netherlands by adapting the bio-based scenarios in the GTAP-based model LEITAP.

2.2 Methodology

The following research activities and methods were used for part I of the report:

- Creation of the baseline situation, i.e. the current use of biomass for bioenergy and bio-based materials, and prognoses for the short term. In order to quantify the current use of biomass, various reports [Sikkema et al., 2007; SenterNovem, 2008] and statistics [CBS, 2008a] were used.
- Development of four scenarios with emphasis on technological development and international cooperation. These scenarios are based on the existing scenarios Welfare and Environment (WLO) for the Netherlands and are consistent with the international SRES (Special Report on Emission Scenarios) from the IPCC;
- Identification and data collection on the cost and performance of biomass conversion technologies, commercialisation dates of new technologies and the future improvements of these technologies by technological learning;
- Inventory of available biomass for the Netherlands including domestic availability from PGG studies and international resources based on state-of-the-art projections;
- Determination of the cost and environmental performance (GHG mitigation and avoided primary energy use) using life-cycle assessment data for biomass from available literature.

2.3 Outline

The structure of this report is as follows. Section 2 describes the baseline situation (2006) for the consumption of fossil energy carriers and biomass, the current structure of the electricity generation sector, chemical industry and fuel production and planned changes in the short term. Section 3 describes the four scenarios developed for this study (NatLowTech, IntLowTech, NatHighTech and IntHighTech) and the socio-economic and technological development in these scenarios. This section focuses on projected developments in energy requirements for electricity, transport fuels and chemicals, and the technologies available to substitute fossil energy with biomass. Section 4 describes the technologies and their techno-economic performance over the projected period (from 2006 to 2030) for the different scenarios. Section 5 describes the demand for biomass as a result of the assumed substitution targets and conversion performance as described in sections 3 and 4 respectively. Section 6 describes the economic performance and greenhouse gas mitigation potential of the different scenarios, plus the related costs, followed by the results (8), discussion (9) and conclusions (10).

3 BASELINE SITUATION

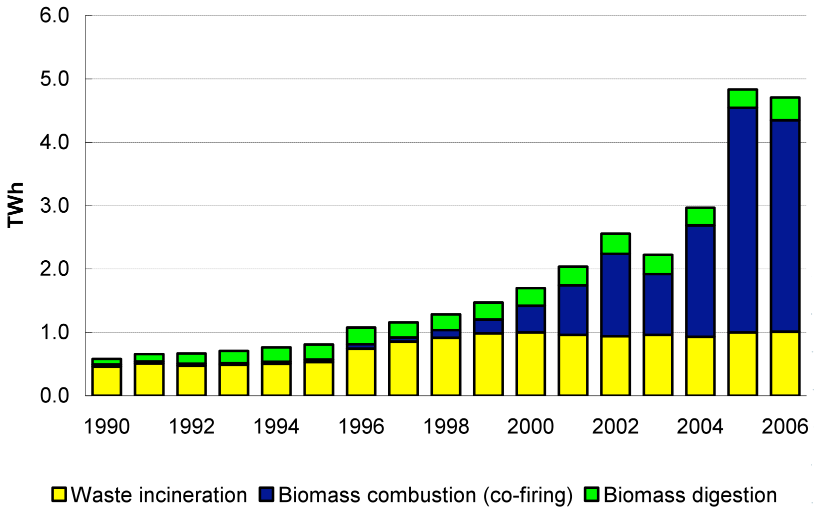
This section describes the current status of (bio-) energy in the Netherlands based on data from literature and databases [Sikkema, Junginger et al., 2007; ECN, 2008; SenterNovem, 2008; 2008a]. This data is used for the baseline situation (2006) of the scenarios, but also for the short-term projections (2010).

Sections 3.1 and 3.2 start with the current (2006) situation for bio-based electricity and heat generation respectively, and the structure of the electricity generation sector in the Netherlands. Section 3.3 describes the production of biofuels for road transport, followed by a description of the chemical industry relating to bio-energy in section 3.4.

3.1 Electricity

The production of electricity from biomass resources in the Netherlands is dominated by co-firing in coal and gas-fired power plants (Figure 5), but also waste incineration and digestion of wet organic waste from manure or sewage treatment sludge are being used to generate electricity and heat.

Figure 5 Electricity generation from biomass (ECN 2008)



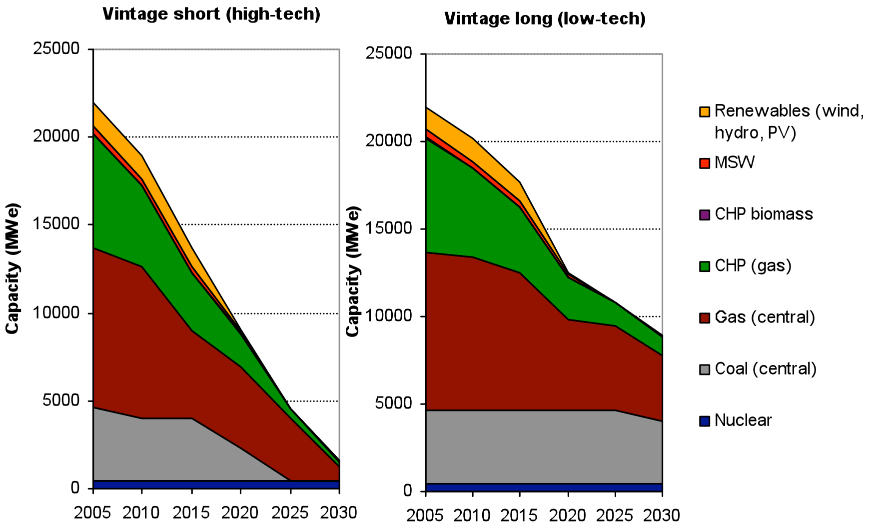
Electricity generation by co-firing in coal-fired power plants decreased by 3.5% between 2005 and 2006 as a result of the freezing of the MEP subsidy [SenterNovem, 2008]. The new subsidy scheme (SDE) and the planned capacity additions of coal-fired power plants [Seebregts, 2007] is expected to result in an increasing share of co-firing biomass in the electricity generation sector from 2008 onwards. In gas-fired conventional power plants with a gas-fired steam turbine, palm oil was used until 2007 but, as a result of sustainability issues, palm oil is no longer used for electricity generation in the Netherlands. We do not consider that this option will become available again in the future.

The production of small-scale decentralised biomass-fuelled CHP plants has increased rapidly over the last five years [SenterNovem, 2008]. At the end of 2006, the total capacity of small-scale CHP plants (<10 MWe) amounted to 66 MWe. The majority of these plants are co-digestion plants using manure and co-products (e.g. agricultural residues and corn) and producing heat and electricity. Larger plants, including those for the combustion of chicken manure, are also being deployed [Sikkema, Junginger et al., 2007].

3.1.1 Structure of the Dutch electricity park

The installed capacity of power generation technologies, including renewables such as wind, biomass, PV (photovoltaics) and hydro, was almost 22 GWe in 2005. To estimate when these plants need to be replaced, vintage data is required of the installed capacities. We used data from [Van den Broek et al., 2008] as shown in Figure 6. They assumed a short and long vintage construction for the lifetimes of existing power generation technologies in the Netherlands. In the low-tech scenarios, a lifetime of 40 years for gas-fired power plants and 50 years for coal-fired power plants is assumed (vintage long). In the high-tech scenarios, the lifetime of both coal and gas-fired power plants is 30 years (vintage short). This implies that in the high-tech scenarios, all coal-fired plants need to be replaced, while in the low-tech scenarios, only one coal-fired power unit of 645 MWe has to be replaced before 2030. Replacement capacities, additional capacity requirements and technologies available differ per scenario (section 4.2.1).

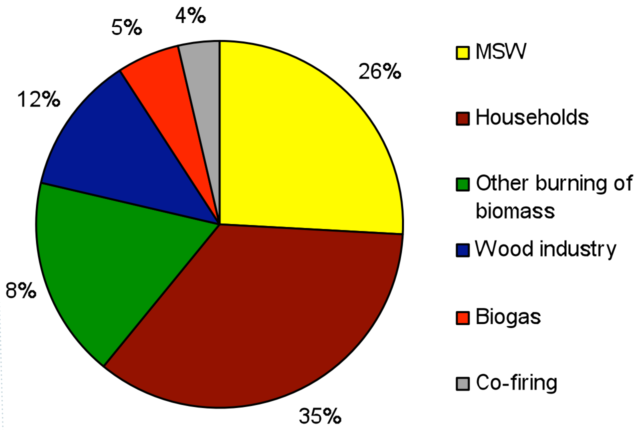
Figure 6 Vintage structure of the Dutch electricity sector [Van den Broek, Faaij et al., 2008]
Renewables include renewable technologies other than biomass (wind, hydro and PV).



3.2 Heat

The production of heat from biomass in 2006 was approximately 14.8 PJ [Sikkema, Junginger et al., 2007], mainly from stoves to heat houses (5.1 PJ)[5] and heat generation from incineration of waste (3.8 PJ) (Figure 7). The total avoided primary fossil energy was 16.9 PJ in 2006 [CBS 2008b].

Figure 7 Heat generation from biomass in 2006 [Sikkema, Junginger et al., 2007]



Although difficult to quantify, the amount of heat generated from biomass in households was fairly constant. Heat generated from biomass in industries increased by 10% in 2006.

This study does not include a detailed review of current and projected heat from biomass as it is not included as a commodity in the top-down model. Nevertheless, cogeneration of heat in waste incineration plants and biomass digestion plants is taken into account to estimate the avoided primary fossil energy and GHG emissions in the bottom-up scenarios.

3.3 Biofuels

Before 2006 hardly any biofuels were used and produced in the Netherlands, but from 2006 onwards, the share of biofuels used in the Netherlands increased rapidly (Table 2). The increasing share of biofuels results from the implementation of the European Directive 2003/30/EG[6] in the 'Besluit biobrandstoffen wegverkeer 2007' (Transport Biofuels Act 2007). This directive requires a blending fraction of 2% (energy basis) to be blended biofuel (in 2007), increasing to 5.57% in 2010. A fraction of 3.5% of petrol and 3.5% (energy basis) of diesel is restricted to be replaced by biofuel, while the remaining fraction can be allocated by choice. For 2020, the

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[5] Heat produced from biomass in house holdings is estimated based on the amount of stoves in the Netherlands, the heating capacity and corrected for degree days in the Netherlands.

[6] http://ec.europa.eu/energy/res/legislation/doc/biofuels/en_final.pdf

European Commission has proposed a more stringent target of 10% biofuels[7] [SenterNovem, 2008]. Please note that during the writing of this report, these blending targets were the subject of debate and new draft targets have recently been adopted by the European Parliament[8]. The 10% blending target for 2020 is maintained, but an interim target of 5% is now set for 2015, of which 1% has to come from non-food or feed fuels (2nd-generation). Furthermore, the 10% target does not have to be met by biofuels alone, but also includes renewable sources such as hydrogen and green electricity. These policy targets could stimulate the introduction of electric vehicles, which would lower the demand for liquid transport fuels. These recent developments are not taken into account in this study.

Table 2 Total biofuels sold in the Netherlands [CBS, 2008]

	2003		2004		2005		2006		2007**	
	TJ	%*	TJ	%*	TJ	%*	TJ	%*	TJ	%*
Biopetrol	0	0	0	0	0	0	1010	0.55	3687	2
Biodiesel	134	0.05	134	0.05	101	0.04	968	0.35	9233	3.24
Total	134	0.03	134	0.03	101	0.02	1979	0.43	12920	2.75

*) fraction of total fuel on an energy basis.
**) first estimates by CBS

3.3.1 Ethanol

Ethanol is not blended with petrol directly, but is converted into ETBE[9] as a substitute for MTBE in petrol. According to [SenterNovem, 2008], ETBE from bio-based ethanol is produced by two companies in the Netherlands, but there is no report of capacities or the source of ethanol for these plants. According to FO Lichts [FO Lichts, 2008], fuel ethanol is made entirely from grain starch in the Netherlands. It is not reported whether or not ethanol or grain starch are imported.

The production capacity of ethanol in the Netherlands is under expansion, with plans for two large units with a total capacity of 700 mln l/a of ethanol (~14.6 PJ_{lhv}/a). These units are planned to be operational before 2010[10]. One unit (Nedalco, 220 mln l/a) will use cellulose material (by-products from the food industry and wood). The other unit (Abengoa, 480 mln l/a) will use grain (starch) as feedstock and will also produce by-products for the food/feed industry [Port of Rotterdam, 2008]. Several smaller projects for ethanol production are also under development, but no figures are given in the literature [Sikkema, Junginger et al., 2007].

[7] http://eur-lex.europa.eu/LexUriServ/site/en/com/2007/com2007_0001en01.pdf

[8] http://ec.europa.eu/energy/strategies/2008/doc/2008_01_climate_action/2008_0609_en.pdf

[9] Ethyl tert-butyl ether, a substitute for methanol derived MTBE (methyl tert-butyl ether), a petrol additive [Hamelinck, 2005].

[10] Please note that recent changes in biofuel policies will affect the realisation of the planned new biofuel production capacities.

Based on the data available, we estimate that ethanol for biofuel is currently produced from grain starch [FO Lichts, 2008]. Although ethanol is also produced from by-products (e.g. molasses) and from fossils (based on ethylene) in the Netherlands, we assume this to be used for ethanol in the food and chemical industries respectively. We have no figures concerning shares of domestic or international production of ethanol feedstocks, although it is reported that wheat is produced for biofuels in the Netherlands (e.g. in the province of Zeeland) [Rabou et al., 2006].

3.3.2 Biodiesel

The production of biodiesel in the Netherlands (from four units) was estimated to be 220 mln l/a in 2007. In addition, 39 mln l/a of PPO[11] was also processed in the Netherlands [SenterNovem, 2008]. The MVO [Product board MVO, 2008] estimated the current capacity of biodiesel production to be 300 kton/a (around 270 mln l/a). The capacity for rapeseed processing is relatively small (4-12 kton/a).

Six additional biodiesel production units are planned to be operational in 2008/9. The total added capacity is estimated to be 1.6 bln l/a [SenterNovem, 2008] to 2.0 bln l/a [Product board MVO, 2008]. The feedstock for biodiesel production ranges from residues (animal fats and used frying oil) to energy crops (soya and rapeseed oil). Most of the new planned units can process multiple feedstocks and are located close to the seaports, because the majority of biomass resources for biodiesel production are going to be imported to the Netherlands [Janssens et al., 2005].

Rapeseed is produced in the Netherlands in Groningen, Achterhoek and Limburg [Rabou et al., 2006], though current production capacities are not reported. The net import of rapeseed increased from 37.1 kton in 2005 to 62.6 kton in 2006. During the first half of 2007, 142.6 kton of rapeseed was imported to the Netherlands [Product board MVO, 2008]. It is not known whether rapeseed or crude rapeseed oil was imported.

3.3.3 Biofuel production

Statistical data on biofuel consumption in the Netherlands is available from CBS [CBS, 2008], but production data (i.e. domestic production or imports, feedstock etc.) is limited. We have therefore made some assumptions based on the available literature as described in sections 3.3.1and 3.3.2, as displayed in Table 3.

The total production capacity of biofuels, is estimated to be 1,860 mln l for biodiesel and 740 mln l for ethanol before 2010, if assumed that the biofuels used in 2006 are produced in the Netherlands. We assume these capacities to be commissioned in 2010.

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[11] Pure Plant Oil (PPO) can be used in modified diesel engines, but has to be processed (transesterification) for conventional diesel engines. The market potential for PPO is therefore limited.

Table 3 Current production of biofuels and required inputs

	Type	Feedstock				Production			
		TJ[1]		kton (fw)		TJ[1]		kton	
		2006	2007	2006	2007	2006	2007	2006	2007
Ethanol		2077	7583	119	436	1010	3687	34	124
Ethanol from grain starch	Grain	2077	7583	119	436	1010	3687	34	124
Biodiesel		968	9233	26	250	968	9233	26	248
RME	Crude rapeseed oil[2]	688	6212	19	168	688	6212	18	167
Residues (oil and fat)[3]	Used frying oil/ animal fat	280	3021	8	82	280	3021	8	81

1) TJ lhv
2) We assumed all biodiesel from energy crops to be rapeseed
3) We assumed that 8 kton biodiesel was produced from frying oil in 2006 and 81 kton in 2007, based on capacities of biodiesel production plants from MVO (2008).

3.4 Chemicals

Apart from energy, fossil fuels are also used as feedstock for the production of materials. The so-called non-energetic use of fossil energy carriers was 579 PJ in 2006, of which 552 PJ was used in the industrial sector (Table 5). Note that this is almost 50% of the total demand for fossil energy in the industrial sectors. The remaining fraction was mainly used for bitumen for asphalt [Rabou, Deurwaarder et al., 2006]. Biomass is already used on a large scale as feedstock for the production of materials (e.g. paper, timber), but these are not reported in the statistics. Current use of biomass in the chemical industry includes the production of pharmaceuticals (for example), but also bulky products such as citric acid and lactic acid [Patel et al., 2006]. There is no quantitative data on the deployment of biomass in the chemical industry for reasons of confidentiality, especially at a national level [Nowicki et al., 2008].

Table 4 Energetic and non-energetic use of energy in the industry in the Netherlands in 2006 (from [Rabou, Deurwaarder et al., 2006], updated to 2006 [CBS, 2008a]

Industry branch	Natural gas	Petroleum products	Coal, and coal products	Electricity	Others	Total
	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]
Fertiliser	91	0	0	2	2	94
Organic base chemistry	33	450	4	11	46	545
Base chemistry + fibres	39	3	0	10	17	70
Other anor. base chemistry	9	19	4	11	7	50
Chemical end products	9	1	0	4	1	15
Glass, ceramics, cement	23	1	1	5	2	32
Base ferro metal (steal)	12	0	95	9	0	116
Base non-ferro metal	4	3	0	21	1	29
Metal products	18	16	0	16	1	50
Others	101	9	1	39	13	163
Total chem. industry	182	473	8	39	73	774
Total	**339**	**502**	**106**	**128**	**90**	**1164**

The non-energetic use of fossil energy carriers includes natural gas, petroleum products, coal and coal products (e.g. coke) and electricity. Natural gas is mainly used as feedstock for the production of ammonia for fertiliser production. Other purposes include hydrogen and carbon monoxide (CO). The latter is used to produce chemicals such as alcohols or acetic acid [Neelis et al., 2003]. Petroleum products, the main feedstock for fossil-based materials, consists of a wide range of chemical feedstocks produced from crude oil in refineries (e.g. bitumen, BTX, and lubricants) and converted into base chemicals in the organic base chemical industry [Neelis, Patel et al., 2003]. Base chemicals such as ethylene are further processed into a range of intermediates and products such as plastics and fibres. Coal is mainly used in the ferrous-metal industry. Non-energetic use of electricity includes mainly electrolysis and galvanisation processes in the non-ferro metal industries.

Table 5 **Final non-energy use of fossil resources in the Netherlands in 2006 (from Deurwaarder et al., 2006], updated to 2006 [CBS 2008a]. The percentages in the right column show the non-energetic use of fossil energy as a fraction of total energy consumption per sector (Table 4).**

Industry branch	Natural gas	Petroleum products	Coal, and coal products	Electricity	Total	Share total energy
	[PJ]	[PJ]	[PJ]	[PJ]	[PJ]	%
Fertiliser	65	0	0	0	65	69%
Organic base chemistry	4	342	2	0	348	64%
Base chemistry + fibres	16	3	0	0	18	26%
Other anor. base chemistry	1	11	2	9	23	46%
Chemical end products	0	1	0	0	1	7%
Glass, ceramics, cement	0	0	0	0	0	0%
Base ferro metal (steel)	0	0	52	0	52	45%
Base non-ferro metal	0	3	0	18	21	72%
Metal products	0	16	0	0	16	31%
Others	0	8	0	0	8	5%
Total chem. industry	86	356	4	9	455	59%
Total	**86**	**382**	**57**	**27**	**552**	**47%**

The non-energetic energy consumption increased substantially, from 493 PJ in 2000 to 579 PJ in 2006, mainly as a result of increased petroleum consumption in the organic base industry (250 PJ in 2000, but 342 PJ in 2006). The non-energetic consumption of natural gas in the organic base industry, mainly used for methanol production, decreased from 15 PJ in 2000 to 3.7 PJ in 2006. The domestic production of methanol in the Netherlands was abandoned in 2005 as it could no longer compete with methanol produced at locations with cheaper natural gas sources available. The factory in Delfzijl is now being converted to produce biomethanol from glycerine, in combination with natural gas (1 mln ton in 2011) [Econcern, 2006]. Glycerine is a by-product from the transesterification process of biodiesel production from vegetable oil.

This study focuses on the substitution of fossil energy carriers in the chemical industry, i.e. the grey shaded rows in Table 4 and Table 5. We thereby exclude the substitution of coal and electricity used in the metal industries. Rabou et al. [2006] estimates that around 33 PJ[12] of cokes can potentially be substituted by charcoal in the ferrous-metal industry.

For the substitution of natural gas, our focus is on the production of synthesis gas produced from natural gas for the production of hydrogen for fertilisers and methanol for base chemicals (section 3.4.2). For the replacement of petroleum products, we choose ethylene as representative route, as it is the dominant intermediate in the organic base chemistry (section 3.4.1) and caprolactam as being representative of functionalised chemicals. Caprolactam is an important feedstock for the production of nylon-6 (section 3.4.3). Fossil-substitution options for non-energy in sectors other than chemicals are not taken into account in this study.

3.4.1 Base C2 chemicals (ethylene)

Ethylene is used for the production of plastics, fibres and other organic chemicals and, on a volume basis, it is one of the largest produced petrochemicals in the world (110 mln ton in 2006) [SRI Consulting, 2008]. The total production capacity of ethylene in the Netherlands increased from 3.1 Mton in 1999 to 3.7 Mton in 2002 [Neelis, Patel et al., 2003; Neelis 2006]. The actual production rate of ethylene was 2.7 Mton in 2002 and, although the production of ethylene has a annual growth rate of 5.7% between 2006 and 2011, this production growth comes mainly from the Middle-East, China and other Asian countries and Oceania [Devanney, 2007]. Therefore we assumed a moderate growth in the production of ethylene, similar to the annual growth rate of non-energetic consumption of petroleum products in the chemical industry between 2000 and 2006 in the Netherlands (1%) to increase ethylene production to 2.9 Mton in 2006.

In the Netherlands, ethylene is mainly produced by the ‘steam cracking’ of naphtha (83%), but ethylene is also produced from steam cracking of gaseous fossil fuels such as propane and ethane [Neelis, 2006]. Contract prices of ethylene in Europe were 945 €/Mton in 2008 [Weddle, 2008], but are volatile as a result of dominating feedstock prices (mainly naphtha from crude oil). No commercial bio-based production of ethylene takes place in the Netherlands, as yet. A linear relation between crude oil prices and the price of ethylene was found by Meesters et al. [2006]. At a crude oil price of 50 US$/bbl, the costs of ethylene are estimated to be 679 €/tonne.

3.4.2 Base C1 chemicals (synthesis gas)

Although synthesis gas can be used as feedstock for a wide range of products and chemicals, it is mainly used for the production of ammonia, methanol, hydrogen and carbon monoxide. Carbon monoxide is used for the production of acetic acid, polycarbonates and alcohols [Neelis, Patel et al., 2003]. Synthesis gas is produced from natural gas in the Netherlands.

[12] Based on a projected coke consumption of 65 PJ in 2030 and a bio-based share of 50% in the base ferrous-metal sector.

The non-energetic energy use of natural gas in the Netherlands for 2006 is given in Table 5. In total 86 PJ of natural gas was used in 2006 for non-energy purposes (of which 76% can be allocated to the production of fertilisers, mainly for the production of ammonia from hydrogen and nitrogen. The second largest fraction of natural gas use for non-energetic purposes is the base chemistry + fibres (18%), e.g. production of polyurethane, polyamide etc. Bio-based production of synthesis gas for any purpose (e.g. biofuel, electricity or chemicals) is still at the demonstration phase and not yet competitive with fossil-based synthesis gas.

3.4.3 Functionalised chemicals (caprolactam)

Caprolactam is mainly used as monomer for the production of nylon-6 fibres and resins. In the Netherlands, caprolactam is produced via hydration of phenol, but other production routes also exist (butadiene, cyclohexane and toluene). The production of fossil-based caprolactam was 189 kton/yr in the Netherlands in 2000 [Neelis, 2006]. International prices for caprolactam range from 1910-1955 euro/tonne in 2007 [Meehan, 2008]. The bio-based production route of caprolactam is still at the development stage [Patel, Crank et al., 2006].

The production of caprolactam in the Netherlands was 189 kton in 2000 (section 3.4.3) and is expected to increase due to the growing production of nylon fibres and increasing demands from Asia. China, Taiwan and the Republic of Korea are main importers of caprolactam [Tefera, 2006]. We estimate the production for 2006 to be 222 kton[13].

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[13] Based on an annual growth rate of the non-energetic consumption of fossils of 2.72% between 2000 and 2006 in the Netherlands. This is consistent with the global annual growth of caprolactam production of 2.9% between 2005 and 2010 [Tefera, 2006].

4 SCENARIOS

To estimate the future potential of biomass for energy and chemicals, we need projections of the development of energy demand, mobility (transport fuels) and development of the chemical industry sector in the Netherlands. We based our projections on the WLO scenarios (welfare, prosperity and quality of the living environment) that project futures for the Netherlands within the IPCC SRES scenario framework [MNP et al., 2004].

This section covers the description of the four scenarios (NatLowTech, IntLowTech, NatHighTech and IntHighTech / IntHighTech AC) that are used for this study, the modifications to the WLO scenarios and specific assumptions in relation to (bio-) energy made for this study. Section 4.1 starts with the general storylines, section 4.2 describes the projected demand for energy, the shares of biomass in the different scenarios and the assumed conversion technologies available. Section 4.3 summarises the assumptions made for the four scenarios. The results of the WLO scenarios are not repeated here, but are summarised in Appendix 1.

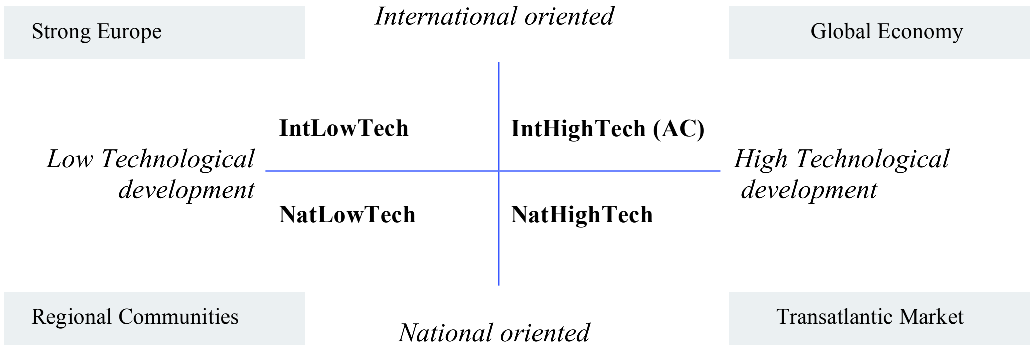
4.1 General Storylines

The WLO study explores the long-term (2040) future of the Netherlands within the (international) context of political, economic and demographic changes. Four scenarios were made for the WLO study, with different considerations of economic growth, technology development, international relations and trade, (international) policies and demography. These scenarios are consistent with the IPCC SRES scenarios (A1, A2, B1 and B2) on international cooperation and economic or environmental orientation. These scenarios are: Global Economy (SRES-A1), Strong Europe (SRES-B1), Transatlantic Market (SRES-A2) and Regional Communities (SRES-B2).

The emphasis in this study is on technological development and market orientation (international or national). These two factors are the main determining factors for the production potential and cost of bioenergy and bio-based chemicals in the Netherlands. The four scenarios in this study are based on these two dimensions for technological development and international cooperation as displayed in Figure 8. The grey-shaded areas show the WLO scenarios and their relation to the scenarios in this study. In addition, two projections are made with the IntHighTech scenario. One with bio-based synthesis gas as chemical representative and one with all chemicals (AC) included to reach a blending target for bio-based raw materials of 25%, consistent with the PGG targets [Rabou, Deurwaarder et al., 2006].

Figure 8 Four scenarios for bioenergy in the Netherlands, 2010 – 2030

The WLO scenarios are displayed in the grey-shaded areas.



The scenarios that include low technological development include technologies that are already commercialised, with limited learning potential in terms of cost reductions and efficiency improvement. The scenarios with high technological development include high economic growth, with large investments in biomass technologies. High-tech options such as 2nd-generation biofuels and gasification become available for biomass conversion in the medium term (> 2010).

In the national scenarios, trade is assumed to be focused in and between European countries (EU27+). This limits the availability of biomass for the Netherlands to sources from the EU27+ in the national scenarios. However, the international scenarios assume a global market for biomass trade. Biomass and biofuels produced at favourable locations, such as ethanol produced from sugar cane in Brazil, becomes available in these scenarios. This lowers the cost of bioenergy and bio-based chemicals and increases the potential as more resources are available.

Detailed assumptions on technological development, bioenergy policies and biomass options for the electricity, transport fuels and chemicals are covered in the following sections.

4.2 Energy demand and bio-energy targets

4.2.1 Electricity

The scenarios for electricity generation are based on projections from the WLO study [Janssen et al., 2006]. The projections for electricity generation per technology are displayed in Figure 9. We made similar assumptions to the WLO scenarios with respect to electricity generation from nuclear power plants and renewables other than biomass (wind, PV and hydro).

In the NatLowTech scenario, the projected capacities of coal and gas-fired power plants for central electricity generation are similar to the WLO scenarios, though some adjustments were made for the IntLowTech scenario[14]. For the high-tech scenarios, we assumed that coal and gas-fired power plants for central electricity generation are replaced by NGCC plants[15] with co-gasification and co-generation of electricity from 2nd-generation biofuel production plants. The shares of central (PC and NGCC plants) and decentralised (e.g. CHP plants) electricity generation and the total final demand of electricity are the same as the WLO projections. The replacement rate for aged capacities is based on the vintage structure by Van den Broek, Faaij et al., [2008] as shown in Figure 6.

In the low-tech scenarios, biomass is used for electricity generation in waste incineration plants (MSW), biomass digestion plants (wet organic residues) and PC plants (co-firing). In the high-tech scenarios, electricity generation from BIG/CC plants (by-products from biofuel production) and co-gasification in NGCC plants are also available.

4.2.1.1 Low-Tech

The development of the electricity generation sector in the low-tech scenario is based on the assumption that current available technologies will improve due to technological learning, but new technologies for power generation will not become available before 2030. The production of electricity from biomass in the NatLowTech scenario is therefore dominated by co-firing in coal-fired power plants (Figure 9), digestion of liquid organic waste and MSW incineration. The performance and cost of biomass conversion into electricity in the low-tech scenarios is presented in Table 11.

We assume that existing PC plants will be fuelled with 10% biomass on a fuel-input basis. This is the maximum fraction of biomass for conventional PC plants. If a higher fraction of biomass is used, additional adjustments are required to the power plant [IEA, 2006a].

For new coal-fired power plants, we assume that pulverised coal plants will be deployed with 20% of biomass co-firing. The projected new coal-fired capacities for the low-tech scenarios are based on projections from the WLO scenarios and prognoses for the short term. Note that shares ranging from 30-60% of biomass co-firing are also reported for new planned coal-fired capacities [Seebregts, 2007].

[14] In the Strong Europe scenario, no new coal-fired capacities are assumed to be deployed until 2020. With the current knowledge that at least one coal-fired power plant will be online before 2015, we substituted 1200 MWe natural gas capacity projected in the WLO-SE scenario by coal-fired capacity in 2020 and used this projection for the IntLowTech scenario.

[15] In the WLO scenarios, both coal and gas-fired power plants are assumed to be deployed. For this study, we substituted the new coal capacities for gas-fired capacities for the NatHighTech and IntHighTech scenarios.

4.2.1.2 High-Tech

Electricity generation in the high-tech scenarios is different from the low-tech scenarios. The lifetime for existing coal and gas capacities is assumed to be 30 years and therefore, more units have to be replaced before 2030. The electricity demand is also higher in the high-tech scenarios as projected by [Janssen, Okker et al., 2006].

For the high-tech scenarios, we assumed biomass gasification plants to be commercially available from 2015 onwards. We assumed that this technology is used for electricity generation from by-products of FT-diesel and ethanol production (2nd-generation) with a BIG/CC plant. Furthermore, we assumed that gas and coal-fired plants will be replaced by NGCC plants with co-gasification of biomass. The share of biomass is fixed to 25% of the fuel input (section 5.1.4). The main advantages of this technology are its high efficiency and low emissions relative to coal-fired power plants.

For the national scenario, we assume that 50% of new NGCC plants will be deployed with co-gasification of biomass. In the high-tech scenario, with the availability of lower priced woody biomass, we assume that all plants will be deployed with co-gasification of biomass.

4.2.1.3 Biomass shares for electricity generation

Figure 9 summarises the electricity generation mix for the four scenarios in the Netherlands. These projections are similar to the WLO scenarios for the total demand of electricity, the shares of nuclear power and renewables other than biomass (wind, PV and hydro), the shares of central and decentralised power generation and the amount of CHP. The share of biomass in the electricity generation mix and the amount of coal and natural gas-fired central power plants are modelled for this study as described above. The resulting shares of biomass for electricity generation in each scenario are shown in Table 6.

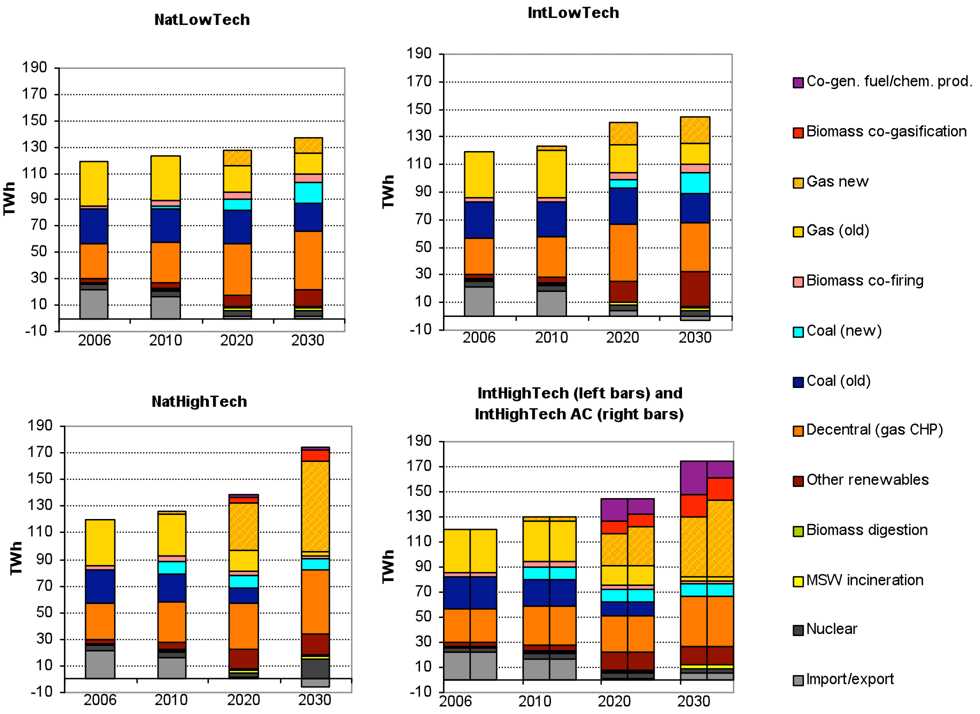
Table 6 Shares of electricity generation from biomass in the different scenarios

Scenario	NatLowTech	IntLowTech	NatHighTech	IntHighTech	IntHighTech AC
Share of electricity from biomass (%)*					
2006	3.5	3.5	3.5	3.5	3.5
2010	4.5	3.9	5.3	5.3	5.3
2020	6.0	5.1	8.8	23.6	19.7
2030	6.8	6.4	9.1	28.7	21.3

*) Shares of electricity produced from biomass as share of total electricity production in the Netherlands

The share of electricity generated from biomass in 2030 ranges from 5.7% in the NatLowTech scenario to 31.4% in the IntHighTech scenario. The main difference between the NatHighTech and IntHighTech scenario comes mainly from a higher share of co-gasification[16] and co-generation of electricity generation from biofuel and chemical production (section 5.2.2 and 5.3.2). The higher blending share of biofuels in the IntHighTech and IntHighTech AC scenario and the production of synthesis gas for chemicals increase the share of electricity generation as visualised in Figure 9. Note that the production of synthesis gas is lower in the IntHighTech AC scenario than in the IntHighTech scenario. This halves the co-production of electricity from fuels and chemicals from 27 TWh to 14 TWh in the IntHighTech AC scenario relative to the IntHighTech scenario in 2030.

Figure 9 Electricity generation (TWh) per scenario, year and technology



The total electricity demand, shares of central and decentralised electricity generation, nuclear power, other renewables than biomass and CHP capacities are similar to the WLO scenarios. The shares of central coal and gas and electricity from biomass are modified for this study.

4.2.2 Biofuels for road transport

For all scenarios, biofuels substitute a fraction of petrol and diesel in the road transport sector. The feedstock for biofuel production depends on the technologies available (2nd-generation biofuels are only available in the high-tech scenarios) and the possibility of importing biofuels from outside the EU (international scenarios). Table 7 summarises the assumptions on technologies, feedstocks and blending

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[16] All new NGCC plants include co-gasification of biomass with a share of 25% on energy base in the IntHighTech scenario, while in the NatHighTech, only 50% of new built NGCC plants include co-gasification of biomass.

policies that are made for the different scenarios. The blending assumptions for the IntLowTech and NatHighTech are based on the EU directive on biofuels (section 3.3). For the NatLowTech scenario, we assumed the 20% target to be infeasible, with limited resources and technologies available. The blending assumptions for the IntHighTech (AC) scenarios are based on the PGG targets (60% substitution in 2030). These blending assumptions are coupled to the projected overall demand for petrol and diesel in the WLO scenarios [Hoen et al., 2006]. In their study, a constant low blending share of 2% was assumed for the RC, GE and TM scenarios. For the SE scenario, they assumed the blending share to increase from 2% to 5.75% for petrol and diesel after 2020. Hoen et al., [2006] estimate small shares for electric vehicles (2% in 2030) due to higher costs and limited governmental support. It should be noted that recent changes in the EU directive on biofuels (section 3.3) also include renewable electricity and hydrogen. A higher share of electric vehicles results in lower demands for liquid transport fuels and higher demands for electricity. As we used the projections of Hoen et al., [2006], these developments are not taken into account in this study.

Except for the blending shares, we assumed fuel demand and shares of diesel, petrol and LPG to be similar to Hoen et al. [2006]. The total demand from the WLO scenarios and fuel types per scenario are displayed in Figure 10.

Table 7 Biofuels and blending assumptions in the different scenarios

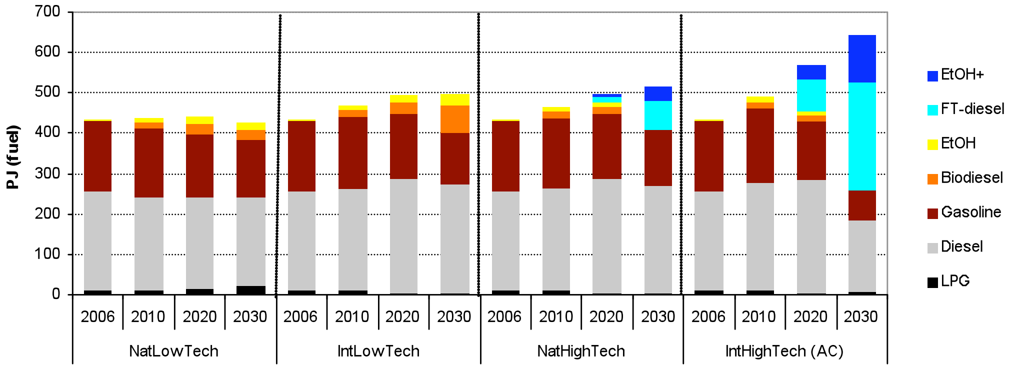
	NatLowTech		IntLowTech		NatHighTech		IntHighTech (AC)*	
Fuel	Biodiesel	Biopetrol	Biodiesel	Biopetrol	Biodiesel	Biopetrol	Biodiesel	Biopetrol
Type	RME	Ethanol	FAME from vegetable oil	Ethanol	Synthetic fuel	Ethanol (lignocellulosic)	Synthetic fuel	Ethanol (lignocellulosic)
Feedstock	EU rapeseed	EU sugar/ starch	Palm oil, Jatropha, rapeseed	Sugar cane	Perennial crops (EU)	Domestic/int. residues, perennials	Perennial crops (int.)	Domestic/int. residues, perennials
% biofuel**								
2006	0.35	0.55	0.35	0.55	0.35	0.55	0.35	0.55
2007	3.5	2	3.5	2	3.5	2	3.5	2
2010	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75
2020	10	10	10	10	10	10	25	25
2030	10	10	20	20	20	20	60	60

*) The blending shares and feedstock types are similar for the IntHighTech and IntHighTech AC scenarios.
**) % energy basis.

The supply of ethanol and biodiesel in the NatLowTech scenario comes from EU starch/sugar crops and EU rapeseed respectively. With only 1st-generation biofuels available from EU resources, the share of biofuels is assumed to be limited to 10%. In the IntLowTech scenario, bulk imports from outside the EU of ethanol, and all types of vegetable oils (e.g. palm oil and jatropha oil), reduce production cost of biofuels and allow for more ambitious blending shares. We assume that 20% of road transport fuels will be substituted by biofuels in 2030. In addition, ethanol is required for the production of ethylene. Ethanol required for ethylene production is also shown in Table 7 (6th column) as a fraction of petrol[17]. The blending shares in brackets in column 6 represent the total shares of petrol that have to be replaced to meet the demand for biofuels and chemicals.

For the high-tech scenarios, we assumed that 2nd-generation biofuels enter the market in 2010. Current and planned capacities of biofuels (2006-2010) will be met by 1st-generation biofuels, but from 2010 onwards, the production of biofuels from 1st-generation technologies will be substituted by 2nd-generation biofuel production technologies based on lignocellulosic feedstocks. Because 1st-generation biofuel plants have an estimated commercial lifetime of 15 years and, to avoid capital depreciation, part of the biofuels produced in 2020 will still be produced by the capacities that were deployed between 2006 and 2010. In 2030, all biofuel plants in the high-tech scenarios are assumed to be replaced by 2nd-generation technologies, as shown in Figure 10.

Figure 10 Road transport fuels in the different scenarios



Demand for LPG, petrol and diesel and the total demand for transport fuels are based on [Hoen, Brink et al., 2006]. The shares of 1st-generation biofuels (biodiesel and EtOH) and 2nd-generation biofuels (FT-diesel and EtOH+) are assumed for this study (Table 7).

Figure 10 displays the demand for transport fuels and the blending shares of biofuels per scenario. The total demands are projections from the WLO scenarios [Hoen, Brink et al., 2006]. In the NatLowTech scenario, the demand for road transport fuels increases only slightly, from 432 PJ in 2006 to 439 PJ as a result of the limited GDP growth in this scenario. Between 2020 and 2030, the demand decreases to 426 PJ. In the IntHighTech scenario, the demand for road transport fuels increases by almost 50% between 2006 and 2030 to 642 PJ in 2030 as a result of strong economic growth. Relatively similar trends are found for the IntLowTech and NatHighTech scenarios (499 and 516 PJ in 2030 respectively).

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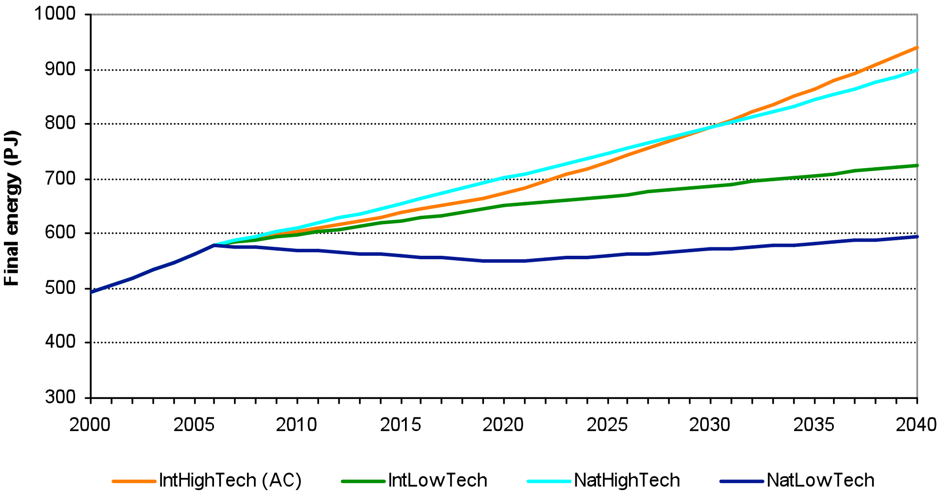
[17] For the macro-economic model, the share of ethanol required for ethylene has to be added as a share of transport fuels because of the model structure.

4.2.3 Chemicals

For the substitution of fossil fuels for raw materials, this study focuses on the chemical industry, which uses 79% of fossil fuels for non-energy purposes (section 3.4). Projections of the future growth in the chemical industry sector were based on the WLO projections from the CPB [Janssen, Okker et al., 2006]. The physical annual growth of the chemical sector (up to 2040) is expected to be 2.5% in the NatHighTech and IntHighTech scenarios, 2.2% in the IntLowTech scenario and 1.2% in the NatLowTech scenario to 2040, as displayed in Figure 11, projections of energy requirements for non-energetic purposes[18]. Because these projections are not sector-specific, we assume a similar growth rate for each sector in the chemical industry. The production of bio-based chemicals and the substitution potential differs per scenario, as discussed in the following sections.

Figure 11 **Final energy consumption for non-energetic purposes in the chemical industry, data for 2000 to 2006 from [CBS, 2008a], projections to 2040 from [Janssen, Okker et al., 2006; CBS 2008a]**



A representative route was selected for each scenario, based on the structure of the chemical industry in the Netherlands, technological development and the availability of international biomass resources.

4.2.3.1 *NatLowTech (no bio-based chemicals)*

The limited amount of biomass resources, in combination with low technological development, limits the possibilities for the production of chemicals from biomass in the NatLowTech scenario. We therefore assumed no production of bio-based chemicals in this scenario.

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[18] Process energy (heat and electricity) for the production of chemicals is allocated to heat and electricity (section 4.2.1).

4.2.3.2 IntLowTech, base C2 chemicals (ethylene)

In the IntLowTech scenario, biomass and biofuel imports from non-EU countries allow for more extensive use of biofuels than in the NatLowTech scenario, but also the production of bio-based chemicals. The production of ethylene from bio-based ethanol has a significant potential, because ethylene is one of the largest chemicals produced in terms of quantity.
We assume that 10% of crude-oil-based ethylene will be produced from ethanol in 2020 and 20% in 2030, similar to the blending assumptions for biofuels in this scenario. Note that more ambitious targets are set in the PGG studies (30% in 2030). We consider 20% to be feasible for substitution of petrochemical ethylene by bio-based ethylene.

The annual growth rate of the non-energetic energy consumption in the IntLowTech scenario is 1.4% between 2000 and 2020, and 0.55% between 2020 and 2040 (Figure 11). Production is projected to increase from 2.9 Mton in 2006 to 3.0 Mton in 2010, 3.2 Mton in 2020 and 3.4 Mton in 2030. This implies that 3.2 Mton * 10% = 320 kton and 3.4 Mton * 20% = 680 kton of ethylene will be produced from bioethanol in 2020 and 2030 respectively.

4.2.3.3 NatHighTech, intermediate chemicals (Caprolactam)

The NatLowTech scenario includes the availability of new technologies, but the potential of biomass resources is limited to European sources. Bio-based production is therefore focused on products with a high added value and limited quantities. We assume that domestically produced biomass will be used for the production of caprolactam, a chemical intermediate for the production of nylon-6.

The production of caprolactam was estimated to be 222 kton[19] in 2006. The domestic production levels for caprolactam for 2010, 2020 and 2030 are projected to be 235, 269 and 305 kton/a respectively. These projections are based on the projected increase in fossil energy consumption for non-energetic energy consumption in the NatHighTech scenario (Figure 11).

The production route of bio-based caprolactam via sugar fermentation to lysine is not yet commercially available [Sanders, Engelen et al., 2006]. We assume this technology to be commercialised between 2010 and 2020, resulting in a 50% bio-based share of caprolactam in 2020 and all caprolactam in the Netherlands to be bio-based by 2030. This implies that 269 kton * 50% = 135 kton and 304 kton (100%) bio-based caprolactam will be produced in 2020 and 2030 respectively.

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[19] Based on an annual growth rate of the non-energetic consumption of fossils of 2.72% between 2000 and 2006 in the Netherlands. This is consistent with the global annual growth of caprolactam production of 2.9% between 2005 and 2010 [Tefera, 2006].

4.2.3.4 *IntHighTech, base C1 chemicals (synthesis gas)*

In the IntHighTech scenario, the combination of high technological development with the availability of global biomass resources allows for the production of bulk chemicals via biomass gasification to synthesis gas.

Synthesis gas, derived from natural gas via SMR, is currently mainly used for the production of hydrogen for ammonia production. Also in other chemical industries, synthesis gas is used for carbon monoxide, hydrogen or methanol synthesis.

The non-energetic energy consumption of natural gas in the chemical industry, including fertilisers, is projected to increase, based on the growth of non-energetic energy consumption in the IntHighTech scenario (Figure 11), from 86 PJ[20] in 2006, to 90 PJ, 100 PJ and 118 PJ in 2010, 2020 and 2030 respectively. We assume bio-based synthesis gas production technology to become commercially available between 2010 and 2020, and bio-based production shares of 50% and 100% in 2020 and 2030 respectively. This implies that 50 PJ and 118 PJ of natural gas for non-energetic purposes will be replaced by synthesis gas in 2020 and 2030 respectively.

4.2.3.5 *IntHighTech AC, base C1, base C2 and intermediate chemicals*

In addition to the four scenarios that include single chemical representatives, an additional scenario is created that includes bio-based production of natural gas and petroleum products and in both the specialty and bulk chemical industries. The blending targets in this scenario are based on the PGG target to substitute 25% of fossil raw materials with biomass as described in Rabou et al. [2006].

For final non-energetic use of natural gas, Rabou et al. [2006] assumes 30% to be replaced by biomass in 2030[21]. Note that in the IntHighTech scenario, 100% replacement of final non-energetic use of natural gas was assumed. The replacement of natural gas is therefore lower in this scenario. Similar to Rabou et al. [2006], we assume 25% of final non-energy use of petroleum products to be replaced by biomass in 2030. The bio-based production routes differ from the production routes assumed by Rabou et al. [2006]. For replacement of petroleum products, we include direct substitution of base chemicals (ethylene) and replacement of intermediate products (caprolactam). Rabou et al. includes fermentation routes as well, but also specific production routes of chemicals (biorefinery).

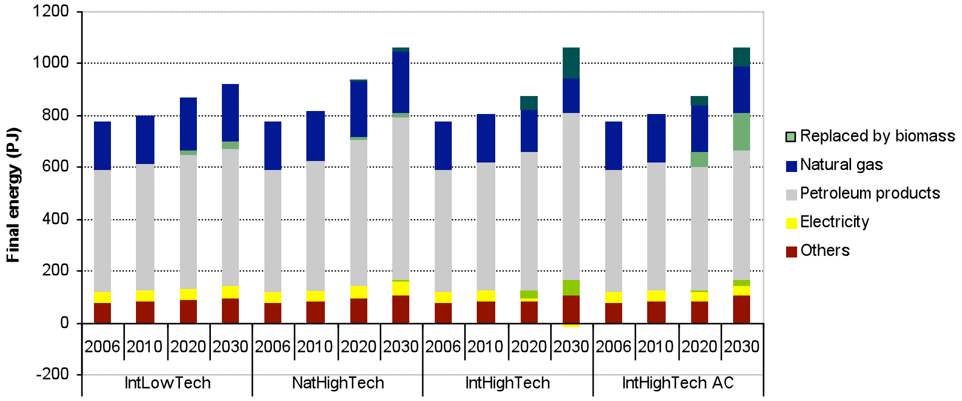
[20] The non-energetic energy consumption of natural gas was higher in 2000 (102 PJ) than in 2006 [Rabou et al., 2006] because the production of methanol from natural gas in the Netherlands was already abandoned for a large part in 2005 and substituted by biomass resources (section 3.4.2).

[21] It should be noted that in the base year of the referred study (2000), methanol was produced from natural gas, whereas in 2006, the reference year of this study, this process was already starting to be replaced by biomass. Therefore, we assumed all

4.2.3.6 Bio-based chemical production shares

Figure 12 shows the total energy demand (energetic and non-energetic) of the chemical industry in the Netherlands for 2006, based on CBS [2008a] and projected to the future using the WLO scenarios for the chemical industry (Figure 11). The NatLowTech scenario is excluded because we assumed no bio-based chemicals for this scenario. The category 'others' includes mainly the energy carriers steam, heat and coal. The diagonal patterns represent the avoided fossil energy by bio-based substitutes.

Figure 12 **Energetic and non-energetic final energy and avoided final energy by bio-based substitution in the scenarios**



Substitution of petrochemical ethylene by a bio-based share of 10% and 20% in 2020 and 2030 respectively in the IntLowTech scenario, results in substitution of naphtha and a reduced demand for petroleum products of 2.7% and 5.4%, or 1.6% and 3.3% of the total energy demand of the chemical industry in 2020 and 2030 respectively. Bio-based production of caprolactam (50% in 2020 and 100% in 2030 in the NatHighTech scenario), results in declined use of natural gas (mainly for ammonia) and petroleum products (mainly for toluene). If synthesis gas is produced from biomass (50% in 2020 and 100% in 2030 in the IntHighTech scenario), natural gas is substituted. Furthermore, electricity is co-generated. In 2030, the amount of co-generated electricity is 30% greater than the total electricity demand in the chemical industry.

In the bottom-up study, we selected representative chemicals in order to quantify the saving potential if substituted by biomass. The top-down models aggregate the chemical industry into two sectors: base chemicals and specialty chemicals. In order to quantify the bio-based blending shares for the top-down model, we used an alternative method. The following assumptions were made:

- In the IntLowTech scenario, bio-based ethylene replaces naphtha. Both naphtha and ethanol are not single sectors/commodities in the top-down model, but are both aggregated in the petrol sector. Therefore we assumed a blending share of petroleum products in the petrol sector in the top-down model.

- In the NatHighTech scenario, bio-based caprolactam replaces a range of base chemicals from different fossil energy carriers such as phenol, ammonium and hydrogen. Instead of modelling these fractions exactly in the top-down model, an aggregated blending share was assumed for the specialty chemicals sector;
- In the IntHighTech scenario, the production of bio-based synthesis gas replaces natural gas in the base chemical industry and electricity. It is not directly possible to account for co-produced electricity in the chemical sector. Therefore, co-produced electricity is allocated to the electricity sector and added to the blending share of bio-based electricity generation.
- In the IntHighTech AC scenario, all chemicals, as described above are integrated into one scenario in order to reach a bio-based blending share of 12.5% in 2020 and 25% in 2030.

Table 8 shows the bio-based production in PJ per scenario derived from the assumed blending shares of the chemical representatives. The net avoided fossil final energy includes co-production of electricity in the IntHighTech scenario (69 PJ in 2030). The relative fractions of fossil energy avoided are based on the non-energetic energy demand in the chemical industry. Only in the IntHighTech scenario, blending shares are in range with the ambition of the PGG platform (25% replacement of fossil raw materials in 2030).

Table 8 Biomass blending shares in the chemical industry

Scenario	IntLowTech		NatHighTech		IntHighTech		IntHighTech AC	
Year[1]	2020	2030	2020	2030	2020	2030	2020	2030
Bulk chemicals (PJ)[2]	409	432	441	499	424	500	424	500
bio-based (%)[3]	4%[6]	7%[6]	N/A	N/A	9%[8]	19%[8]	13%[9]	25%[9]
Specialty chemicals (PJ)[4]	102	108	110	125	106	125	106	125
bio-based (%)[5]	N/A	N/A	4%[7]	7%[7]	9%[8]	19%[8]	13%[10]	25%[10]

1) Bio-based chemicals are only assumed to be available in 2020 and 2030 in the scenario projections.
2) Non-energetic energy in the bulk chemical industry (80% of total non-energetic use of fossil energy for chemicals as projected in figure x).
3) Specialty chemicals include caprolactam and bio-based synthesis gas as feedstock for the production of specialty chemicals.
4) Non-energetic use of energy in the specialty chemical industries (20% of total non-energetic use of fossil energy for chemicals as projected in figure x).
5) Bulk chemicals include bio-based ethylene and bio-based synthesis gas for the production of bulk chemicals.
6) Replacement of 10% and 20% fossil based ethylene by bio-based ethylene in 2020 and 2030 respectively. These shares show these replacements as a fraction of the total fossil energy requirement for non-energetic purposes in the bulk chemical industry.
7) Replacement of 50% and 100% fossil based caprolactam by bio-based caprolactam in 2020 and 2030 respectively. These shares show these replacements as a fraction of the total fossil energy requirement for non-energetic purposes in the specialty chemical industry.
8) Replacement of 50% and 100% fossil based synthesis gas by bio-based synthesis gas in 2020 and 2030 respectively. These shares show these replacements as a fraction of the total fossil energy requirement for non-energetic purposes in the specialty and bulk chemical industries as synthesis gas is assumed to be used for 80% in bulk chemicals and 20% in specialty chemicals.
9) Replacement of synthesis gas and bulk chemicals from petroleum products (ethylene representative) of respectively 15% and 12.5% in 2020 and and 30% and 25% in 2030.
10) Replacement of synthesis gas for specialty chemicals and specialty chemicals from petroleum products (caprolactam representative) of respectively 15% and 12.5% in 2020 and and 30% and 25% in 2030.

4.1 Scenario overview

The scenario assumptions for electricity generation, biofuel production and chemical production as described in the sections above are summarised in Table 9. The following chapter describes the technological and economic performance of these technologies.

Table 9 Scenarios, technologies and feedstock types

Scenario	Electricity					Transport fuels		Chemicals		
	Co-firing PC plants	Co-gasification NGCC plants	CHP digestion	Waste incin-eration	Other	Biodiesel	Ethanol	C1 bulk chemicals	C2 bulk chemicals	Specialty chemicals
NatLowTech	Existing 10% bio-based share, new 20%	N/A	State-of the art	State-of-the art	N/A	FAME (rapeseed)	Ethanol (starch crops)	N/A	N/A	N/A
IntLowTech	Existing 10% bio-based share, new 20%	N/A	State-of the art	State-of-the art	N/A	FAME (jatropha/ palm oil)	Ethanol (sugar cane)	N/A	bio-based ethylene	N/A
NatHighTech	Existing 10% bio-based share	12.5% bio-based share new NGCC plants	State-of the art	State-of-the art	Combined cycle (residues biofuels)	FT-diesel	Ethanol lignocellulosic biomass	N/A	N/A	bio-based caprolactam
IntHighTech	Existing 10% bio-based share	25% bio-based share new NGCC plants	State-of the art	State-of-the art	Combined cycle (residues biofuels/chemicals)	FT-diesel	Ethanol lignocellulosic biomass	bio-based synthesis gas	N/A	N/A
IntHighTech AC	Existing 10% bio-based share	25% bio-based share new NGCC plants	State-of the art	State-of-the art	Combined cycle (residues biofuels/chemicals)	FT-diesel	Ethanol lignocellulosic biomass	bio-based synthesis gas	bio-based ethylene	bio-based caprolactam

5 TECHNOLOGIES

This chapter gives an overview of the technologies in the different scenarios and the assumed cost and performance of these technologies. Based on literature, we made cost and performance estimates for 2006 to 2030 per technology as described for electricity generation (5.1), biofuel production (5.2) and bio-based chemicals (5.3). This chapter ends with an overview of the technological assumptions in the different scenarios (5.4).

5.1 Electricity generation

For electricity generation from biomass, the following options were considered: MSW incineration (5.1.1), electricity and heat from biogas production via anaerobic digestion (5.1.2), co-firing in PC plant (5.1.3) and co-firing in NGCC plants via gasification (5.1.4). The last option is only available in the high-tech scenarios. Co-generation of electricity from advanced bioethanol, FT-diesel production and hydrogen production are described in section 5.2.2.

5.1.1 Waste incineration

Waste incineration plants are used for the combustion of heterogeneous waste from domestic and industrial sources. The majority of these plants produce heat and electricity with waste processing capacities ranging from 8 kton dm/a (4 $MW_{th\ input}$ capacity) to 1,150 kton dm/a (387 $MW_{th\ input}$ capacity) in the Netherlands. The average electric efficiency of existing plants is ~15%, but new plants are expected to be built with electric efficiencies of 26-29% [Vereniging Afvalbedrijven, 2007].

For this study, we assume replacement and additional capacities with high electric efficiencies (29%). Capital and O&M costs are based on Tilburg et al. [2008]. For high-efficient MSW plants, investment costs are estimated to be 2700 €/kWe. O&M costs are estimated to be 1.4 €/MWh and the annual load is assumed to be 6000 hours.

We assumed no improvements of performance because the efficiency is limited by fuel properties and corrosive gases in the flue gas stream. Capital costs are estimated to remain constant over time because MSW incineration plants are based on mature technologies with limited learning potential.

MSW plants use fossil energy (natural gas) mainly to meet emission standards by improving combustion conditions. The required natural gas is taken into account for estimating the primary energy avoided and GHG emissions by combustion of MSW (Bosselaar et al. 2006). The specific natural gas consumption of MSW plants was 0.03 $MJ_f/MJ_{waste\ input}$ in 2006 (CBS 2008a). We assumed the specific gas consumption of MSW plants to remain constant over the projected period to 2030.

5.1.2 Anaerobic digestion of manure and organic waste

Anaerobic digestion is a process where bacteria digest biodegradable matter, in the absence of oxygen, to mainly methane, H_2S and CO_2. Biogas can be upgraded and injected into the gas grid, but we assume that it is combusted in a gas engine to produce heat and power (CHP).

The cost and performance of digestion technologies depend mainly on feedstock properties, locations and scale. In this study, one representative technology is selected for digestion of all wet organic waste streams. Note that this is aggregated, as in reality manure digestion plants at farm level perform differently to, for example, digestion plants for organic household waste (GFT) or sewage sludge from water treatment plants [Van Tilburg et al., 2007; Meijer et al., 2008]. In this study, manure, swill, water treatment sludge and organic household waste are aggregated into one biomass resource cluster (wet organic waste). The conversion efficiencies and cost of these residue and waste fractions are also aggregated, as are the avoided GHG emissions and fossil energy (section 7.2).

We selected as reference technology a digestion plant that processes 50% manure and 50% of other organic compounds (e.g. organic waste from food processing). If only manure is digested, investment costs could more than triple as a result of the decreased biogas production and related power generation. Mono-digestion of manure is therefore often considered to be not economically feasible [Meijer, Teeselink et al., 2008].

The electric efficiency of biomass digestion plant is estimated to be 15% based on [IEA, 2008]. Van Tilburg et al. [2008] report electric efficiencies of 26%. It should be noted though that these plants include co-digestion of energy crops (maize) to improve overall plant efficiency.

Capital investments are 3700 €/kWe for a 1000 kWe. Fixed O&M costs are 435 €/kWe [Van Tilburg, Lensink et al., 2007]. Although feedstock costs for wet organic waste streams are negative (Table 13), we assume these to be zero to account for processing cost of substrate from the digester. The costs of electricity generation are estimated to be 10.4 cents/kWh including revenues for heat production[22].

5.1.3 Co-firing in pulverised coal plant

Electricity generation by co-firing of biomass in PC plants is a mature and well-demonstrated technology (~150 units worldwide [IEA, 2008]) for reducing CO_2 emissions, while costs remain limited as the technology profits from economies of scale of the PC plant, high conversion efficiency of the PC boiler and turbine section and environmental control technologies of the PC plant. The fraction of biomass for co-firing ranges from 0.5-10% on an energy basis, with typical values of around 5% [IEA, 2008]. New plants, modified for multifuel combustion, allow for biomass

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[22] Economic lifetime = 10 years, discount rate = 10%, load factor = 7500 h/a, gas price = 6 €/GJ.

shares of 40% on an energy basis [Dornburg et al., 2007].

Biomass feedstock types used for co-firing range from chicken manure, agricultural residues (straw), RDF, waste wood (A and B quality) and wood pellets. It should be noted though that agricultural residues are usually not combusted directly in PC boilers because of fuel properties. Co-firing via gasification or combustion in circulating fluidised bed boilers is possible for RDF, chicken manure and agricultural residues though [IEA, 2008].

The electric efficiency of PC plants with co-firing can decrease as a result of coal substitution by biomass. The main reasons for decreased efficiency are reported by Damen and Faaij [2003]:

- Energy requirement of the coal mills might increase when biomass is added as a result of the biomass structure;
- Decreased boiler efficiency as a result of biomass properties (e.g. chemical composition and moisture content) and related gas stream properties (heat exchange coefficient);
- A decrease in carbon burnout might occur;
- Biomass has a lower calorific value than coal. The volume flow of fuel, air and resulting flue gas increases for similar boiler and turbine capacity of a PC plant without co-firing. Especially in existing plants, designed for a maximum gas volume, fuel inputs need to be reduced resulting in decreased steam production (de-rating).

The estimated decrease in efficiency ranges from insignificant to 1% point for a 10% energy share of biomass [IEA, 2006a]. This implies that the efficiency of co-firing biomass is, on average, 0-10% points lower than the efficiency of coal combustion in a PC plant [IEA, 2006a].

For this study, we assume that biomass is converted into pellets before used for co-firing[23]. The energy requirement and GHG emissions for pre-treatment (e.g. wood drying) are thereby allocated to biomass production and are assumed to have similar efficiencies to coal combustion. Although pelletising of biomass increases fuel production cost, this is justified by better fuel handling, transport and storage [Dai, et al., 2008].

State-of-the-art PC plants have a net efficiency of around 45-46% lhv [DTI, 2006]. The most recently built supercritical PC plants in the Netherlands (1994) have net efficiencies of 42.6-43% [Lako, 2004], but the average net efficiency of coal-fired power plants in the Netherlands is estimated to be 39%, as less efficient subcritical plants are still operational in the Netherlands.

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[23] Only domestic clean wood residues (mainly secondary and tertiary residues) are assumed to be co-fired directly as they have a lower moister content than fresh wood and include relatively short transport distances (assumed 100 km). For transport by ship or train, pelletising becomes economic.

For new plants, we assume a maximum co-firing share of 20% on energy base [IEA, 2008]. Cost and performance data of the PC plant (excluding co-firing) are derived from [Van den Broek, Faaij et al., 2008] and are estimated to improve over time. The TCI of the co-firing unit, in addition to investment costs of the PC plant, are estimated to be 250 €/kW, and O&M costs 38% of the TCI for the co-firing system [Dornburg, Faaij et al., 2007]. Technologies for the co-firing section are standard mature technologies for which limited cost reductions are expected [Ruigrok et al., 2003]. Therefore we assumed cost of the co-firing unit to be constant over the projected period.

5.1.4 Co-firing by biomass gasification and combustion in combined cycle

There are two main concepts for biomass co-firing in NGCC plants. Co-firing by upstream combustion and downstream steam-side integration and co-firing by upstream gasification. The first concept uses heat from biomass combustion for steam production that is fed to the steam turbine of the combined cycle. The second concept requires gasification of biomass to synthesis gas. The synthesis gas is mixed with the fuel gas input and combusted in the gas turbine, thereby making use of the high conversion efficiency of the combined cycle [Zwart, 2003]. In this study we focus on the concept of co-firing by upstream gasification because of the high performance [Zwart, 2003].

The maximum share of biomass-derived synthesis gas is restricted by the gas turbine hardware. The low calorific value (LCV) of biomass-derived synthesis gas limits the share of biomass synthesis gas to 10-20% (energy base) if used in existing gas turbines with dry low-NO_x combustion chambers [Ree et al., 2000]. We assume that only newly built NGCC plants include co-firing by gasification of biomass with a biomass share of 25% (energy base). These plants will be designed for combustion of natural gas and LCV gas from biomass. According to [Zwart, 2003], co-firing shares of 25% are achievable with limited gas turbine modifications. For higher shares, major modifications are required (e.g. water/steam injection for NOx reduction), which results in high capital investment costs.

Based on [Feber et al., 2000], we assume for the short term (2010)[24] a gasifier at atmospheric pressure with cold gas cleaning and a cold gas efficiency[25] of 75% to be used. For the long term (2030) we assume a pressurised gasifier (at 15 bar) with hot gas cleaning and a cold gas efficiency of 93% to be available.

[24] Although Feber et al. [2000] assume short-term estimates for 2000, we assume these estimates to be representative for 2010 as a result of limited developments in gasification technology and optimistic assumptions of Feber et al. [2000].

[25] The cold gas efficiency is the fraction of thermal energy input of the gasifier feedstock that is converted into chemical energy in the synthesis gas output of the gasifier. Note that the overall plant efficiency can be higher as a result of heat integration between the gasifier and the power island.

The net efficiency[26] of the NGCC plant with co-firing of biomass improves, as a result of GTCC and gasifier performance, from 52% in 2010 to 56% in 2020 and 60% in 2030. The investment costs of the gasifier decrease from 410 €/kWth in 2010 to 340 €/kWth in 2030. The capital costs and performance data of the NGCC power island are derived from [Van den Broek, Faaij et al., 2008]. The capital costs of the biomass gasification unit, O&M costs of the total plant and efficiency are based on [Feber and Gielen, 2000].

5.2 Biofuel production

For the production of transport fuels from biomass, we considered 1st-generation technologies to be used in the low-tech scenarios (5.2.1), whereas in the high-tech scenarios (5.2.2), 2nd-generation technologies will become commercially available from 2010 onwards.

5.2.1 Low-tech scenarios

5.2.1.1 Ethanol from sugar beet

Conventional ethanol, produced via fermentation of sugars from sugar beets yields ethanol and pulp as a co-product. Electricity is required for pre-treatment of the sugar beets. Heat (steam) and electricity are required for the diffusion, pasteurisation, fermentation and distillation processes. Pulp is sold as animal feed.

The yield of ethanol production from sugar beets is estimated to be 0.292 kg/kg (dw) or 0.45 MJ/MJ (LHV) [Deurwaarder et al., 2007]. Capital investments are estimated to be 55.5 M€ for a 100 kton/a ethanol plant. Future capital investment costs are expected to decrease by 10% between 2006 and 2030 according to Hamelinck et al. [2006]. O&M costs are estimated to be 6.2% of the capital investments annually [Hamelinck et al., 2007].

The efficiency of the process can be improved by biogas production of pulp, beet crowns and leaves or proteins for the production of chemicals. We do not take biogas production into consideration because using beet pulp as animal feed is economically attractive, with revenues ranging from 100-247 €/tonne ethanol [Smeets et al., 2005]. The extraction of proteins for the production of chemicals (biorefinery) is potentially interesting, but the technology is still in an experimental stage and limited data is available [Sanders, Engelen et al., 2006].

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[26] Net efficiencies of the NGCC plant are derived from Van den Broek et al. [2008] and improve from 56% in 2006 to 63% in 2030. The efficiency penalty of co-gasification depends on the gasifier type. In 2006 the efficiency penalty is 6% points, while in 2030 it is 3% points as a result of the more efficient gasifier used in the long term.

5.2.1.2 *Ethanol from starch (wheat)*

The production of ethanol from wheat grain (starch) requires milling and hydrolysis before fermentation. The milling process produces bran as co-product. The fermentation and distillation processes produce ethanol and DDGS (Distiller's Dried Grain Solubles). Bran and DDGS have a market value of 19 €/tonne and 148 €/tonne (fw) respectively [Hamelinck and Hoogwijk, 2007]. The total revenue is 8.6 €/GJ ethanol produced.

The conversion efficiency of ethanol from grain is estimated to be 0.52 MJ/MJ (LHV), based on a yield of 0.34 kg/kg (dw) [Elsayed et al., 2003], which is the average yield found in literature[27] [Smeets, Junginger et al., 2005]. We assume the efficiency to remain constant over the projected period because we expect little technology progress in the fermentation process. Capital investments, O&M costs and scale factors are based on [Hamelinck and Hoogwijk, 2007]. The capital investment is estimated to be 62.4 M€ for a 100 kton plant (92 MW_{LHV}), O&M costs are 2.5% of capital investments and the scale factor is 0.6[28]. We assume future plants (from 2010 onwards) to have a capacity of 200 kton/a as a result of the increasing demand for ethanol. Process energy (natural gas for steam) is expected to decrease by 10% in 2020 and 20% in 2050 due to plant optimisation [Hamelinck and Hoogwijk, 2007]. We assume 15% reduction in process energy for 2030.

5.2.1.3 *Ethanol from sugar cane*

Ethanol production from sugar cane includes pre-treatment processes to extract the sugars (chopping, shredding, mixing with water and crushing). Ethanol is produced via fermentation, purification and distillation of the sugar juice. Bagasse (fibrous material) is produced as a co-product, which is burned for electricity generation. Ethanol production plants generate sufficient electricity for own use. Surplus electricity generated is sold to the grid [Smeets, Junginger et al., 2005].
The yield of ethanol production from sugar cane averages 85 l/tonne sugar cane (mc = 73%) or 0.40 MJ/MJ_{LHV}. Yields could improve through new crop varieties with higher sucrose content and process improvements to 95 l/tonne (mc = 73%) or 0.45 MJ/MJ_{LHV} in the long term [Damen, 2001]. If excess trash and bagasse were converted into ethanol by hydrolysis, the yield of ethanol could increase to 177 l/tonne (mc = 73%) according to Damen. In this study, the option of ethanol imports from Brazil is only available in the IntLowTech scenario in which we assume that gasification technology, as well as ethanol production from lignocellulosic materials and lighter sugar contents, will not become commercially available in the projected period to 2030. We assume the average yield for ethanol production for 2006 (0.40 MJ/MJLHV) that gradually improves to 0.45 MJ/MJ_{LHV} in 2030. Excess bagasse and other residues are assumed to be burned in a CHP plant to produce electricity and heat for the process.

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[27] Smeets et al. [2005] report an average yield of 362 l/t fw grains (mc = 16%, ethanol density = 0.79 kg/l).

[28] The USDA FAS reports investment costs of 6 dollar cent for a 200 mln litres production plant and 10 dollar cent for a 50 mln litres production plant [Hamelinck and Hoogwijk, 2007].

The capital costs of ethanol production are estimated to be 55.4 M€ for a 112 kton/a ethanol plant and O&M costs are 13% of the capital investment cost annually [Hamelinck and Hoogwijk, 2007]. Future cost estimates are also reported, but include advanced technologies (BIC/CC), which we assume not to become commercially available in the low-tech scenarios. Therefore, we estimate future costs based on technological learning assuming gradual cost reductions. Van den Wall Bake [2006], reports a progress ratio of ethanol production from sugar cane of 0.81 (excluding feedstock). With an annual growth rate in ethanol production from sugar cane of 5% [Van den Wall Bake, 2006] capital costs decrease from 55.4 M€ to 38.8 M€ for a 112 kton/a plant.

5.2.1.4 Biodiesel (FAME)

The production of biodiesel from vegetable oil or oil and fat residues refining followed by transesterification with kalium hydroxide (KOH) and methanol producing methyl esters. These can be blended with diesel and combusted directly in unmodified diesel engines. The feedstocks for FAME are vegetable oils (e.g. palm oil, jatropha oil, rapeseed oil) or used fat and oil residues. Before transesterification, crude vegetable oil must be refined, which requires, heat, electricity and chemicals.

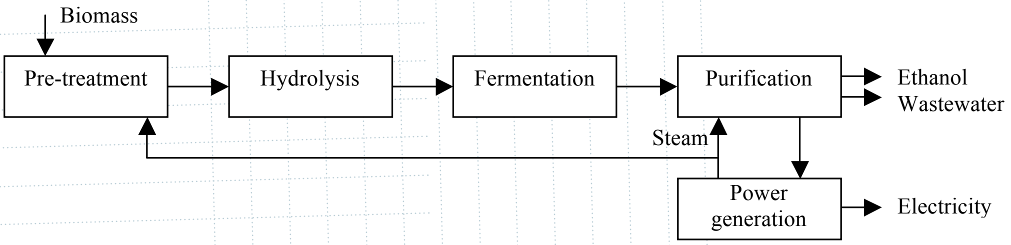
The main by-product from the transesterification process is glycerine, which can be used as animal fodder, or process chemical. In the Netherlands, glycerine from RME production is, amongst others, used for the production of methanol [Focus on Catalysts, 2007]. It should be noted though that revenues for glycerine are expected to decrease or even become negative as a result of increasing supply by biodiesel production [Dornburg, Faaij et al., 2007]. Current prices of crude glycerine are 500-700 €/tonne delivered [Rafiq, 2008]. We assume a market price of 600 €/tonne crude glycerine for 2006 and estimate that the price will be halved in 2010, to 300 €/tonne, as a result of the increased supply. In the long term we estimate the price of crude glycerine to drop to 150 €/tonne in 2020 and to zero in 2030 [Dornburg, Faaij et al., 2007]. The yield of crude glycerine is around 3.0*10-3 kg per MJLHV biodiesel produced from vegetable oil [Dornburg, Faaij et al., 2007; Hamelinck and Hoogwijk, 2007]. The yield of crude glycerine from oil and fat residues is slightly lower ($2.7*10^{-3}$ kg per MJ_{LHV} biodiesel produced) [Deurwaarder, Lensink et al., 2007].

Investment costs for the biodiesel production plant from vegetable oil are estimated to be 20 M€ for a 100 ktonne/a biodiesel plant. O&M costs are assumed to be 3.5% of the Capex annually [Hamelinck and Hoogwijk, 2007]. The conversion efficiency of crude rapeseed oil to biodiesel is close to 1 MJ_{fuel}/MJ_{HHV} because methanol is not accounted for as energy input commodity [Dornburg, Faaij et al., 2007]. Methanol consumption is accounted for in the GHG balance and operating costs of FAME production. The capital investment costs for FAME production from oil and fat residues are derived from [Deurwaarder, Lensink et al., 2007] and are estimated to be 15 M€ for a 50 kton/a FAME production plant. Operating costs are assumed to be similar to the vegetable oil FAME plant.

Future costs of FAME production from vegetable oil or oil and fat residues are based on the technological learning potential of RME in Germany [Berghout, 2008]. We assume parallel trends in cost reductions for the EU27+ and estimate industrial processing cost to reduce bhy 9% between 2006 and 2020, and 12% between 2020 and 2030[29].

5.2.2 High-tech scenarios

5.2.2.1 Ethanol from lignocellulosic biomass



Apart from sugar and starch, ethanol can also be produced from lignocellulosic biomass (e.g. agricultural residues or forest residues, energy crops such as short rotation coppice (SRC) or miscanthus). The production of ethanol from lignocellulosic biomass is more complex than the sugar/starch processes, because a pre-treatment process is required to resize the feedstock and break up the structure of the lignocellulosic material into lignin, hemicelluloses and cellulose. Hemicelluloses can be fermented into ethanol, while cellulose requires a hydrolysis process. The cellulose and hemicelluloses material are about 2/3 of the feedstock by weight, depending on biomass type [Hamelinck, Van Hooijdonk et al., 2005]. Lignin cannot be converted into ethanol and is used for electricity and heat generation that is partly used on the production side.

Estimates of the techno-economic performance of lignocellulosic conversion to ethanol in 2010, 2020 and 2030 are derived from bottom-up analysis by [Hamelinck, Van Hooijdonk et al., 2005]. Cost reductions and improvements in performance due to technological learning are addressed by economies of scale and technological change. Systems for the short term (2010) include technologies that are already commercially available or demonstrated in pilots. Systems for the medium term (2020) include technologies that are at the pilot stage or promising laboratory stages while for the long term (2030), technologies are included that are being developed in laboratories, but are expected to be commercially available in 2030. The selected systems and their techno-economic performance are summarised in Table 10. Note that these cost projections have an uncertainty range of 50% as a result of the methodology used [Hamelinck and Faaij, 2006]. A detailed description of the technologies can be found in [Hamelinck, Van Hooijdonk et al., 2005].

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[29] Although Berghout [2008] estimates 11-13% cost reductions for 2020, the biodiesel share of 20% for this estimate corresponds with the projections of 2030 in this study.

Table 10 Costs and performance of ethanol production from lignocellulosic biomass (based on Hamelinck et al., 2005)

	2010	2020	2030
System	**Short term**[a]	**Medium term**[b]	**Long term**[c]
Scale (MWthermal input)	400	1000	2000
Investment cost (€/kWHHV EtOH)[d]	2100	1200 – 1600	900
O&M (% investment)	6.4	5.0	3.6
Cost (excl. fuel and revenues) (€/GJEtOH)[e]	14.25	7.56 – 10.08	5.23
Efficiency (MJEtOH/MJbio)[f]	0.35	0.39	0.47
Electricity generation (MJe/MJbio)	0.04	0.14	0.04

a) Dilute acid pre-treatment, on-site enzyme production, enzymatic cellulose hydrolysis, SSF configuration (cellulose hydrolysis and C6 fermentation integrated in one reactor vessel), boiler and steam turbine.

b) Steam explosion pre-treatment, off-site enzyme production, enzymatic cellulose hydrolysis, SSCF configuration (enzymatic hydrolysis and co-fermentation in one reactor vessel), BIG/CC.

c) Liquid hot water pre-treatment, CBP configuration (enzyme production, enzymatic cellulose hydrolysis and co-fermentation in one reactor vessel), boiler and steam turbine.

d) Including technological development and economies of scale.

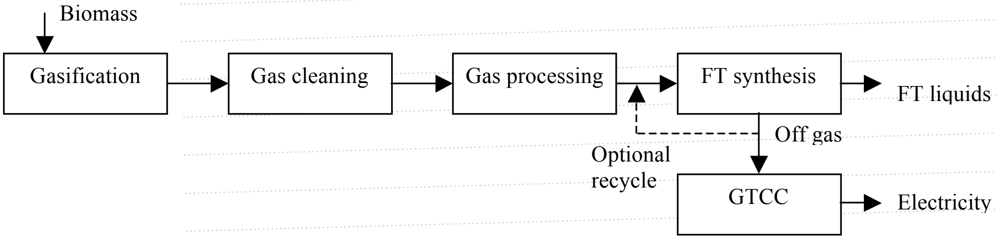
e) Total capital requirement = 118% of total investment cost, lifetime = 15 years, discount rate = 10%, load factor = 8000 h/yr.

f) HHV

5.2.2.2 Fischer-Tropsch transportation fuel

The general production route of Fischer-Tropsch (FT) diesel from biomass via gasification is presented in Figure 13. Before gasification, the biomass feedstock requires pre-treatment. Pre-treatment of biomass can be done at the site, but also close to the production area to reduce shipment cost [Deurwaarder, Lensink et al., 2007]. For this study, we assume biomass to be pelletised close to the source of production and shipped as pellets to the Netherlands, where they are converted into FT-diesel.

Figure 13 Fischer-Tropsch liquids production with gas turbine combined cycle (GTCC), general process [Hamelinck, Faaij et al., 2004]



The system selection and data on the techno-economic performance of the FT-diesel plant are derived from [Hamelinck et al., 2004]. For biomass gasification, [Hamelinck, Faaij et al., 2004] assumes a direct fired, oxygen-blown circulating fluidised bed (CFB) gasifier to reduce downstream equipment cost. Pressure was assumed to be 25 bar (higher pressure requires heavy equipment construction and expensive feeding). The system includes tar cracking and BTX[30] removal, wet gas cleaning technology for other impurities, no reforming (methane and other light hydrocarbons into CO and H_2) and a once through solid-bed FT reactor with 90% conversion efficiency [Hamelinck, Faaij et al., 2004].

The capital costs of a 156 MW_{LHV} output FT-diesel plant (105 kton/a biodiesel) are estimated to be 292 M€ for a current plant. For the long term (2030) Hamelinck et al. [2006] estimated costs to decrease by 15% through learning and 5% due to process improvements, to 235 M€ for a 156 MW_{LHV} output plant. No figures are provided for the medium term. Therefore we assumed a cost reduction of 10% via technological learning and 3% from process improvements in the medium term (2020),[31] while we assume the cost estimates for the current situation representative for 2006 to 2010[32].

The current and future O&M costs are estimated to be 4.4% of the investment cost. The efficiency of the fuel conversion of the FT-diesel plant is 41% (LHV) and electricity is co-produced with an efficiency of 3.2% (LHV). We assume the efficiency to remain constant over the projected period, similar to Hamelinck et al. [2004].

5.3 Chemicals

We assumed that bio-based chemicals will not be produced in the NatLowTech scenario. For the other scenarios, the following options are considered:

- IntLowTech: C2 (ethylene);
- IntHighTech: C1 (synthesis gas);
- NatHighTech: N-chemicals (caprolactam).

5.3.1 C2 (ethylene)

The production of petrochemical ethylene is mainly based on steam cracking of naphtha (83%) and other fossil resources (see section 3.4.1). Naphtha is refined from crude oil and cracked by steam cracking to produce ethylene and by-products (fuel oil and fuel gas). Fuel gas is used for the production of process heat and other processes on the side; fuel oil is sold as transport fuel [Wielen et al., 2006]. The bio-based production route includes ethanol production and dehydration of ethanol to ethylene. The production process of ethanol differs per biomass feedstock type as described in section 5.2.1. The fossil and bio-based production routes, as used in this study, are displayed in Figure 14.

The production cost of fossil-based ethylene is based on the linear relation between

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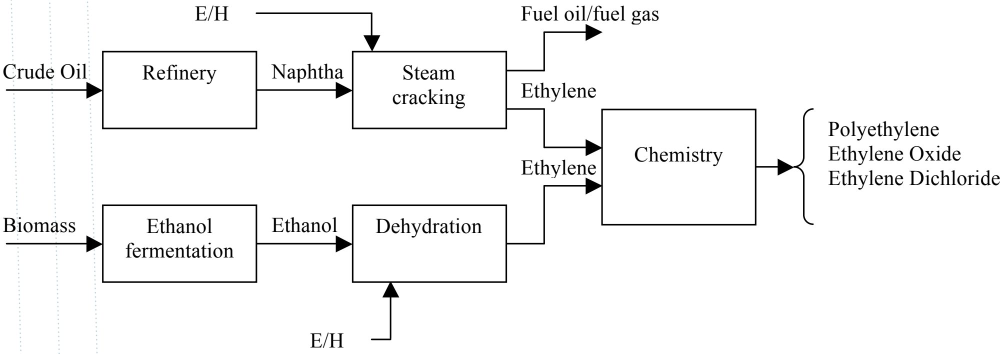
[30] Benzene, Toluene, Xylenes.

[31] Cost reductions through technological learning exhibit a logarithmic trend. Therefore, we assume that the largest cost reductions are achieved between 2010 and 2020. Note that more research is required to make more accurate cost trends for these new technologies.

[32] The production of biodiesel from biomass via FT synthesis is still in a pre-commercial phase. Cost reductions are expected as a result of technological learning when the technology is deployed on a commercial scale.

crude oil prices and prices of fossil raw materials found by Meesters [Meesters, 2006]. For an oil price of 50 $US\$_{2006}$/bbl, the price of fossil-based ethylene was estimated to be 679 €/tonne. The capital and O&M costs of the bio-based ethylene production route (via ethanol dehydration) are derived from Patel et al. [Patel, Crank et al., 2006]. The investment costs are 410 €/tpa and O&M costs are 5 €/ton (including energy and utility costs) and are assumed to be constant over time[33]. A capital charge factor of 30% was assumed consistent with Patel et al. [Patel, Crank et al., 2006].

Figure 14 Production of ethylene, based on [Wielen, Nossin et al., 2006]



5.3.2 C1 (Synthesis gas)

For substitution of fossil-based synthesis gas by bio-based synthesis gas, we selected hydrogen production as representative route as shown in Figure 11. Although we also assume synthesis gas, methanol and carbon monoxide to be replaced by bio-based synthesis gas, the hydrogen production route is considered as representative route because the majority of synthesis gas is used for hydrogen production. Natural gas is converted into synthesis gas by steam methane reforming (SMR). The carbon monoxide in the synthesis gas is shifted at lower temperatures with steam to CO_2 and hydrogen. In some cases, acid gas removal is also required (AGR) before the CO_2 capture/hydrogen separation process. For the bio-based process route, pre-treated biomass is gasified in a gasifier and the produced synthesis gas is cleaned before it is shifted and acid gas is removed. The CO_2 separation process is similar to the natural gas process.

The current and future techno-economic performance of hydrogen production from biomass via gasification was analysed by [Hamelinck et al., 2002] in the context of advanced transport fuels for fuel cell vehicles (FCV). We consider this process to be representative for the chemical industry. System selections and the overall plant performance are therefore taken from [Hamelinck and Faaij, 2002] as summarised below.

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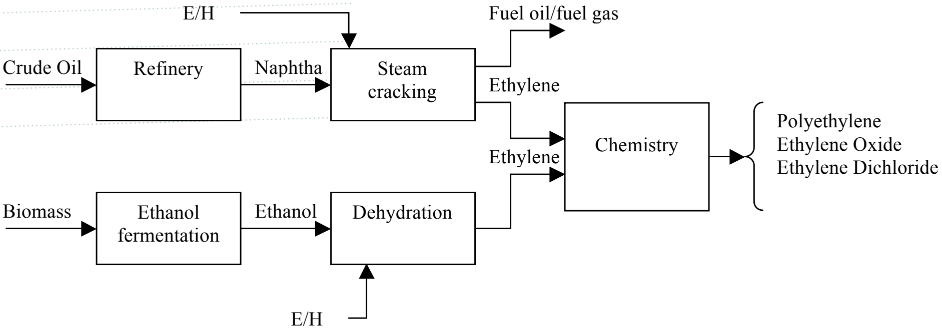
[33] We assumed that cost and performance of petrochemical ethylene and bio-based ethanol are constant in time (no learning) because these processes are mature, standardised chemical processes with limited learning potential. Production cost of the bio-based route decrease in time as a result of learning in ethanol production as described in section 5.2.1.

Figure 15 Synthesis gas route from natural gas to chemicals, based on [Hamelinck and Faaij, 2006; Song and Guo, 2006]



For hydrogen production from natural gas, we consider a 126 kton/a output plant (527 MW_{LHV} hydrogen output). Cost and performance of hydrogen production via SMR were taken from NREL [Rutkowski, 2008]. The capital investment costs for this plant are 145 M€ for 2006-2010 and decrease to 108 M€ in 2030. O&M costs are estimated to be 4% of the investment cost annually, and the conversion efficiency is 0.73 $MJ/MJ_{LHV.}$ The conversion efficiency does not improve in the projected period [Rutkowski, 2008].

For hydrogen production from lignocellulosic biomass, we consider the short, medium and long-term projections of cost and performance from Hamelinck et al. [Hamelinck and Faaij, 2002; Hamelinck and Faaij, 2006]. The short-term estimates are used for 2006-2010 because we expect little progress between 2006 and 2010. The medium and long-term estimates are used for 2020 and 2030 respectively. The conversion efficiency improves from 0.31 MJ/MJ_{LHV} in 2010 to 0.36 and 0.37 MJ/ MJ_{LHV} for 2020 and 2030 respectively. The hydrogen production plant is estimated to increase from 28 tonne/a in 2010 to 86 tonne/a in 2020 and 166 tonne/a in 2030, with a scale factor of 0.86. Capital investment costs are estimated to be 1035 €/ tonne, 648 €/tonne and 583 €/tonne in 2010, 2020 and 2030 respectively for the assumed scales. O&M costs are 4% of the investment cost. Electricity is co-produced with an efficiency of 16.9-19.7% (HHV).

5.3.3 Caprolactam

For the production of caprolactam, a variety of conversion routes are possible from both fossil resources and biomass. Petrochemical-based caprolactam can be produced via at least four production routes (butadiene, cyclohexane, phenol and toluene), but in the Netherlands, caprolactam is produced via phenol hydration[34] with ammonium sulphate as co-product. Steam, fuel and electricity are required to run the process [Neelis, 2006].
Bio-based caprolactam is produced from lysine synthesis. Lysine can be produced

[34] $2\ C_6H_5O(l) + 17.08\ NH_3(g) + 3\ H_2(g) + 4.52\ S(s) + 3.02\ H_2SO_4(l) + 6.78\ O_2(g) + 4.52\ H_2O(g) \rightarrow 2\ C_6H_{11}ON(l) + 7.54\ (NH_4)\ 2\ SO_4(s)$ [Neelis, 2006].

via fermentation or can be extracted directly. Extraction of lysine directly from plant residues or GMO biomass can potentially lower the production cost significantly, because cost-intensive fermentation processes can be avoided [Sanders, Engelen et al., 2006]. In this study, the fermentation route is chosen because extraction processes and improved biomass production with lysine accumulation are far from commercialisation. The production route of lysine to caprolactam is also not yet commercialised, but is being developed by DSM and TU Delft [Sanders, Engelen et al., 2006]. We assume that this process is commercially available from 2010 onwards.

Production cost and yields of caprolactam production via lysine fermentation of fermentable sugars are based on [Patel, Crank et al., 2006]. The production yield of caprolactam from fermentable sugars is 0.39 kg/kg. Investment costs are estimated to be 1300 €/tpa and O&M costs are 460 €/tonne caprolactam. For the conversion of sugar beet to fermentable sugars, cost data are derived from [USDA, 2006] and conversion data from [Elsayed, Matthews et al., 2003]. The yield of co-produced pulp (mc = 97%) is 1.56 kg/kg soiled sugar beets. Sugar beet processing requires electricity for preparation, shredding and diffusion and steam for diffusion. Pulp is sold for animal feed.

Elsayed et al. present a detailed overview of ethanol processing from sugar beets. We assume that the pre-treatment processes, i.e. preparation, shredding and diffusion (reverse osmosis), are similar for lysine fermentation as for ethanol fermentation. The yields of fermentable sugars from soiled sugar beets are estimated to be 0.14 kg/kg.
We assumed production costs of fermentable sugars to be 50% of the production of refined sugars[35]. The revenues for co-produced pulp are estimated to be 6 €/tonne pulp [Hamelinck and Hoogwijk, 2007].

5.4 Technology assumptions

Table 11 and Table 12 summarise the production costs and performance of the conversion technologies for electricity, biofuels and chemicals. The underlying assumptions are presented in the technology descriptions (sections 5.1- 5.3).

The conversion efficiencies and costs are used to estimate the demand for biomass and production cost, based on the scenario assumptions (section 4). The demand for biomass and costs are discussed in the following sections (section 6 and 7 respectively).

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[35] No explicit cost estimations were found for processing of sugar beets to fermentable sugars. Production costs of refined sugars from sugar beets in the US are estimated to be about 426 €/ton including revenues of by-products (pulp and molasses) [USDA, 2006]. For fermentation, raw sugar beet juice does not have to be processed in to crystallised sugars. Costs are therefore assumed to be 50% of crystallised sugar production.

Table 11 Cost and performance of electricity generation technologies (left) and biofuel production (right) per year (data presented in LHV and dm)

Electricity generation				
Technology	**2006**	**2010**	**2020**	**2030**
Conversion efficiency in %				
NGCC	56	58	60	63
NGCC Co-gasification (25%)	50	52	56	60
PC	40	46	49	52
PC Co-firing (10%)	40	46	49	52
PC Co-firing (20%)	40	46	49	52
MSW	13	29	29	29
Biomass digestion	15	15	15	15
Capex (€/kW)				
NGCC (reference)	500	500	450	450
NGCC Co-gasification (25%)	704	697	617	592
PC (reference)	1200	1182	1100	1053
PC Co-firing (10%)	1225	1207	1125	1078
PC Co-firing (20%)	1225	1232	1150	1103
MSW	2700	2700	2700	2700
Biomass digestion	3700	3700	3700	3700
Opex (€/GJ)				
NGCC (reference)	1.4	1.3	1.3	1.2
NGCC Co-gasification (25%)	5.0	5.0	5.0	5.0
PC (reference)	9.1	8.7	8.1	7.4
PC Co-firing (10%)	9.6	9.2	8.7	8.0
PC Co-firing (20%)	9.6	9.7	9.2	8.7
MSW	1.4	1.4	1.4	1.4
Biomass digestion	58.0	58.0	58.0	58.0
Generating cost (excl. Feedstock) (€/MWh)				
NGCC (reference)	10	10	9	9
NGCC Co-gasification (25%)	17	17	16	15
PC (reference)	27	27	25	23
PC Co-firing (10%)	28	27	26	24
PC Co-firing (20%)	28	28	27	25
MSW	61	61	61	61
Biomass digestion	104	104	104	104
CoE (€/MWh) including fuel costs				
NGCC (reference)	49	47	45	43
NGCC Co-gasification (25%)	58	57	52	49
PC (reference)	45	42	40	37
PC Co-firing (10%)	49	45	42	40
PC Co-firing (20%)	49	48	45	43
MSW	65	62	62	62
Biomass digestion	104	104	104	104

Biofuel production				
Technology	**2006**	**2010**	**2020**	**2030**
Conversion efficiency in GJfuel/GJbiomass				
FAME (veg. oil)	1.0	1.0	1.0	1.0
FAME (oil and fat residues)	1.0	1.0	1.0	1.0
EtOH from starch (wheat)	0.52	0.52	0.52	0.52
EtOH from sugar (sugar beet)	0.45	0.45	0.45	0.45
EtOH from sugar (sugar cane)	0.40	0.43	0.44	0.45
FT- diesel	0.41	0.41	0.41	0.41
EtOH from lign. biomass	0.33	0.33	0.36	0.44
Capex (€/GJ)				
FAME (veg. oil)	0.63	0.63	0.57	0.55
FAME (oil and fat residues)	0.94	0.94	0.86	0.83
EtOH from starch (wheat)	2.77	2.10	2.10	2.10
EtOH from sugar (sugar beet)	2.48	2.44	2.36	2.24
EtOH from sugar (sugar cane)	2.20	2.07	1.79	1.54
FT- diesel	7.66	7.66	5.81	4.85
EtOH from lign. biomass	9.17	9.17	6.18	4.20
Opex (€/GJ)				
FAME (veg. oil)	2.31	2.31	2.29	2.28
FAME (oil and fat residues)	2.40	2.40	2.37	2.37
EtOH from starch (wheat)	3.86	3.72	3.32	3.21
EtOH from sugar (sugar beet)	2.20	2.17	2.13	2.07
EtOH from sugar (sugar cane)	2.43	2.29	1.98	1.70
FT- diesel	2.87	2.87	2.18	1.82
EtOH from lign. biomass	5.00	5.00	2.63	1.29
Revenues (€/GJ)				
FAME (veg. oil)	1.61	0.80	0.40	0.00
FAME (oil and fat residues)	1.61	0.80	0.40	0.00
EtOH from starch (wheat)	8.56	8.56	8.56	8.56
EtOH from sugar (sugar beet)	5.17	5.17	5.17	5.17
EtOH from sugar (sugar cane)	0.73	0.73	0.73	0.73
FT- diesel	1.28	1.28	1.28	1.28
EtOH from lign. biomass	1.69	1.69	5.31	1.26
Fuel production cost (excl. feed				
FAME (veg. oil)	1.33	2.13	2.46	2.84
FAME (oil and fat residues)	1.74	2.54	2.83	3.20
EtOH from starch (wheat)	-1.94	-2.75	-3.14	-3.26
EtOH from sugar (sugar beet)	-0.49	-0.56	-0.68	-0.87
EtOH from sugar (sugar cane)	3.90	3.63	3.03	2.51
FT- diesel	9.25	9.25	6.71	5.38
EtOH from lign. biomass	12.47	12.47	3.49	4.23

Only available in the high-tech scenarios

Table 12 Cost and performance of bio-based chemical production

Chemicals				
Technology	**Year**			
	2006	**2010**	**2020**	**2030**
Conversion efficiency in kg/kg (dm)				
Ethylene from ethanol	0.61	0.61	0.61	0.61
Caprolactam (sugar beet)	0.39	0.39	0.39	0.39
Hydrogen (woody biomass)	0.05	0.05	0.06	0.06
Capex (€/tpa)				
Ethylene from sugar cane	410	410	410	410
Caprolactam (sugar beet)	1300	1300	1300	1300
Hydrogen (woody biomass)	8811	8811	5513	4966
Opex (€/tonne)				
Ethylene from sugar cane	17	17	17	17
Caprolactam (sugar beet)	460	460	460	460
Hydrogen (woody biomass)*	-807	-807	-927	-940
Production cost (excluding feedstock) (€/tonne)				
Ethylene from sugar cane	140	140	140	140
Caprolactam (sugar beet)	850	850	850	850
Hydrogen (woody biomass)	228	228	-279	-357
Production cost (including feedstock (€/tonne)				
Ethylene from sugar cane	907	855	802	756
Caprolactam (sugar beet)	1473	1473	1473	1473
Hydrogen (woody biomass)	1999	1999	1224	1135
Prices of fossil chemicals (including feedstock (€/tonne)				
Ethylene	678	678	678	678
Caprolactam	1488	1488	1488	1488
Hydrogen	737	737	717	696

*) Including revenues from electricity generation of 14 €/GJ (based on NGCC reference plant).

6 DEMAND AND SUPPLY OF BIOMASS

This section describes the demand for (and supply of) biomass, based on the projected energy demand from the WLO scenarios (chapter 4), the assumed substitution fractions of biomass and the used conversion technologies. Section 6.1 describes the demand for biomass to be used for heat and power, biofuels and chemicals, based on data from chapter 4. Section 6.2 describes the supply of biomass from both domestic and international sources.

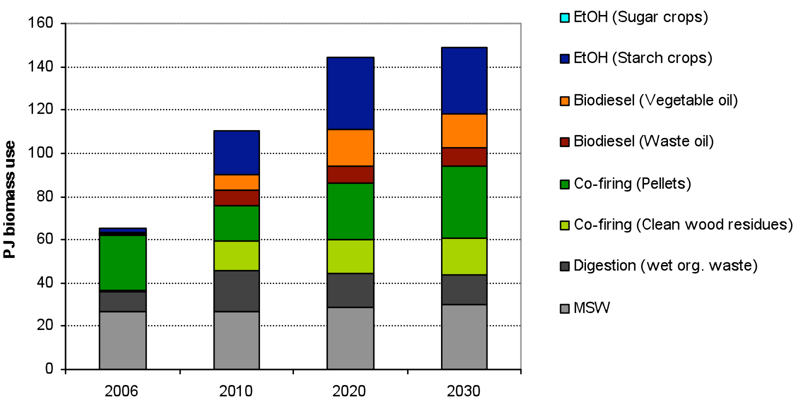
6.1 Demand for bioenergy and bio-based chemicals

The demand for biomass to be used for energy generation and the production of bio-based materials are described per scenario in section 6.1.1 through 6.1.4. The demand is based on assumed bio-based electricity generation, transport fuels and chemicals produced from biomass and the respective conversion efficiencies. Included are residues from domestic resources. These are included because the demand depends on domestic availability of these resources plus the demand for bioenergy crops and imported biomass. The demands for MSW, wet organic waste (digestion) are similar in all scenarios, as is the production of biodiesel from domestic fat and oil residues, because the demands are the same as the supply of these streams within the Netherlands. The demand for biomass in the different scenarios is also summarised in the results section in Figure 34.

6.1.1 NatLowTech

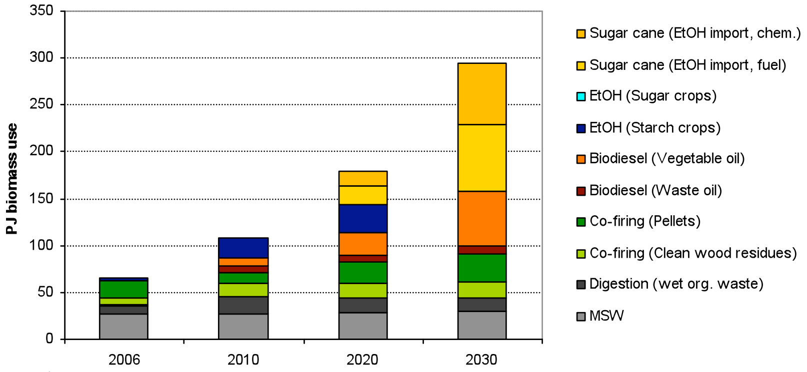
Due to conservative assumptions on bioenergy and the exclusion of bio-based chemicals, the demand for biomass can be met for a large fraction by domestic residues (Figure 16). For co-firing, wood pellets also have to be imported from other European countries because the domestic supply of clean wood residues is not sufficient (e.g. from EU forestry residues). Dedicated sugar/starch and oil crops have to be produced in the Netherlands or other European countries for biofuel production. In this scenario we assumed starch crops (wheat) to be used for ethanol production and rapeseed for biodiesel production. Note that part of biodiesel is also produced from domestic oil and fat residues.

Figure 16 Biomass demand for the NatLowTech scenario



6.1.2 IntLowTech

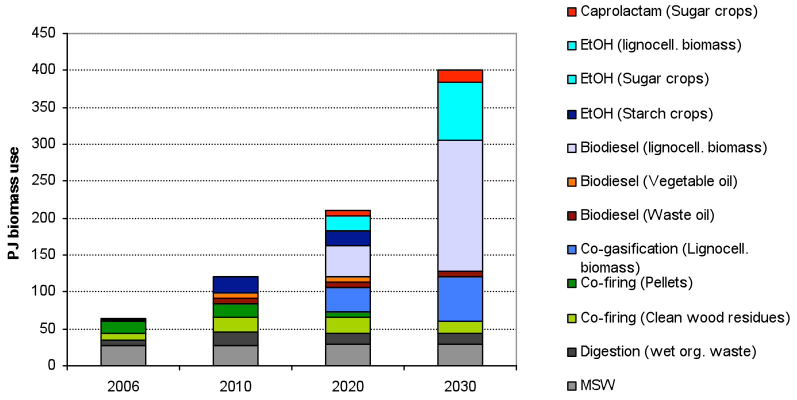
Figure 17 Biomass demand for the IntLowTech scenario



Although the technological development, and therefore the performance of biomass conversion technologies in the IntLowTech scenario, are similar to the NatLowTech scenario, almost twice the amount of biomass is required relative to the NatLowTech scenario (Figure 17). The biomass demand for electricity generation is almost similar in the IntLowTech scenario because we assumed similar technologies and blending shares (10% co-firing in existing PC plants and 20% co-firing in new PC-plants). The amount of biomass required for biofuel production is much larger as a result of higher blending shares (20% in 2030) and the higher absolute demand for transport fuels in the IntLowTech scenario. In 2020 and 2030, ethanol demand required for ethylene production also adds significantly to the total demand (19 PJ and 72 PJ of sugar cane in 2020 and 2030 respectively).

6.1.3 NatHighTech

Figure 18 Biomass demand for the NatHighTech scenario



The total demand for bioenergy crops is a little higher in the NatHighTech scenario than in the IntLowTech scenario (Figure 18). Although limited sugar crops are required for the production of bio-based caprolactam, the introduction of 2^{nd}-generation biofuel production technologies in 2020 and 2030 increases the demand for lignocellulosic biomass. The dominant share is required for biodiesel production via FT-synthesis because the energetic conversion efficiency from lignocellulosic biomass to FT-diesel is relatively low (41%) compared to transesterification processes of 1st-generation biodiesel production (~100%). Note that FT-synthesis still outperforms 1st-generation diesel production in terms of primary energy and avoided GHG emissions (section 7.2).

6.1.4 IntHighTech

Figure 19 Biomass demand for the IntHighTech scenario

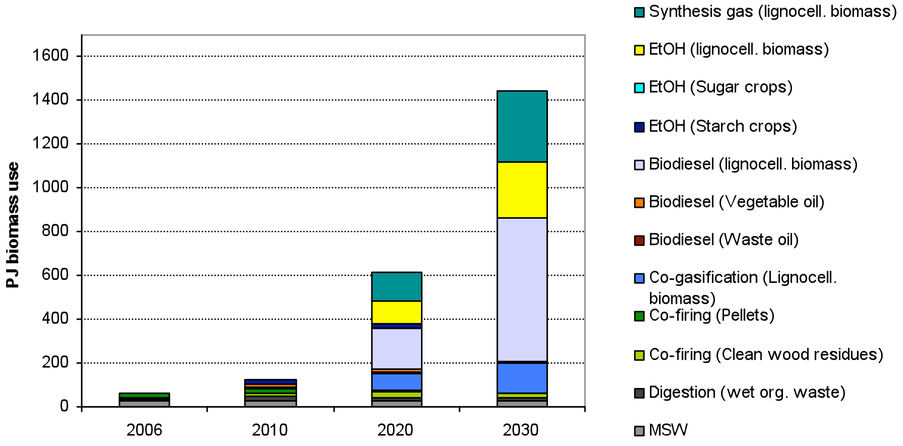


Figure 19 displays the demand for biomass for the IntHighTech scenario. The total demand for bioenergy is about ten times higher than the biomass demand in the NatLowTech scenario in 2030. The demand for biomass in the electricity sector is limited by the demand for co-firing in existing PC plants and co-gasification in new NGCC plants to 20%. The demand for lignocellulosic biomass for gasification and production of FT-diesel and hydrogen is dominant in this scenario. Note that part of the biomass that is used for the production of 2nd-generation biofuels and synthesis gas is converted into electricity by co-production with biofuels and chemicals, as shown in Figure 9.

6.1.5 IntHighTech AC

Figure 20 Biomass demand for the IntHighTech AC scenario

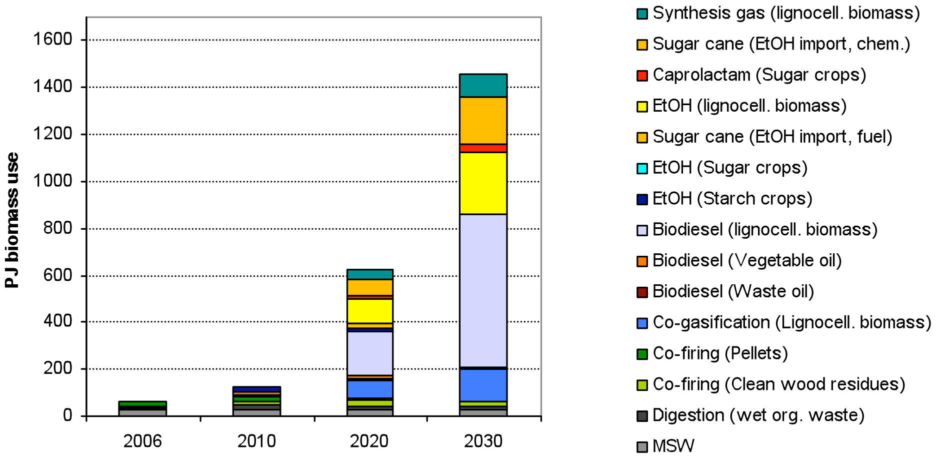


Figure 20 summarises the demand for biomass in the IntHighTech AC scenario. Apart from the production of chemicals and co-generation of electricity in the chemical industries, this scenario is similar to the IntHighTech scenario. There is little difference in the total amount of biomass required (about 10 PJ), but the biomass production mix is different. In this scenario, sugar is required for caprolactam production and ethanol production, the feedstock for ethylene. Note that also ethanol from lignocellulosic biomass is produced in this scenario, although this is not integrated into the production model for chemicals. As ethanol from sugar cane is in the same price range and is a robust greenhouse gas saver, the difference between these options will be limited.

6.2 Biomass supply

For the production of bioenergy and bio-based chemicals, both residues and energy crops from domestic and international resources are required. For all scenarios, we assumed that available domestic residues would be used before energy crops. The domestic supply of biomass is described in section 6.2.1. Since the domestic supply of biomass is not sufficient to meet the demand in all scenarios, additional biomass has to be imported. We limited the supply of biomass in the National scenarios to EU27+ resources, while in the International scenarios, global biomass resources are available for the Netherlands.

6.2.1 Domestic supply

The supply of biomass from Dutch resources exists from residue streams (primary[36], secondary[37] and tertiary[38]) and the production of dedicated energy crops. Since production land is scarce in the Netherlands, the main supply will be available from residue streams as shown in Table 13. Estimations of the domestic supply of biomass in 2010 and 2030 are based on [Koppejan et al., 2005] and PGG studies [Rabou, Deurwaarder et al., 2006; Sanders, Engelen et al., 2006; Kip et al., 2007]. Values for 2020 are interpolated from 2010 and 2030 figures.

Table 13 Availability of domestic biomass resources, based on [Koppejan and Boer-Meulman, 2005; Rabou, Deurwaarder et al., 2006; Kip, Lammers et al., 2007]

	Energy content [PJ/year]				Price[6] [Euro/GJ supplied]		Conversion option
Biomass resource type	**2006**	**2010**	**2020**	**2030**	**Nominal**	**Min - Max**	
Oil and fat residues[1]	0.3	10	11	12	7	2.0 -10	Transesterification (F)
Solid organic waste[2]	-	56	76	96	1	-4.8 - 4.8	Combustion (H)
Wet organic waste[3]	8	19	16	14	-7	-30.0 - 0	Digestion (E/H)
Clean wood[4]	8.2	39	44	49	1	0.0 - 10	Co-firing/gasification (E/F/C)
Residues from agriculture and landscape maintenance[5]	0	4	44	83	0	-8.3 - 6	Gasification (E/F/C)
Municipal solid waste	27	27	29	30	-12	-12 - -12	Combustion (E/H)
Energy crops	7.8	0	27	54	N/A	N/A - N/A	All
Grass production	0	0	26	51	N/A	N/A - N/A	Gasification (E/F/C)
Total	**47**	**154**	**219**	**283**			

1) Animal fat, discarded frying oil, fatty acids
2) Separated wood (C quality), food processing residues (excluding fat and oil residues, swill), assorted wood from waste streams, RDF (refuse-derived fuel, only organic fraction), non-compostable fractions. Current (2006) use for E / H unknown.
3) Manure, swill, water treatment sludge, organic household waste, landfill gas
4) Fresh residue wood (blocks and shredded), clean wood residues, separated wood (A and B), sawdust & curls, oil seed residues.
5) Grain straw, verge grass, grass hay, hemp & flax, straw
6) Average cost of biomass at factory gate (based on Koppejan et al., 2005)

Oil and fat residues

Oil and fat residues from slaughter and other food industries are already used for electricity generation and the production of biodiesel via transesterification. We assumed all future fat and oil residues to be used for the production of biodiesel as

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[36] Primary by-products are biomass by-products that become available directly at the source of production, such as grain straw, sugar beet tops and leaves, wood thinning etc. These by-products are already available, but are often left in the field because usage for energy purposes would require complex logistics and processing systems [Rabou et al., 2006].

[37] Secondary by-products are becoming available from processing of biomass, such as molasses from sugar production, or peals and oil seed residues from vegetable oil production [Rabou et al., 2006].

[38] Tertiary by-products are becoming available after the usage phase (e.g. manure, demolition wood, organic household waste etc.) [Rabou et al., 2006].

it is more advantageous to substitute petroleum products than coal or gas for electricity generation. Note that not all fat and oil residues might be suitable for the production of biodiesel. The impact on the final results at the level of detail of this study is marginal though.

Solid organic waste

Solid organic waste is the largest source of biomass available (86 PJ in 2030). This stream is very difficult to process though because of its heterogeneous content and contaminations. Furthermore, solid organic waste consists mainly of fractions that can be used for the production of RDF (refuse-derived fuel), of which the organic fraction is mainly pre-consumer waste paper. RDF paper is already used in the cement industry (heat) [Sikkema, Junginger et al., 2007]. We therefore allocated solid organic waste streams to heat production, which is not included in this study.

Wet organic waste

Wet organic waste streams include manure, swill, wastewater treatment sludge and organic household waste. We also included landfill gas[39] in this group as similar conversion options are used (small-scale CHP plants using biogas).

Although chemicals and transport fuels could also be produced form these residue streams [Rabou, Deurwaarder et al., 2006], we did not take these options into account, to avoid complexity of the model.

Clean wood

The clean wood fraction includes fresh residue wood (shredded and blocks), secondary wood residues (sawdust, curls and oil seed residues) and tertiary clean wood residues (A and B quality). Clean wood is assumed to be used for co-firing in efficient coal-fired power plants in the low-tech scenarios, and also for the production of transport fuels, chemicals and electricity via gasification in the high-tech scenarios. The costs of clean wood residues range from 0-10 €/GJ [Rabou, Deurwaarder et al., 2006], but the average costs are ~1 €/GJ. At costs above 3 €/GJ, imported woody crops become competitive.

Residues from agriculture and landscape maintenance

Lignocellulosic residues from landscape maintenance and agriculture are not directly suitable for co-firing in PC plants [IEA, 2008], but are assumed to be suitable for gasification (electricity, FT-diesel, synthesis gas) or 2nd-generation ethanol production. Because these technologies are only available in the high-tech scenarios, the amount of residues available for bioenergy and bio-based chemicals is larger in the high-tech scenarios than in the low-tech scenarios.

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[39] Landfill gas is combusted in comparable engines as biogas from anaerobic digestion. It has a higher efficiency though because it does not require fermentation. In order to avoid complexity of the model, we corrected the amount of landfill gas for the fermentation efficiency.

The production of primary by-products by agriculture is estimated to increase from 2 Mton/a DM in 2006 (30 PJ/a) to 3 Mton/a (45 PJ/a) in 2030, but 1 Mton/a DM might have to be left in the field to supply soil carbon and nutrients [Sanders, Engelen et al., 2006]. The net availability of primary-by products from agriculture is therefore estimated to be 2 Mton/a DM (30 PJ/a) in 2030, similar to [Sanders, Engelen et al., 2006].

Primary by-products from landscape maintenance such as verge grass or wood thinning also have the potential to become a significant source of bioenergy [Rabou, Deurwaarder et al., 2006]. The total availability of primary by-products from landscape maintenance is estimated to increase from 1.4 Mton/a DM in 2000 to 3.2 Mton/a DM (53 PJ) in 2030, as a result of increased productivity and larger areas of nature, recreation and forests in the Netherlands in 2030 [Kip, Lammers et al., 2007]. Harvesting, transportation and processing of these bio-energy sources are expected to be economically feasible in 2030 [Rabou, Deurwaarder et al., 2006; Kip, Lammers et al., 2007].

Similar to [Koppejan and Boer-Meulman, 2005], we assume that only a limited amount of primary by-products is available (4 PJ) in 2010. Our projections for 2030 are based on PGG studies estimating that 30 PJ/a will be available from agriculture [Sanders, Engelen et al., 2006] and 53 PJ/a from landscape maintenance [Kip, Lammers et al., 2007].

Municipal solid waste (MSW)

Municipal solid waste (MSW) is a heterogeneous source of energy consisting of organic and non-organic matter. Only energy produced from the organic fraction of MSW is considered bioenergy. The biogenic fraction of MSW was 47% (energy base) in 2004 [Bosselaar and Gerlagh, 2006]. We assumed this fraction to be constant over the projected period.

The biogenic fraction of MSW was 27 PJ in 2006, but limited increase is expected. Rabou et al. [2006] estimated the organic fraction of MSW to be 30 PJ in 2030. The amount of electricity produced from these waste fractions is expected to improve more rapidly due to replacement of retired MSW plants by more efficient technologies (section 5.1.1).

Dedicated energy crop production

The production potential of dedicated energy crops in the Netherlands is very uncertain and depends largely on agricultural subsidies and types of crops cultivated. Janssens et al. [2005] estimate the technological potential of arable land available around 47,000-62,500 ha. According to Rabou, Deurwaarder et al. [2006], 10% or 200,000 ha could be used for biomass production in 2030. Efficient biomass production of lignocellulosic crops, with yields of 16 ton DM/ha, would result in 3 Mton DM/a or 54 PJ. Furthermore, 300,000 ha of grass land could potentially become available as a result of the decreasing livestock and increasing trends in efficiency in the Netherlands. [Rabou, Deurwaarder et al., 2006] estimate that 30% of grass could be extracted from the currently produced grass (12 Mton). This would result in 3 Mton DM or ~50 PJ.

6.2.2 Types of (imported) energy crops

Although the demand ranges widely between the scenarios, in all scenarios the domestic supply of biomass from residues is not sufficient to meet the demand for bioenergy and bio-based chemicals. Dedicated energy crops are therefore required and, because the domestic supply potential of energy crops is limited, we considered biomass production within an international context. For the national scenarios, biomass is available from the EU27+[40] while global resources are available for the Netherlands in the international scenarios.

The production potential and cost of biomass from EU27+ resources are based on results of the REFUEL project [Fischer et al., 2007; Wit et al., 2007], including starch crops (wheat), sugar crops (sugar beet), oil crops (rapeseed and sunflower) and short rotation coppice (eucalyptus, poplar, willow). The supply curve results of this project are displayed in Appendix 3. The global supply of biomass for bioenergy is based on Hoogwijk et al. [2005] and Dornburg et al. [2008].

6.2.2.1 Rapeseed EU27+

Rapeseed methyl ester is produced from rapeseed, an annual crop that is cultivated on a four-year time basis, alternated with other crops to avoid soil impoverishment and plant diseases [Berghout, 2008]. Rapeseed is harvested, while rapeseed straw is either left on the field to maintain soil nutrients or sold as a by-product.

After harvesting, rapeseed is transported to the oil production plant where oil is extracted from the seeds by mechanical pressing and chemical extraction with solvents (hexane). Next to crude rape oil, rape meal is produced as by-product that can be used for animal fodder.

6.2.2.2 Jatropha oil

Jatropha oil is produced from jatropha shrubs that can be cultivated on low-quality agricultural land, with yields of around 2 tonne oil/ha/a and ranges from 1-4 tonne oil/ha/a, depending on the quality of the soil. The jatropha oil extraction process from the oil seeds produces crude jatropha oil and press cake (2.1 kg/kg crude jatropha oil). Press cake is used as fertiliser, with a market price of 35 €/tonne [Dornburg, Faaij et al., 2007]. The production cost of jatropha oil is estimated to be 5.4 €/GJ in 2006, rising to 4.4 €/GJ in 2030, including transport to the Netherlands.

6.2.2.3 Palm oil

Oil palm cultivation takes place in tropical regions, with main production shares in Malaysia and Indonesia. Crude palm oil (CPO) is extracted from oil palm fruit by

[40] EU27 + Norway, Switzerland and Ukraine.

pressing the outer layer of the palm fruit. CPO mills are located close to the oil palm production side to avoid build-up of fatty acids in harvested palm fruit. The inner kernel of the palm fruit is transported and crushed in a crushing plant and delivers palm kernel oil and kernel meal [Hamelinck and Hoogwijk, 2007]. Kernel meal is used as animal feed.

Production costs of palm oil are estimated to be 7.4 €/GJ in 2006, rising to 5.7 €/GJ in 2030, based Dornburg et al. [2007] and including cost of transport to the Netherlands.

6.2.2.4 Sugar cane

For the production of ethanol in the IntLowTech scenario, we assume ethanol from sugar cane as a major source of bioenergy for the Netherlands. The production of sugar cane is more economic than the production of e.g. starch for ethanol. The production costs of sugar cane are estimated to be 2.7 €/GJ [Damen, 2001; Hamelinck and Hoogwijk, 2007].

6.2.2.5 Sugar beet EU27+

Due to the high moisture content of sugar beets (75% [Wit, Faaij et al., 2007]), transport costs are relatively high. Therefore, we assumed sugar beets to be produced locally. The production costs of sugar beet are estimated to be 6-7.5 €/GJ [Wit, Faaij et al., 2007]. Local transport costs add 0.8 €/GJ.

6.2.2.6 Wheat crops (starch) EU27+

Wheat crops are already used on a large scale for the production of ethanol in Europe. The production costs of wheat are around 8.5-10 €/GJ, including transport to the Netherlands from other EU countries [Wit, Faaij et al., 2007].

6.2.2.7 Short rotation forestry, tropical wood

There is a wide range of woody biomass corps available that can be used for bioenergy production. For the international scenarios, we assumed that woody crops are produced from short rotation forestry in tropical regions. These crops are produced on agricultural land with good soil qualities and are harvested every 4-6 years (in the case of eucalyptus).

We used production cost estimates from Dornburg et al. [2007] for eucalyptus production in tropical regions. Eucalyptus is assumed to be produced and pelletised closed to the source of production. Pellets are shipped to the Netherlands to avoid high transport costs. The total production costs, including pre-treatment and transport, are estimated to be 3.3 €/GJ in 2006, falling to 2.7 €/GJ in 2030.

6.2.2.8 Short rotation forestry EU27+

Short rotation forestry in temperate climate regions include crops that are typically harvested every 3-6 years, and include species such as willow and poplar wood [Dornburg, Faaij et al., 2007]. Costs for woody crops produced in the EU27+ are based on REFUEL [Wit, Faaij et al., 2007] and are estimated to be 4.3 €/GJ, including pre-treatment and transport to the Netherlands.

6.2.3 Imported biomass, demand and availability

The demand for biomass for bioenergy and bio-based chemicals in 2030 varies between 144 PJ for the NatLowTech scenario (Figure 16) and 1458 PJ in the IntHighTech scenario (Figure 19). Although a substantial part can be met by domestic residues ranging from 16% in the IntHighTech scenario to almost 70% in the NatLowTech scenario, imports of dedicated energy crops or residues are required in order to meet the demand for bioenergy in the Netherlands.

A wide range of studies is available that analyse the global potential of biomass for bioenergy of which the most important studies are described in Dornburg, Faaij et al. [Dornburg, Faaij et al.]. The resulting supply potentials of global biomass resources of these potential biomass studies range widely from 0 to over 1,500 EJ in 2050, mainly as a result of assumptions on land availability for energy crop production and crop yields. Dornburg, Faaij et al. [2008] estimated that around 500 EJ of biomass could potentially be available in 2050 from sustainable sources (residues, forestry and energy crops).

This study does not include estimations on global biomass demand for the future. To quantify if the amount of biomass required for the Netherlands is feasible according to projected availabilities we assumed that the fraction of biomass available for the Netherlands equals the quotient of the primary energy demand of the Netherlands and the primary energy demand in the EU27+ for the national scenarios and the world for the international scenarios. We used the WLO projections for primary energy use for the Netherlands and projections by the IEA World Energy Outlook [IEA, 2007][41] for projections of the European and global energy demand through 2030 (Table 14). Primary energy consumption in the Netherlands was 3.3 EJ in 2005 [CBS, 2008] and is projected to be 3.0 EJ in the NatLowTech scenario, rising to 4.5 EJ in the IntHighTech scenario in 2030. The share of primary energy consumption in the Netherlands relative to Europe and the world was 4.2% and 0.7% respectively in 2005. The global share in the international scenarios is projected to decrease to 0.5- 0.7% in 2030. The shares relative to Europe range from 3.4 to 5.5% in the national scenarios in 2030. The ratios of primary energy consumption in the Netherlands relative to Europe and the world are assumed to be similar to the shares of European and global biomass production available for the Netherlands in this study.

[41] Although projections of the 'Four Futures of Europe' scenarios [Bollen et al., 2004] are more consistent with the national WLO scenarios, these projections are limited to the EU15 region, while this study deals with the EU27+ region for supply of biomass in the national scenarios [Wit et al., 2007]. We therefore used projections by the IEA OECD-Europe region for the National scenarios.

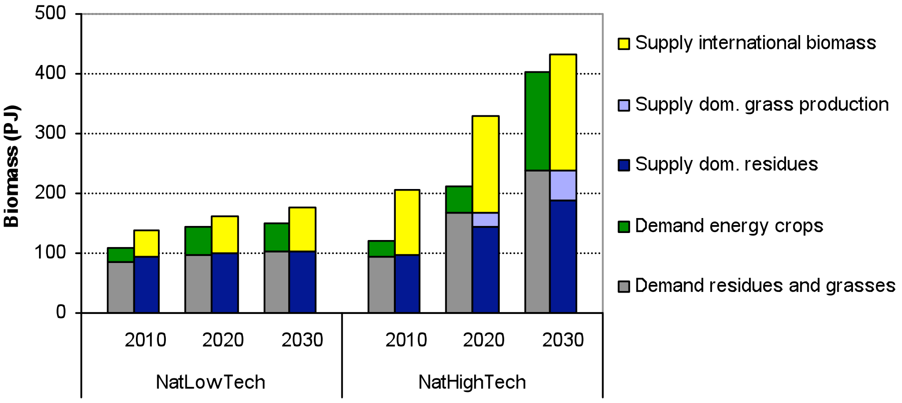
Table 14 Primary energy requirements for the World and Europe [IEA, 2007] and the Netherlands [Janssen et al., 2006]

Scenario	Baseline	Projections		
	2005	2010	2020	2030
World (alt. - ref. scenario)[a]	478.5	526.1 - 536.4	604.7 - 644.9	660.8 - 741.9
OECD-Europe (alt. - ref. scenario)[b]	78.5	79.5 - 81.0	80.9 - 85.4	80.9 - 89.1
NatLowTech - NatHighTech[c]	3.3	3.3 - 3.5	3.2 - 3.8	3.0 - 4.5
IntLowTech - IntHighTec[d]	3.3	3.4 - 3.5	3.6 - 4.0	3.5 - 4.5
NatLowTech and NatHighTech[e]	4.2%	4.0% - 4.4%	3.8% - 4.7%	3.4% - 5.5%
IntLowTech and IntHighTech[f]	0.7%	0.6% - 0.7%	0.6% - 0.7%	0.5% - 0.7%

a) Global projections of the World Energy Outook 2007 [IEA, 2007] for the alternative policy and reference scenario respectively.
b) OECD-Europe projections of the World Energy Outlook 2007 [IEA, 2007] for the alternative policy and reference scenario respectively.
c) Projections of primary energy consumption in the NatLowTech and NatHighTech scenario respectively (based on the WLO RC and TM projections [Janssen et al., 2006]
d) Projections of primary energy consumption in the IntLowTech and IntHighTech scenario respectively (based on the WLO SE and GE projections [Janssen et al., 2006]
e) Share of the primary energy consumption in the Netherlands relative to Europe
f) Share of the primary energy consumption in the Netherlands relative to the world

Figure 21 and Figure 22 show the demand and supply of biomass for the Netherlands in the national and international scenarios respectively. The demand in these figures is the result of the produced bioenergy and bio-based materials and conversion efficiencies in this study. The supply of biomass is based on projection studies on the potential supply of biomass for bioenergy. Domestic production of energy crops is not dealt with separately as production in the Netherlands is already included in the potential of biomass for the EU27+.

Figure 21 Biomass demand and potential supply in the national scenarios (biomass available from EU27+ sources)

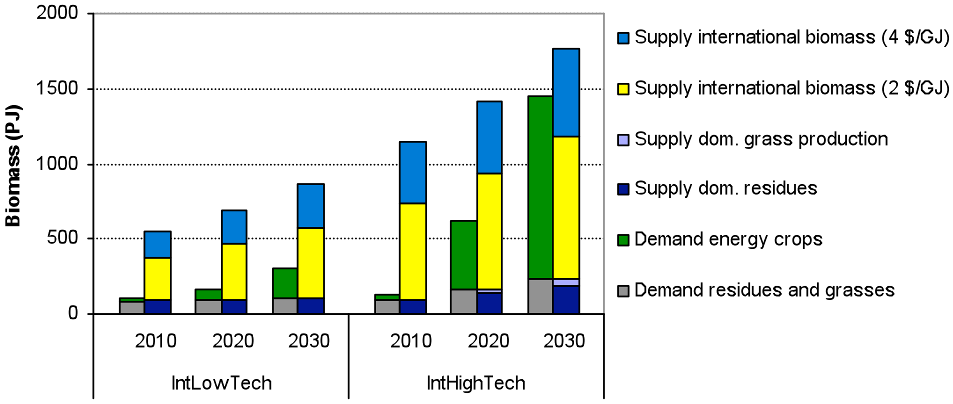


Domestic supply based on PGG [Rabou, Deurwaarder et al., 2006; Kip, Lammers et al., 2007], EU27+ supply based on REFUEL [Wit, Faaij et al., 2007].
Imports of biomass in the national scenarios are limited to EU27+ resources. The

amount of biomass that can be produced in this region was estimated to be 3.2 EJ[42] to 18.4 EJ[43] depending on crop type [Wit, Faaij et al., 2007]. In this study, we considered rapeseed and starch crops representative for the NatLowTech scenario. For the NatHighTech, we considered woody crops (willow and poplar) to be representative. For potentials, we only included the production potential within a lower price range,[44] as also shown in the appendix.

In both national scenarios, sufficient biomass is available to meet the demand, but the difference between supply and demand is small, even with the assumption that only high-yield woody crops are produced in the NatHighTech scenario. If domestic grass production is not taken into account, production prices of woody crops could increase to 4 €/GJ, excluding pre-treatment and transport to the Netherlands.

Figure 22 Biomass demand and potential supply in the international scenarios (biomass available from global sources)



Domestic supply based on PGG [Rabou, Deurwaarder et al., 2006; Kip, Lammers et al., 2007], international supply based on global supply of woody energy crops in the IPCC SRES scenarios [Hoogwijk, Faaij et al., 2005].

In the international scenarios, global sources of biomass are assumed to be available for the Netherlands. For the IntLowTech scenario, this is mainly vegetable oil for biodiesel from jatropha and palm fruit and ethanol from sugar cane. In the IntHighTech scenario, woody biomass is mainly required (Figure 19). We used projections by Hoogwijk et al. [2005], who estimated the amount of global biomass for bioenergy available in the SRES scenarios if SRC is produced. The IntLowTech and IntHighTech scenarios correspond with the SRES B1 and SRES A1 scenarios respectively. Hoogwijk [2005] estimated a geographical potential of 244 EJ in the

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[42] Oil crops (rapeseed and sunflower).

[43] Grassy crops including production on grassland.

[44] Production price: <6 €/GJ for oil crops, <7 €/GJ for starch crops, <2.5 €/GJ for woody crops.

SRES B1 and 390 EJ in the SRES A1 scenario for 2030. About 40% of the geographical potential can be produced below 2 US$$_{2000}$/GJ and about 65% can be produced below 4 US$$_{2000}$/GJ. The economic potentials for <2 and <4 US$/GJ are displayed in Figure 22.

For the IntLowTech scenario, international biomass resources are sufficiently available to meet the demand for bioenergy and bio-based chemicals in the Netherlands. It should be noted though that supply projections are based on woody crops (SCR) whereas the required biomass consists of oil crops and sugar crops. The supply of these lower-yield crops (especially vegetable oil) could therefore be substantially lower. For the IntHighTech scenario, the high demand for woody crops (more than 1200 PJ in 2030) results in imports of more costly biomass feedstocks.

7 ECONOMIC AND ENVIRONMENTAL PERFORMANCE

The performance and economics of the conversion technologies and cost of crop production in this study are discussed in section and section 6 respectively. This section covers the economic (7.1), energetic and environmental performance (7.2) of the complete production chains of fossil and bio-based production considered in this study.

7.1 Cost data

7.1.1 Fossil fuels

Cost assumptions for the fossil fuels in this study are given in Table 15. In this study, biofuels for road transport are included that are direct substitutes of fossil fuels (petrol and diesel). It depends on the prices of the fossil fuels saved by substitution, what the additional costs or profits are. Prices of diesel and petrol are linked to crude oil prices with prices ranging from 1.2 to 1.4 times the price of crude oil on mass basis [JRC et al., 2007]. Similar to [Wielen, Nossin et al., 2006], we selected a ratio of 1.2 for both petrol and diesel for the production costs of diesel and petrol. For prices of diesel and petrol at the filling station, we used data from BOVAG [2008]. The estimated diesel and petrol prices are also displayed in Table 15.

Table 15 Prices of fossil fuels and transport fuels for crude oil at 50 $\text{US\$}_{2006}$/bbl

	€$_{2006}$/GJ	€$_{2006}$/l
Coal	2	
Natural gas	6	
Crude oil price[a]	6.8	(0.25)
Diesel[b]	8.5	(0.30)
Petrol[b]	9.3	(0.30)
Diesel[c]	42	(1.17)
Petrol[d]	52	(1.62)

a) US$2006 to €2006 exchange rate: 0.80.
b) Production price (1.2 times the price of crude oil on mass basis).
c) Consumer price at filling station, including distribution cost (0.068 €/l), profits from oil company and filling station (0.014 and 0.035 €/l respectively), (excise) taxes (0.382 €/l) and turnover tax (19% of price at filling station).
d) Consumer price at filling station, including distribution cost (0.068 €/l), profits from oil company and filling station (0.014 and 0.048 €/l respectively), (excise) taxes (0.694 €/l) and turnover tax (19% of price at filling station).

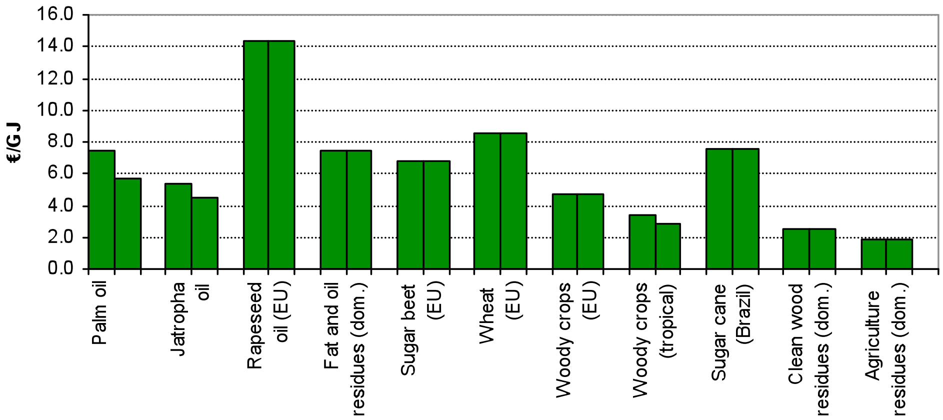
7.1.2 Cost of biomass

Biomass production costs are based on bottom-up estimates from various studies including cost reductions from improvements in agriculture as described in section 6.2. The cost of EU crops (rapeseed, sugar beet, wheat and woody crops) are assumed constant because we considered the supply range that is available under a certain production price as shown in the cost supply curves. Thereby, technological learning results in an increased supply for the given cost range [Wit, Faaij et al., 2007]. Prices for domestic residues are derived from Rabou et al. [2006] and prices for non-EU energy crops are derived from Dornburg et al. [2007] and Hamelinck et al. [2007].

Biomass production costs include capital cost for management (e.g. machinery, fertiliser, seeds etc.) labour costs and land-rent costs. The production costs also include the first step of pre-treatment, e.g. oil extraction from oil seeds and pelletising of woody biomass and agricultural residues [Hamelinck et al., 2005; Dornburg, Faaij et al., 2007] and transport.

Note that the cost estimates for biomass feedstock represent production costs and not market prices. The influence of feedstock prices by increasing the demand are assessed in the follow-up part of this study, using macro-economic modelling.

Figure 23 **Cost of biomass feedstocks at factory gate (€/GJ)**



Left bars are for 2006, right bars are for 2030.

The prices of biomass feedstock are cheapest[45] for agricultural residues (1.85 €/GJ) and clean wood residues (2.5 €/GJ). The prices of dedicated energy crops are lowest for woody crops produced in tropical regions (3.4 and 2.8 €/GJ in 2006 and 2030 respectively) and highest for rapeseed oil produced in the EU27+ (14.3 €/GJ). The costs for conversion are relatively low though for vegetable oils, as shown in Figure 24. Vegetable oils from palm fruit (7.4 to 5.7 €/GJ) or jatropha (4.5 to 5.4 €/GJ) are much cheaper than vegetable oil from rapeseed. The prices for biodiesel production are therefore considerably lower in the IntLowTech scenario than in the NatLowTech scenario. In the High-Tech scenarios, biodiesel is produced from woody biomass.

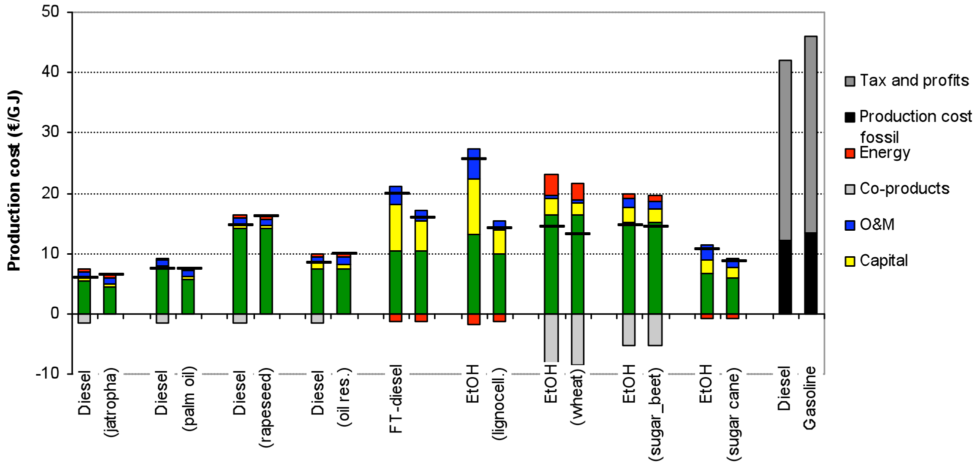
[45] Note that wet organic waste and municipal solid waste are assumed to be free delivered at factory gate (Table 13).

7.1.3 Conversion

7.1.3.1 Biofuel production

The production costs of biodiesel including feedstocks are displayed in Figure 24. The production of diesel is most economic if palm oil or jatropha oil is imported, followed by biodiesel from fat and oil residues. Note that the production cost of biodiesel from vegetable oils becomes more expensive in the future because we assume that value of co-products (glycerine) reduces to zero in 2030 as a result of oversupply from biodiesel production. The learning potential of the conversion process is limited because the production cost is dominated by biomass feedstock. Imported ethanol produced from sugar cane has the best economic performance followed by ethanol from starch and sugar beet. In 2030, ethanol from lignocellulosic biomass becomes more attractive than ethanol from sugar beet or wheat as a result of technological change (efficiency improvements, economies of scale and capital cost reductions by learning), but ethanol from sugar cane remains the cheapest option for ethanol.

Figure 24 **Production cost of biofuels**



The left columns are for 2006, the right columns are for 2030. Petrol and diesel production cost and price at filling stations are included (oil price = 100 US$/bbl). Figure partly based on Hamelinck et al., [2007].

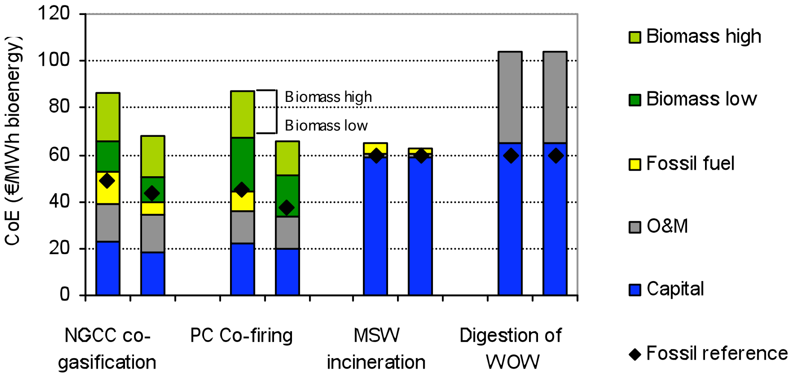
Production costs of biodiesel from jatropha and palm oil were estimated to be 5.8 to 6.5 €/GJ for jatropha and 7 to 8 €/GJ for palm oil. Diesel from jatropha and palm oil are actually estimated to be cheaper than diesel at a crude oil price of 50 $\text{US\$}_{2006}$/bbl (10.7 €/GJ diesel).

The production cost of diesel from rapeseed is the most expensive 1st-generation biodiesel available as a result of high feedstock cost (Figure 23). The production of 2nd-generation biodiesel via FT-synthesis is the most expensive option in 2006 but, due to up scaling and technological learning, production costs are close to rapeseed diesel in 2030 (13.3 to 17.5 €/GJ for FT-diesel[46] compared to 16.2 €/GJ for rapeseed diesel). Production of ethanol from sugar cane is the most economic in all cases (11 €/GJ in 2006 to 8.6 €/GJ in 2030). The production costs for 2030 are conservative compared to other studies [Damen, 2001; Hamelinck and Hoogwijk, 2007] as we assumed little technological development in the Low-Tech scenario. For the High-Tech scenarios, ethanol from sugar cane is not available. For ethanol production from sugar beet, Hamelinck reports production cost of 25-40 €/GJ$_{HHV}$ [Hamelinck and Faaij, 2006; Hamelinck and Hoogwijk, 2007]. We estimated costs of 14.4-15 €/GJ mainly due to lower feedstock prices. Production of ethanol from wheat is estimated to be 13-14 €/GJ. Production costs of 2nd-generation ethanol from lignocellulosic biomass decrease substantially as a result of technology change[47] and up-scaling. For 2006, we estimated production costs of 17-22 €/GJ, but these could potentially decrease to 7.5-11 €/GJ in 2030. Although this is cheaper than ethanol from sugar beet or wheat in 2030, ethanol from sugar cane remains the cheapest option available.

7.1.3.2 Production of bioelectricity

In this study, we considered four options available for electricity generation from biomass: co-firing in PC plants, co-gasification in NGCC plants, incineration of MSW and heat and power production from combustion of biogas in CHP plants. The CoE of the options considered are shown in Figure 25.

Figure 25 Cost of electricity generation from biomass



Left bars are for 2006, right bars are for 2030.

The costs of co-firing and co-gasification depend on the price of biomass. The fossil references are for the NGCC co-gasification and PC co-firing plants, similar plants

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[46] The production cost varies as various lignocellulosic biomass sources are available as shown in Figure 23.

[47] Shift from SSF (simultaneous saccharification and fermentation) in the short term to SSCF (simultaneous saccharification and co-fermentation) in the long term [Hamelinck et al., 2005].

without co-gasification and co-firing of biomass respectively. The reference CoE of the MSW and digestion plant is based on the revenues given for electricity fed to the grid in 2007 (60 €/MWh) [Meijer, Teeselink et al., 2008].

The co-gasification and co-firing option include high and low biomass costs. The lower boundaries for co-gasification and co-firing are for electricity generation from agricultural residues (1.3 €/GJ at factory gate) and clean wood residues (2.5 €/GJ at factory gate) respectively. The higher boundaries are for electricity generation from woody crops produced in the EU (national scenarios). The electricity generation costs and revenues for co-generation at biofuel and hydrogen production plants are allocated to biofuel production.

7.2 Environmental performance

To analyse the environmental performance of the different biomass conversion routes, the primary energy consumption and GHG emissions of both the bio-based production routes and the petrochemical production routes are analysed. From these results, the GHG mitigation and avoided primary energy potential and costs are determined.

We accounted for 1st and 2nd-order energy inputs and related GHG emissions. Third-order energy inputs, i.e. the energy requirements for constructing and dismantling of capital goods [Damen and Faaij, 2003], were not accounted for in this study.

Data for GHG emissions of 1st-generation energy crop production are derived from Smeets et al. (in progress) because this study reports detailed geographical data on N2O emissions from energy crop production. For reasons of consistency, primary energy data and data on woody crops, residues and waste are derived from JRC et al. [2006]. This study was also used by Smeets et al. (in progress) for emissions other than N2O. The data is presented in Appendix 5.

7.2.1 Biofuel production

Figure 26 shows the non-renewable energy requirement for the production and distribution of the different fuel types in this study for 2006[48]. The renewable energy requirements, embedded in the biomass feedstocks are not included in these figures.

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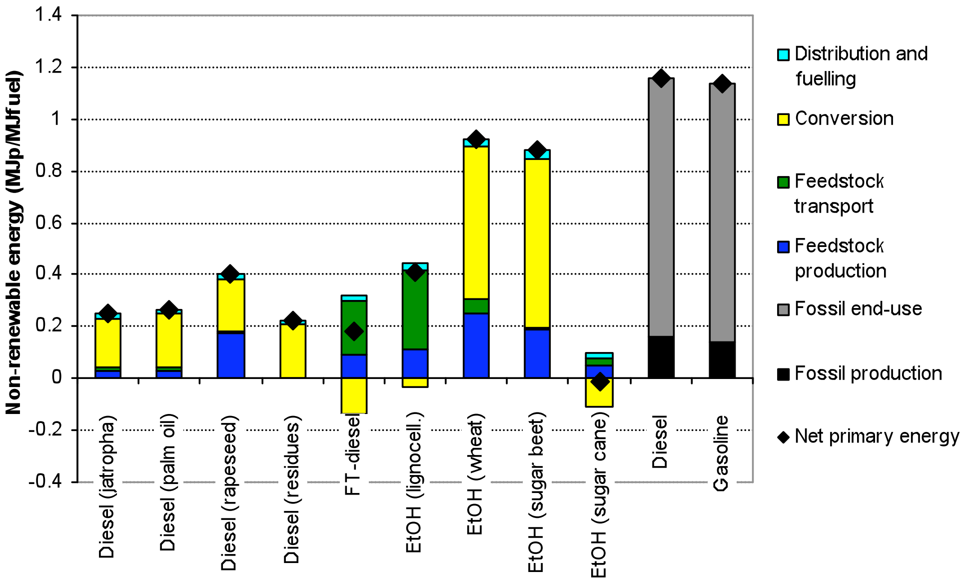
[48] The results for other years (2010-2030) are presented in .

Figure 26 Non-renewable energy requirement for transport fuel production and distribution for 2006

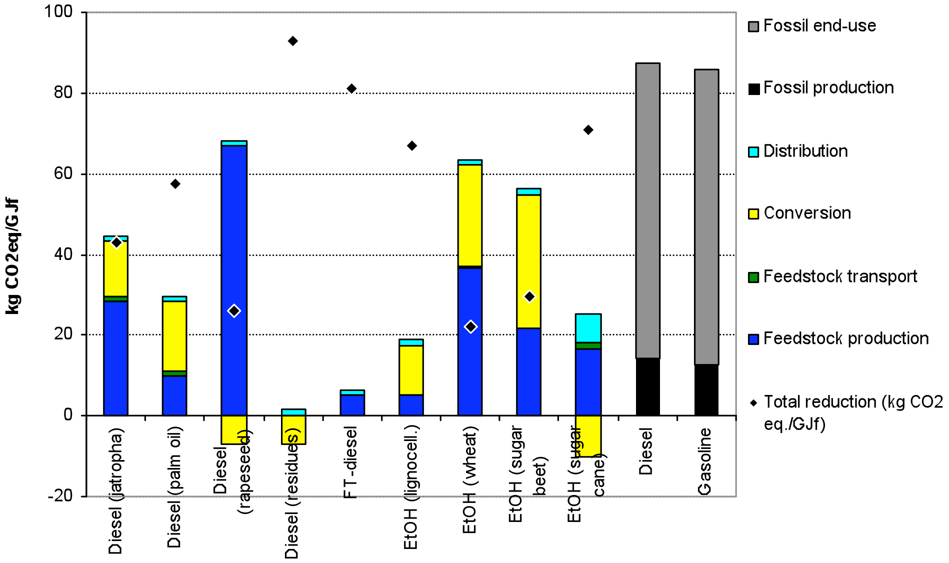


There is little difference in the energy requirement for conversion to FAME from jatropha, palm oil, rapeseed and fat and oil residues. The main share of conversion energy is used as steam. Other contributors are e.g. methanol and other process chemicals in the transesterification process.

Feedstock production of rapeseed requires is more energy intensive than palm oil and jatropha oil production due to fertiliser consumption. Note that this has a larger impact on GHG emissions due to emissions of N_2O as displayed in Figure 27. Electricity, co-produced in the production of FT-diesel, EtOH+ and ethanol from sugar cane results in negative energy use for the conversion processes.

Ethanol production from wheat and sugar beet are relatively energy-intensive processes. Main contributors are grain drying and sugar extraction from sugar beets and ethanol distillation [Hamelinck and Hoogwijk, 2007; JRC, EUCAR et al., 2007].
The production of sugar cane ethanol has the best energetic performance as electricity is co-generated from sugar cane residues.

Figure 27 Greenhouse gas emissions from transport fuel production (well-to-tank) and reductions relative to the reference (diesel/petrol) for 2006



Greenhouse gas emissions from the production of biofuels are displayed in Figure 27 display. The total emissions of GHGs are the differences between the net total GHG balance of the bio-based chains and the fossil references, which is diesel for biodiesel and petrol for ethanol as shown in the right columns of Figure 27. Data on greenhouse gases for biomass production are derived from [Smeets, Bouwman et al., in progress], who conducted an extensive analysis of the impact of N_2O emissions on the overall environmental performance of 1st-generation biofuels. For GHG emissions from conversion processes and from the production of 2nd-generation feedstocks we used data from EUCAR [2007]. For transport emissions and pre-treatment of woody biomass (pelletising), we used data from Hamelinck et al. [2005] and the assumed transport routes as described in Appendix 4.

7.2.2 Electricity

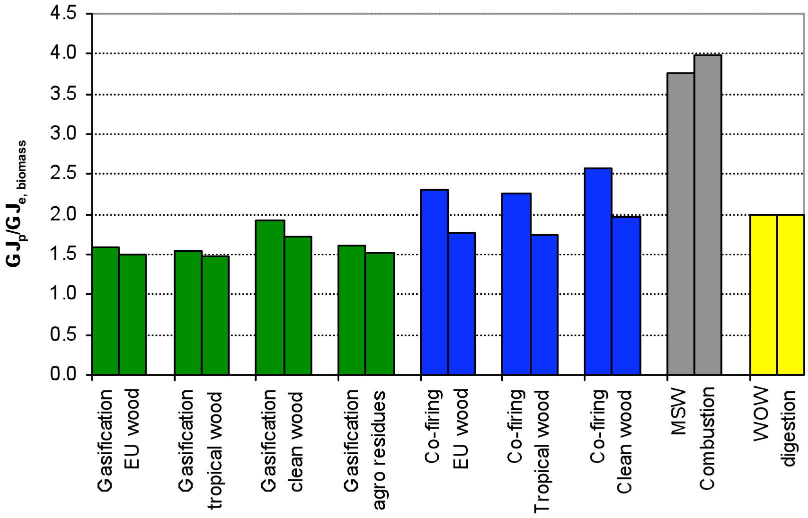
GHG emissions from coal mining and regional storage are estimated to average 5.1 kg CO_2 eq./GJ, while transport adds 4.6 kg CO_2 eq./GJ coal [Koornneef, 2008]. The direct emissions from coal combustion are estimated to be 94.6 kg CO_2/GJ [Vreuls, 2004]. We did not take direct emissions of N_2O and CH_4 into account because these fractions are relatively small because of the high furnace temperature in PC plants. Note that fluidised bed combustion plants emit significant amounts of N_2O emissions as a result of the lower combustion temperature [Koornneef, 2008]. The net GHG emissions per kWh_e depend on the performance of the power plant.

Direct GHG emissions from combustion of biomass are absorbed during growth and result in net zero emissions of CO_2. Although co-firing of biomass in PC plants potentially results in direct emission reductions of NO_x and SO_2 [Tillman, 2000; Dai, Sokhansanj et al., 2008], these pollutant emission reductions are not taken into account, which implies that these are similar to the reference PC plant without co-firing of biomass.

Figure 28 shows the avoided primary per conversion option and biomass input. For the co-gasification plants, the avoided primary energy is relative to a conventional NGCC plant. For co-firing this is a conventional PC plant and for electricity generation from MSW combustion and digestion of wet organic waste, we selected the average Dutch efficiency and fuel mix as reference (43.1% in 2006 [Bosselaar and Gerlagh, 2006]).

Primary energy avoided per unit of electricity generated is highest for MSW plants as heat is co-produced (CHP) and the energy requirement for feedstock pre-treatment is allocated to waste processing rather than electricity generation. The co-firing option appears to perform better than the gasification option because the efficiency of the reference PC plant is lower than the NGCC reference plant (more primary energy is substituted) and because gasification comes with an efficiency penalty.

Figure 28 Avoided primary energy (fossil) per unit of electricity produced from biomass relative to the fossil references (gas-fired NGCC for gasification, coal-fired PC plant for co-firing and the average efficiency of the Dutch energy mix for MSW and WOW)

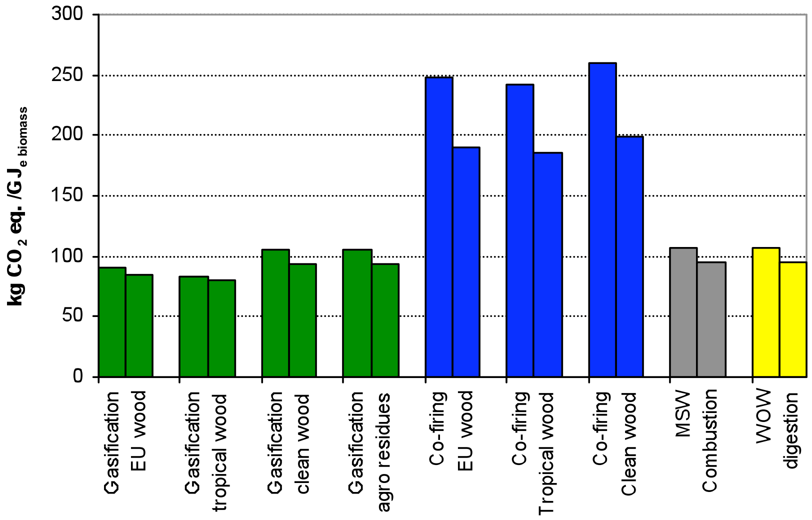


Left bars are for 2006, right bars are for 2030.

The GHG emissions avoided per unit of electricity generated from biomass are displayed in Figure 29. Biomass co-firing results in the largest reductions in GHG emissions. This is mainly due to the assumed reference plant (PC plant) as coal has a high emission factor.

Co-firing and co-gasification of residues perform better than combustion of woody crops due to GHG emissions from feedstock production and transport to the Netherlands. For biomass digestion and MSW incineration plants, we only took the GHG emissions avoided from electricity and heat production into account. Note that the environmental performance of digestion plants improves significantly if avoided emissions from manure processing (mainly methane) are taken into account. For MSW, emissions from waste processing (e.g. emissions from refuse dumping) are already controlled. It is therefore reasonable to account only for GHG emissions avoided from energy (heat and electricity) generated by MSW incineration.

Figure 29 GHG emissions avoided per unit of electricity produced from biomass

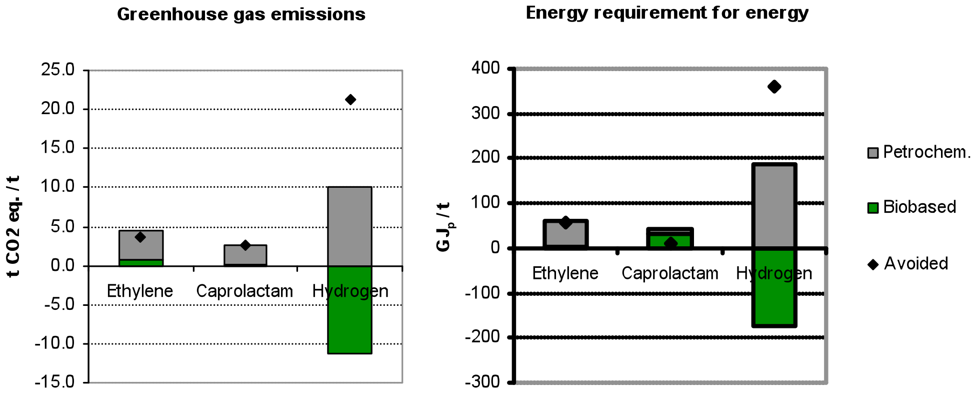


Left bars are for 2006, right bars are for 2030.

7.2.3 Bio-based chemicals

For the production of chemicals, three options were selected for this study: ethylene from sugar cane, caprolactam from sugar beet and synthesis gas from lignocellulosic biomass. These bio-based chemicals are direct substitutes of the petrochemicals ethylene (from steam cracking of naphtha), caprolactam (from hydration of phenol) and hydrogen (from steam methane reforming of natural gas). Note that for every bio-based route, fossil energy is still required. The difference between the non-renewable energy requirement of the fossil route and the bio-based route is the fossil energy saving potential of the bio-based option. The total energy requirement of the fossil and the bio-based processes and GHG emissions are displayed in Figure 30. The underlying data is presented in Table 27.

Figure 30 (Avoided) Greenhouse gas emissions and primary fossil energy for the production of chemicals



The negative bar for hydrogen is the result of fossil energy avoided from co-production of electricity. The diamonds indicate the avoided primary energy per tonne of bio-based production.

Ethylene from ethanol requires energy for conversion of ethanol to ethylene (electricity and natural gas), but during the production of ethanol, electricity is co-generated from co-products, mainly bagasse. The net electricity requirement for the total process is therefore close to zero. The energy requirement of the total production chain of ethylene production from sugar cane ethanol was estimated to be 1.4 GJ_p/tonne ethylene, based on the primary energy requirement for ethanol production from sugar cane (Figure 26) and energy requirements for ethanol dehydration [Patel, Crank et al., 2006]. We estimated primary energy use of petrochemical ethylene production to be 59.5 GJ_p / tonne ethylene, based on data from Neelis [2006]. The avoided primary energy is 58.1 GJ_p/tonne bio-based ethylene.

Greenhouse gas emissions from the production of ethylene from naphtha are estimated to be 1.3 t CO_2 eq./t ethylene (cradle to factory gate). We assumed all CO_2 to be vented into the atmosphere during product usage and waste processing. The total life-cycle emissions of petrochemical ethylene are 4.4 t CO_2 eq./t ethylene (cradle to grave without energy recovery) [Patel, Crank et al., 2006]. Production of ethylene from sugar cane was estimated to be 0.7 t CO_2 eq./t ethylene. The avoided GHG emissions are therefore estimated to be 3.7 t CO_2 eq./t ethylene.

There are various production processes and conversion routes that include synthesis gas. As described in section 5.3.2, we used hydrogen production as representative route because hydrogen production is the main process of natural gas consumption for non-energetic purposes in the Netherlands (section 3.4.2). Note that CO_2 emissions from hydrogen only occur in the production stages, while in other synthesis gas routes, e.g. methanol, carbon is also stored in the product.

The process of steam reforming of natural gas requires natural gas as feedstock and as fuel to produce process heat. In addition, electricity is required. The primary energy use of hydrogen production is estimated to be 186 GJ_p / tonne hydrogen [NREL, 2008]. GHG emissions are estimated to be 10 t CO_2 eq./t hydrogen produced [NREL, 2008]. If hydrogen is produced from lignocellulosic biomass, electricity is co-generated. This process thereby becomes a net producer of energy, which improves the energetic and GHG mitigation potential substantially as shown in Figure 30. The avoided primary energy and GHG emissions are estimated to be 312 GJ_p/tonne and 21 t CO_2 eq./t for bio-based hydrogen production respectively.

For the energy requirement for fossil-based caprolactam, we used data from [Patel, Crank et al., 2006]. Production of caprolactam from phenol requires process energy (steam and electricity) and indirect energy for the production of materials used in the process. The total primary energy consumption of petrochemical caprolactam is estimated to be 43 GJ/tonne caprolactam. The production of bio-based caprolactam from sugar beets is estimated to be 31 GJ/tonne caprolactam, as process energy remains high for the bio-based substitute. Major improvements could be made if sugar cane was used as feedstock, but this feedstock is not available in the NatHighTech scenario as it is produced outside the EU.

GHG emissions are estimated to be 3 tonne CO_2 eq./tonne petrochemical caprolactam and 0.1 tonne CO_2 eq./tonne bio-based caprolactam. The GHG emission saving potential is therefore higher than the energetic performance as shown in Figure 30.

8 RESULTS

This section summarises the results of large-scale introduction of biomass in the electricity, transport and chemicals for the scenarios NatLowTech, IntLowTech, NatHighTech, IntHighTech and IntHighTech AC as described in section 4. Section 8.1 describes the main results. A range of alternative assumptions on fossil fuel and biomass prices are discussed in the sensitivity analysis (8.2).

8.1 Projections

The results are given for bio-based production in PJ final energy (Figure 31), avoided primary energy (Figure 32), GHG emissions avoided (Figure 33), the required biomass (Figure 34) and the net cost per sector (Figure 35). The assumptions underlying these results are described in section 4 through section 7.

Figure 31 Electricity, transport fuels and chemicals produced from biomass per scenario (PJ)

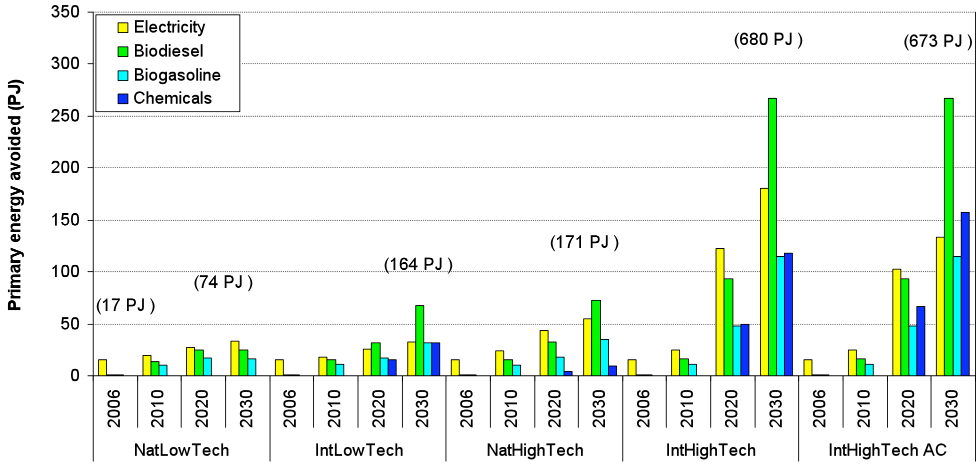


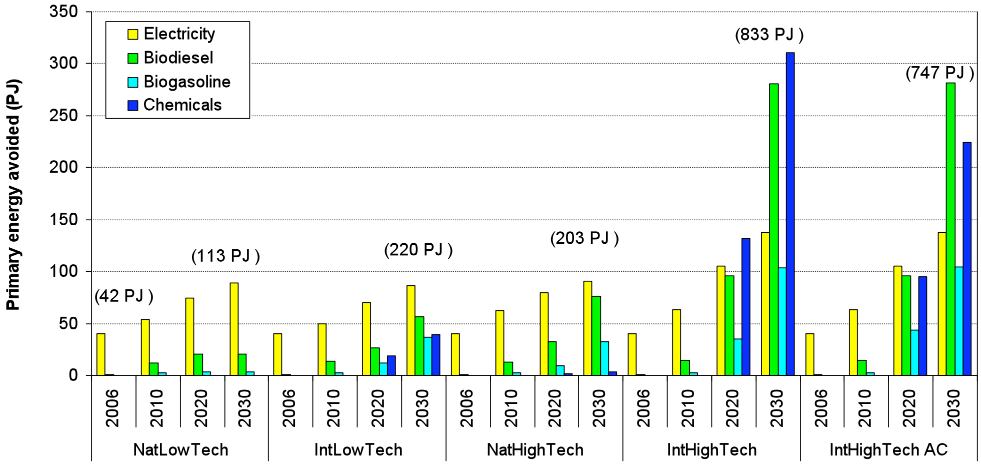
Figure 31 displays the amount of electricity, transport fuels and chemicals produced from biomass in PJ final energy the different scenarios. Although some chemicals are already produced from biomass, these are not shown in this graph as we focused on petrochemicals that we assumed to be substituted by bio-based chemicals (ethylene, caprolactam and synthesis gas). These are not produced from biomass in the initial situation. Due to the scale, the initial shares of biodiesel and ethanol for road transport fuels (0.35% and 0.55% respectively in 2006) are not visible on this graph.

Shares of electricity generation are almost similar in the Low-Tech scenarios (5.7% and 6.7% of total electricity for the NatLowTech and IntLowTech respectively). The reason is that the amount of new coal-fired generation capacities is limited in both scenarios and old plants with a lower co-firing share (10%) are continued to be used over the projected period (long vintage). In the High-Tech scenarios, the amount of electricity generated from biomass is significantly higher because generating capacities have a shorter lifetime (short vintage) and are replaced by more efficient

NGCC plants with a co-gasification share of 25%. Furthermore, co-produced electricity from 2nd-generation biofuels and production of synthesis gas in the IntHighTech scenario adds significantly to electricity production these scenarios. Note that avoided primary energy (Figure 32) and GHG emissions (Figure 33) of co-generated electricity at fuel processing and bio-based chemical production are allocated to biofuels and bio-based chemicals. The amount of transport fuels produced is a result of the different assumptions on blending in the different scenarios as displayed in Table 7 in combination with a higher demand of transport fuels in the High-Tech scenarios.

The difference in chemicals produced from biomass in the scenarios is mainly a result of the chosen options (ethylene, caprolactam and synthesis gas) and the quantity produced in the Netherlands. The amount of caprolactam produced is relatively small compared to bulk production of ethylene or synthesis gas as we considered limited biomass available in the NatHighTech scenario for bio-based chemical production.

Figure 32 Avoided primary fossil energy from bio-based production of electricity, transport fuels and chemicals



The large-scale introduction of biomass in the electricity, transport and chemical sectors results in avoided use of fossil energy. The amount of fossil energy avoided depends on the performance of the biomass production and conversion routes as discussed in detail section. Figure 32 summarises the amount of primary energy avoided per scenario and sector.

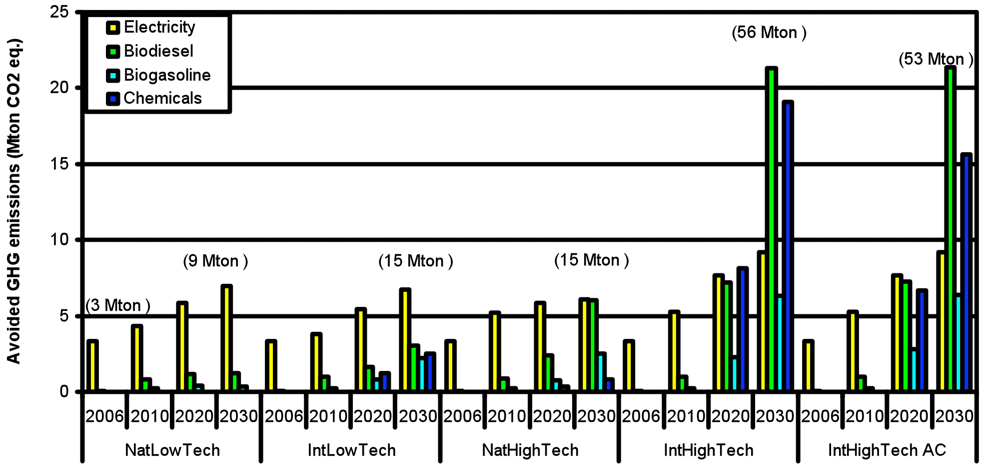
The total primary energy avoided in 2030 ranges from 113 PJ in the NatLowTech scenario, to 220 PJ, 203 PJ and 833 PJ in the NatHighTech, IntLowTech and IntHighTech scenario respectively. The avoided primary energy in the IntHighTech AC scenario is a little lower than in the IntHighTech scenario due to the reduced co-production of electricity from chemicals.

The avoided primary energy from electricity generation is relatively large compared to the amount of electricity produced as displayed in Figure 31. This is inherent to the conversion efficiency of electricity generation and the amount of primary energy required producing one unit of electricity.

Primary energy avoided from biofuel production is relatively small in the NatLowTech scenario as a result of ethanol production from starch and biodiesel production from rapeseed. Especially ethanol production from starch crops is a relatively energy-intensive process. In the IntLowTech scenario, we see different results for biofuels as sugar cane ethanol is introduced and the blending share is higher (20% in 2030). With similar blending shares, the primary energy avoided is slightly higher in the NatHighTech scenario as a result of the introduction of 2nd-generation biofuel production. For the IntHighTech scenario, this increases as a result of the higher blending share (60% in 2030).

For chemicals, mainly synthesis gas produced from biomass in the IntHighTech scenario results in high avoided primary energy (350 PJ_{prim}. in 2030). Natural gas is avoided for the production of synthesis gas (both feedstock as process energy). Furthermore, electricity is co-generated in the production process of hydrogen, which increases the amount of primary energy avoided substantially by 168 PJ_{prim}. in 2030. Production of caprolactam from sugar beet does not result in large savings of primary energy, as the bio-based process is also relatively energy intensive. Ethylene production from ethanol saves almost 60 PJ_{prim}. in 2030, mainly in form of petroleum products, i.e. naphtha.

Figure 33 Avoided greenhouse gas emissions from bio-based production of electricity, transport fuels and chemicals



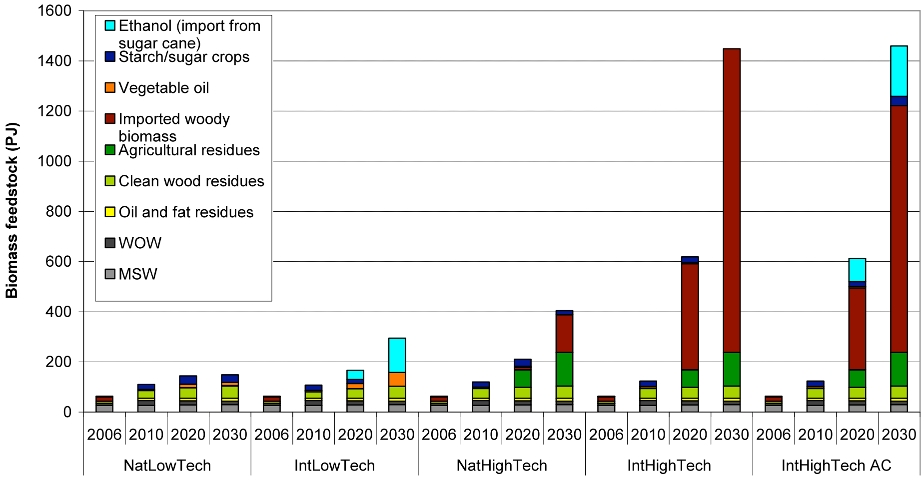
During production, transport, processing and usage of bio-based electricity, transport fuels and chemicals, GHG emissions occur. Important factors are N_2O emissions from feedstock production and fossil energy use during the whole product life-cycle, as discussed in detail in section 7.2. Figure 33 displays the avoided GHG emissions as a result of biomass substitutes in the different scenarios. Production of electricity is dominant in the Low-Tech scenarios as co-firing in coal-fired power plants replaces carbon-intensive coal.

In the High-Tech scenarios, we assumed that coal-fired power plants will be phased out and replaced by NGCC plants. Co-gasification in NGCC plants results in less GHG avoided as natural gas is replaced in co-gasification plants. Note that phasing out coal plants results in decreased fossil emissions in the electricity sector that are not taken into account as only the avoided GHG emissions due to biomass use are displayed in Figure 33.

The introduction of 2nd-generation transport fuels in the High-Tech scenarios in 2020 shows the better GHG performance of these technologies. Although the IntLowTech and NatHighTech have similar fractions of biofuels, avoided greenhouse gases are significantly higher in the NatHighTech scenario (6.8 Mton) than in the IntLowTech scenario (3.7 Mton). The amount of GHG avoided by transportation fuels in the IntHighTech scenario increases to 28 Mton in 2030 as a result of the high blending share for transport fuels in combination with large-scale production of 2nd-generation biofuels.

For chemicals, limited GHG savings can be made by caprolactam production from sugar beet (0.6 Mton in 2030) in the NatHighTech scenario as a result of its environmental performance (section 7.2) and the limited amount produced. Ethylene produced from ethanol in the IntLowTech results in savings of 3.4 Mton in 2030 that is only slightly lower than the amount of GHG emissions avoided in the transport sector (3.7 Mton in 2030). In the IntHighTech scenario, GHG avoided from synthesis gas production are significant (20 Mton in 2030), as a result of the large amount (118 PJ in 2030) and the good environmental performance of the conversion process including co-production of electricity.

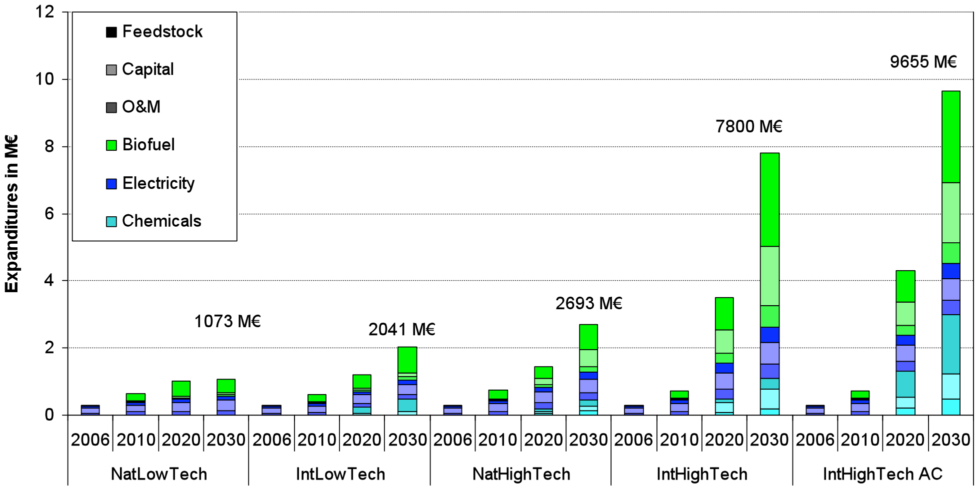
Figure 34 Required biomass per scenario in crops, imported biomass and domestic residues



The demand for biomass for electricity generation, production of transport fuels and of chemicals is discussed in detail in section 6. Figure 34 summarises the results for all scenarios side by side to show the difference between the scenarios.

The main difference between the Low-Tech and High-Tech scenarios is the demand for crop types. While in the Low-Tech scenarios, oil and sugar/starch crops are dominant for the production of transport fuels and chemicals (ethylene from sugar cane), lignocellulosic crops dominate the High-Tech scenarios. Lignocellulosic crops are used for the production of electricity (co-gasification), transport fuels (FT-diesel and ethanol) and chemicals (synthesis gas). Note that also domestic agricultural residues and residues from landscape maintenance are assumed to be used for these sectors.

Figure 35 Capital expenditures, operational expenditures (O&M) and feedstock cost per sector in bln €



Credits for co-production of electricity are subtracted from feedstock costs. Capital expenditures are annualised using a fixed charge factor of 11-13%, depending on the lifetime of the plant (section 5) and a discount rate of 10%.

Figure 35 summarises the capital, O&M and feedstock costs for the introduction of biomass in the sectors electricity, transport and chemicals. The expenditures, as presented in Figure 35, are not the additional investments required for the substitution of fossil energy by bioenergy, but it shows the expenditures made for the production of electricity, transport fuels and chemicals from biomass.

Expenditures for bioenergy production increase from 0.29 bln € in 2006 to 1.1 bln € in 2030 in the NatLowTech scenario. For electricity generation, costs are dominated by capital and O&M because mainly low-priced domestic residues (clean wood) are used for co-firing and digestion and combustion of waste. For biofuel production, costs are dominated by feedstock (rapeseed and wheat). Also in the IntLowTech scenario, the main cost shares include feedstock costs, as ethanol is imported from

Brazil for transport fuels and the production of chemicals (ethylene) and vegetable oils (jatropha and palm oil) are imported for biodiesel production.

In the NatHighTech scenario, total expenditures are higher than in the IntLowTech scenario (2.0 bln € and 2.7 bln € in 2030 respectively), but the share of feedstock costs are lower in this scenario (41% in 2030) than in the IntLowTech scenario (63% in 2030) as a result of capital-intensive advanced conversion options used. For the IntHighTech scenario, biofuel production dominates the scenario as a result of the high blending share (60%). Total expenditures increase to 7.8 bln € in 2030. The total expenditures in the IntHighTech AC scenario are higher (9.7 bln €) as a result of higher feedstock cost (sugar).

Figure 36 Greenhouse gas mitigation costs per scenario and sector

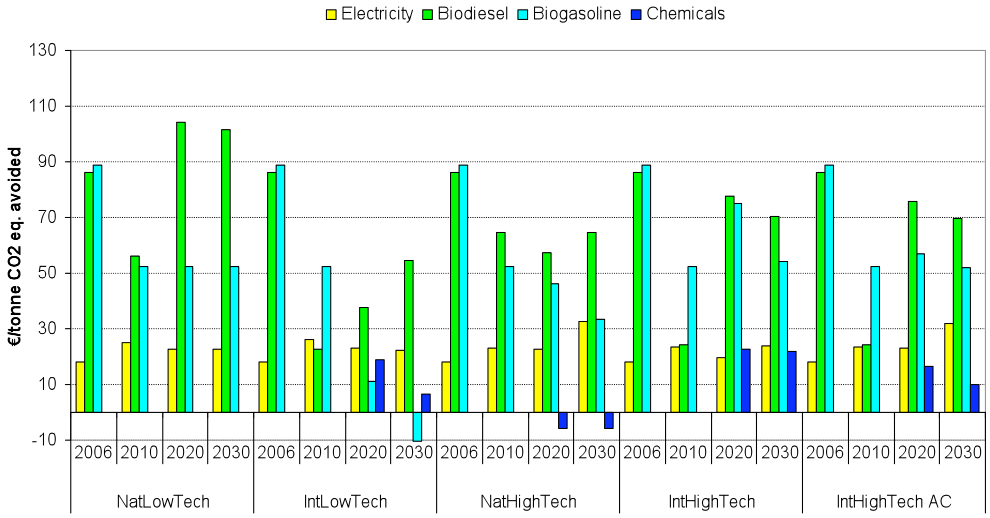


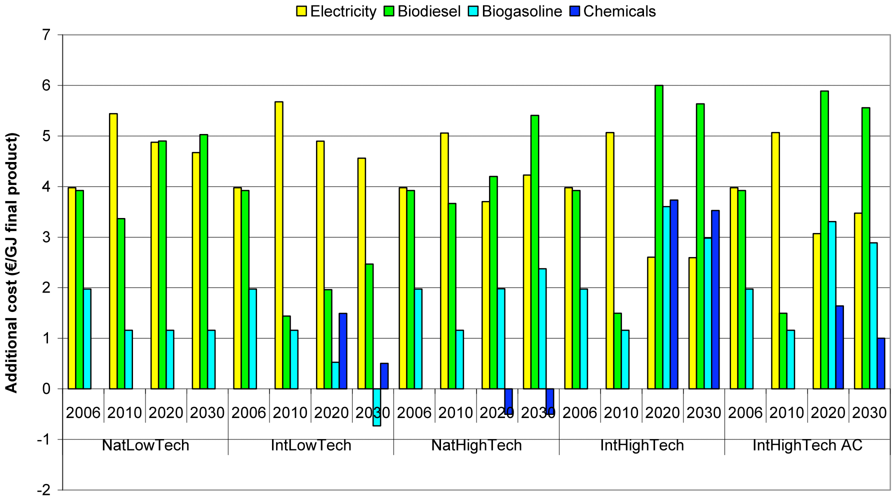
Figure 36 shows the GHG mitigation costs per sector. These costs are calculated for an oil price of 50 US$$_{2006}$/bbl, coal prices of 2 €/GJ and natural gas prices of 6 €/GJ. The mitigation cost are lowest for electricity generation in the Low-tech scenarios, but increase in the High-Tech scenario as biomass replaces electricity generated from NGCC plants. The costs for co-gasification in a NGCC plant are higher than for co-firing in a PC plant and the avoided GHG emissions are lower. Note that the total GHG emissions are lower though in this scenario as coal-fired power plants are phased out.

The mitigation costs for biodiesel production in the NatLowTech scenario decrease between 2006 and 2010 as a result of cheaper oil and fat residues available for biodiesel production, but increase again when more biodiesel has to be produced in 2020 and 2030 and more rapeseed has to be imported. The mitigation costs for ethanol are lower than for biodiesel production (45 €/tonne CO_2 eq. in 2030) as ethanol production from starch has a better environmental performance (Figure 33).

In the IntHighTech scenario, the mitigation costs for electricity generation are almost similar to the NatLowTech scenario (5 €/tonne CO_2 eq. in 2030) because the majority of biomass is co-fired in existing PC plants in both scenarios. The mitigation costs for biodiesel production are lower in the IntLowTech scenario despite the higher blending share (20% in 2030). Biodiesel from jatropha oil and palm oil and ethanol from sugar cane are cheaper and have a higher mitigation potential than biodiesel from rapeseed and ethanol from starch used in the NatLowTech scenario. Because ethanol from sugar cane is cheaper than fossil fuel in 2030, the mitigation costs become negative. Mitigation costs for biodiesel and biopetrol decrease in the NatHighTech scenario when 2nd-generation technologies are introduced in 2020 to around 50-57 €/tonne CO_2 eq. for biodiesel and 19-37 €/tonne CO_2 eq. for biopetrol. The mitigation costs for biofuels are higher in the IntHighTech scenario (44 €/tonne CO_2 eq. and 27 €/tonne CO_2 eq. for biodiesel and biopetrol respectively) because more wood has to be imported to meet the blending share of 60% in 2030.

Caprolactam production from biomass is cheaper than production of caprolactam from petrochemicals. The mitigation costs are therefore negative in the NatHighTech scenario (-6 €/tonne CO_2 eq.). Hydrogen produced from biomass remains more expensive than hydrogen produced from woody biomass at natural gas prices of 6 €/GJ. If the gas price increases, biomass becomes more economic.

Figure 37 Specific additional costs relative to the fossil references



8.2 Sensitivity analysis

This section describes the results of the projections for a range of alternative assumptions for key parameters in the model. These are: fossil fuel prices, biomass prices and the introduction of a CO_2 credits.

8.2.1 Sensitivity cases

The following sensitivity cases are explored:

1) Lower and higher fossil fuel prices

For this case, we explored the results for alternative fossil fuel prices that are 50% lower and 50% higher than the base case assumptions as displayed in Table 16.

Table 16 Fossil fuel prices, sensitivity case assumptions

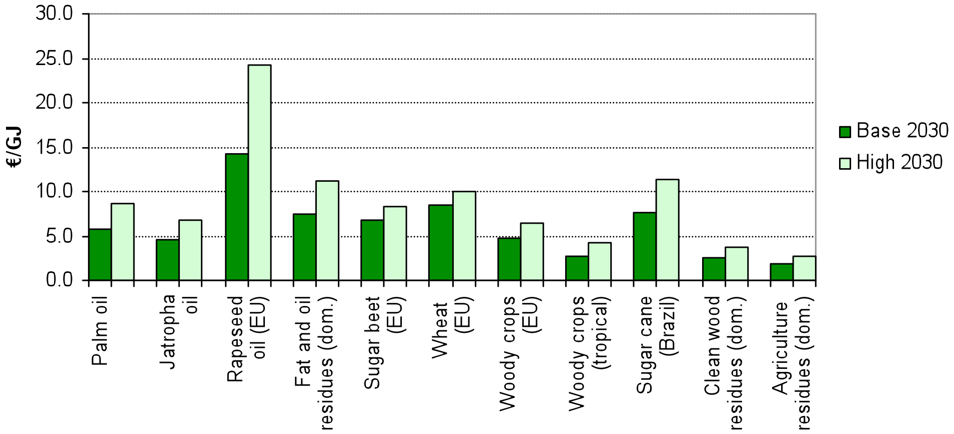
		Base	Low	High
Oil price	US$/bbl	50	25	75
Natural gas	€/GJ	6	3	9
Coal	€/GJ	2	1	3

2) Higher biomass prices

A large fraction of the production cost of bioenergy and bio-based chemicals is related to feedstock cost. This share is larger for 1st-generation technologies such as FAME that requires limited processing and smaller for 2nd-generation technologies such as FT-diesel that includes capital-intensive technologies. The projected costs for feedstock are derived from recent biomass potential studies for the EU27+ for the NatLowTech and NatHighTech scenarios [Wit, Faaij et al., 2007] and global projections for the IntLowTech and IntHighTech (AC) scenarios [Hoogwijk et al.]. The potential for biomass in the EU27+ is for 33% in the EU15 (highest production cost), 33% in the EU12 new Member States (medium production costs) and 33% in Ukraine (lowest production cost). The potential is based on the assumption that agriculture in Ukraine will develop similar to e.g. Poland subsidised by EU programmes on agriculture. This study does not explore the possibilities of whether Ukraine will develop an agricultural market for bioenergy crops, but shows the results if Ukraine is excluded from the market for bioenergy crops in the NatLowTech and NatHighTech scenarios.

For biomass from the EU27+, we assumed that 33% of the lowest cost share, as displayed on the cost-supply curves, will not be available. For non-European biomass (eucalyptus, jatropha, palm oil, sugar cane) and for domestic residues, we assumed a 50% increase in supply cost. Figure 38 displays the costs at the factory gate for the base case and the high-cost scenarios.

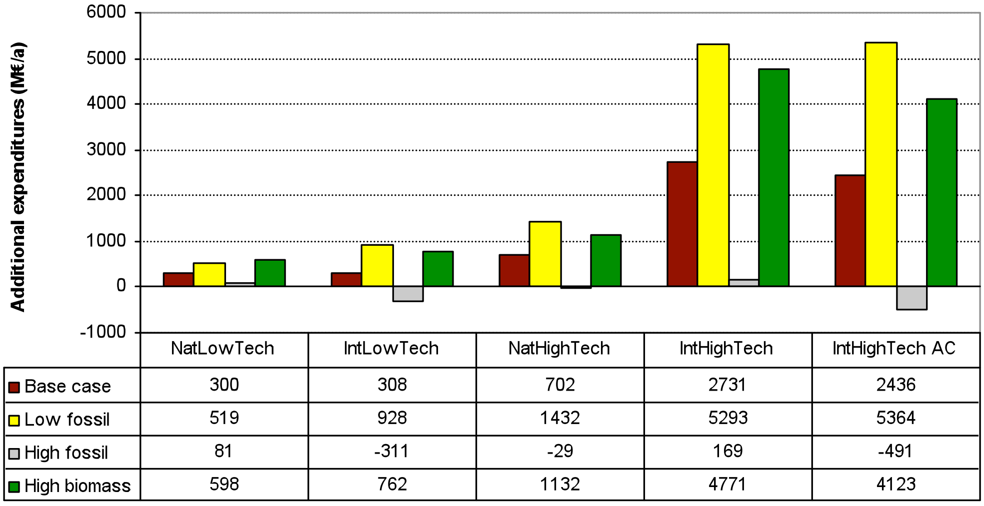
Figure 38 Cost of biomass feedstocks at the factory gate (€/GJ) for the base and high biomass cost sensitivity case



8.2.2 Sensitivity cases results

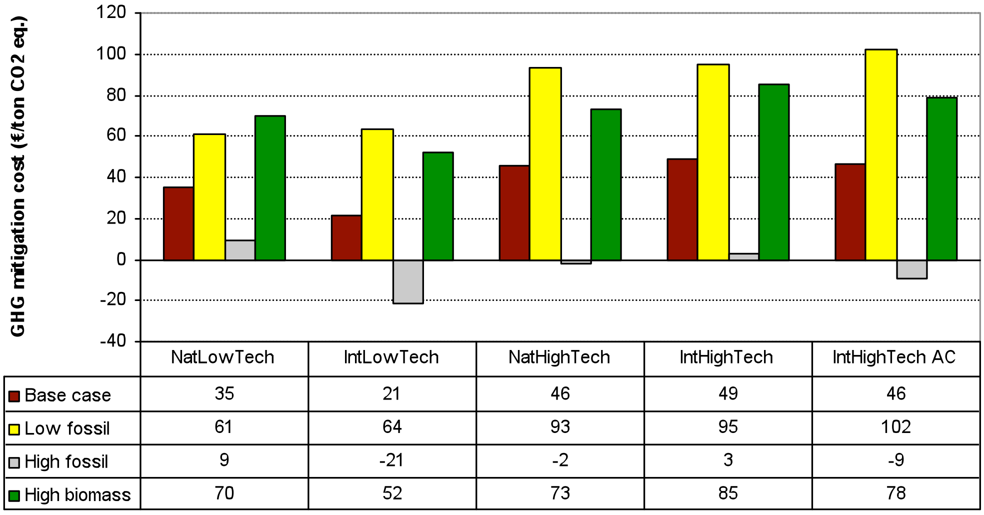
Figure 39 and Figure 40 display the results of the sensitivity for the alternative fossil fuel and biomass cost as explained above. It should be noted that final energy demands and related demands for primary fossil energy and bioenergy sources do not change for the sensitivity cases as these are modelled exogenously. This is different from the top-down sensitivity cases where final demands for energy and biomass are modelled endogenously. Furthermore, capital and O&M costs do not change for higher fossil energy prices although, in reality, capital and O&M costs also tend to increase when fossil energy prices increase. The results for mainly capital-intensive technologies in the HighTech scenarios could therefore be too optimistic for biomass in the high fossil fuel price cases.

Figure 39 Additional cost for bio-based substitution for the base case and sensitivity cases



	NatLowTech	IntLowTech	NatHighTech	IntHighTech	IntHighTech AC
🟥 Base case	300	308	702	2731	2436
🟨 Low fossil	519	928	1432	5293	5364
☐ High fossil	81	-311	-29	169	-491
🟩 High biomass	598	762	1132	4771	4123

Figure 40 GHG mitigation cost for the base case and sensitivity cases



	NatLowTech	IntLowTech	NatHighTech	IntHighTech	IntHighTech AC
🟥 Base case	35	21	46	49	46
🟨 Low fossil	61	64	93	95	102
⬜ High fossil	9	-21	-2	3	-9
🟩 High biomass	70	52	73	85	78

The additional cost shows the difference between bio-based and fossil-based production. If fossil fuel prices are 50% lower than assumed in the base case, the additional cost for bio-based production increase by 73% (NatLowTech) to 200% (IntLowTech). If fossil fuel prices are 50% higher than the base case, additional costs for bio-based production decrease by 73% to 200% for these scenarios respectively.

9 DISCUSSION

This section covers the discussion of the methodology, uncertainties in data and assumptions and their implications to the final results. The results are discussed in section 8.

9.1 Scenarios

This study includes four scenarios for future projections of technology development, global cooperation and demand for energy for the Netherlands. Projections of socio-economic development (e.g. GDP, population) and the related demand for energy per sector are derived from existing scenarios. The scenarios NatLowTech, IntLowTech, NatHighTech and IntHighTech are based on the Regional Communities (RC), Strong Europe (SE), Transatlantic Market (TM) and Global Economy (GE) scenarios respectively of the WLO study [Janssen, Okker et al., 2006]. Specific to this study are technologies for (bio-) energy and bio-based production of chemicals and their current and future performance.

One important difference between the WLO scenarios and this study is that we assumed high technological development for bioenergy conversion technologies in the scenarios with high economic development whereas the WLO scenarios include high technological development of carbon mitigation technologies in the scenarios with European and national environmental policies and limited economic development. If biomass was only considered for GHG mitigation, higher biomass shares in the NatLowTech and IntLowTech (RC and SE) scenarios would be a rational choice. From an energy security, i.e. dependency on fossil resources, higher blending shares, technological development as a result of increased experience as considered in this study, is a reasonable choice.

9.2 Technologies and techno-economic performances

There are numerous technologies available to convert biomass into bioenergy and bio-based materials. In order to limit the complexity of the model, a selection of technologies was made that are currently used and are likely to have a large potential in the projected period to 2030.

For the Low-Tech scenarios, biomass conversion options are assumed that are already used on commercial scales (biodiesel from vegetable oil, ethanol from fermentation of sugar/starch, co-firing of woody biomass). The cost and performance of these conversion options are relatively certain as empirical data is available[49]. Because biomass feedstock cost make up the largest share, the main uncertainty in the cost of these technologies are biomass prices[50].

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[49] An exception is biodiesel from jatropha in the IntLowTech scenario. Experience and therefore also empirical data for this energy crop is still limited [Struijs, 2008].

[50] Most conventional biomass conversion technologies have limited capital cost compared to advanced conversion options. Feedstock costs are usually higher though.

For the high-tech scenarios, we assumed technologies to become commercially available that are now in demonstration phases or close to commercialisation (synthesis gas for combustion (GTCC), FT-synthesis or production of chemicals, Ethanol from lignocellulosic biomass and bio-based caprolactam for nylon-6 production). We assumed these technologies to be commercialised in 2020, but not yet available for 2010. It should be noted though that these technologies will only become commercially available if significant effort is made (RD&D). This factor is not taken into account in this study as the development of these technologies takes place on a global level. Quantification of the impact of RD&D investments in the Netherlands within an international context is beyond the scope of this study.

The selection of conversion options in this study is based on current expectations for technologies that will probably be in commercial operation over the projected period to 2030. The selection is limited as it does not include cost optimisation and the selected conversion options are based on today's understanding and expectations for the future. Especially in the longer term, more advanced options, such as fuel cells for power generation or transport, might also become available before 2030. Also specialty/functionalised chemicals from biorefinery concepts are expected to be commercialised within the projected period [Sanders, Engelen et al., 2006] and are not included in this study due to limitations of data and of the LEITAP model to deal with multi-output technologies. These options could increase the potential for bioenergy and related energy and GHG emissions avoided as a result of efficiency improvements. On the other hand, we also assumed that advanced technologies develop over time. Ethanol from lignocellulosic biomass is assumed to become about 50% cheaper as a result of technological learning, economies of scale and innovation. It should be noted that these cost reductions are only feasible if large-scale investments are being made in the development of these technologies.

Furthermore, the assumed techno-economic performance of technologies that are not yet demonstrated on commercial scales is more uncertain than existing technologies, as the underlying data is based on bottom-up engineering models or pilot demonstrations. It is often found that the cost of these technologies appear to be higher for the first installations that are built on commercial scales as a result of engineering optimism and project contingencies [Rubin et al., 2004]. Results of bottom-up techno-economic estimations using engineering modelling (e.g. Aspen+) come with an uncertainty range of 30% [Hamelinck and Faaij, 2006]. Conversion efficiencies of 2nd-generation biofuel production plants have an uncertainty range of 10% (5% for 1st-generation plants) [Hamelinck and Hoogwijk, 2007].

9.3 Energetic and environmental performance of biomass conversion options

In order to quantify the energetic and environmental performance of the bio-based substitutes of fossil energy in this study, the primary energy and GHG emissions of the fossil conversion routes and bio-based conversion routes were estimated based on existing LCA work. For the fossil production routes, but especially for the bio-based production routes, the results of LCA studies vary widely. Key uncertainties in fossil production include conversion efficiency and selected conversion routes[51] and allocation of energy and GHG emissions to co-products. For bio-based production routes, key uncertainties include feedstock types and yields, emissions from cultivation (mainly N_2O), allocation of co-products and conversion efficiency and selected reference systems for land use and substitution and effects of indirect land-use change. Although transport energy and emissions are also location-specific, their share in the total chain is limited. No attempt was made for this study to quantify the range of uncertainty. Rather we used best estimates of existing studies and used allocation by substitution credits to take co-products into account. It should be noted though that different allocation methods (e.g. allocation by energy content) results in different outcomes, especially for first generation energy crops that include multiple co-products. The impact of other land-use reference systems are given in **Appendix V.

9.4 Cost and supply of (bio-) energy

For fossil energy carriers, we assumed a crude oil price of 50 US$$_{2006}$/bbl, natural gas 6 €/GJ and coal 2 €/GJ. The cost or benefits of substituting fossil energy by biomass will largely depend on the development of the prices of fossil energy carriers. The impact of alternative fuel price assumptions does not influence the potential in this study as biomass shares are based on the physical potential. The mitigation costs are highly sensitive to alternative (fossil) fuel price assumptions as shown in the sensitivity analysis (8.2).

The demand for biomass in this study is based on projections of final energy demand and chemicals and aimed shares of biomass substitutions for electricity, transport fuels and chemicals. Key uncertainties in the projected demand for biomass crops are the conversion efficiencies of biomass to final energy carriers or chemicals and the total demand for final energy and chemicals in the scenarios. The final demands of electricity, transport fuels and chemicals are based on the WLO-projections [Janssen, Okker et al., 2006].

The demand for imports of biomass also depends on available biomass from domestic resources. Because cultivation land is scarce in the Netherlands, the main sources of domestic biomass are residues (primary, secondary and tertiary). In this study it is assumed that all residues available are used for bioenergy or bio-based chemicals. The projected availability of residues was 100 PJ for the low-tech scenarios and 226 PJ for the high-tech scenarios in 2030, as we assumed that agricultural residues such as straw could only be used in advanced conversion

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[51] For chemical production, a range of conversion options exists. For example syngas can be produced from natural gas, as is the main feedstock in the Netherlands, but also from coal or petroleum products. In this study, the main production routes as used in the Netherlands are assumed.

options. The maximum amount of biomass produced in the Netherlands was estimated to be 450 PJ in 2030 [Rabou et al., 2006], but we excluded solid organic waste in this study and considered energy crop production within an international context. If more residues are available, it could lower the mitigation cost and increase the mitigation potential relative to energy crops. More research is required to make a more exact quantification about the feasibility of domestic biomass supply for bio-based materials and energy including required logistics and collection systems. Domestic crop production will probably increase the cost as land and labour prices are relatively high in the Netherlands compared to e.g. Eastern Europe. More advanced bio-based production options including GMO crops and biorefineries, that optimise the efficiency of bio-based production, could make domestic production in the Netherlands more beneficial. However, this study is limited to conventional energy crops and thermal and fermentation conversion processes.

As already concluded by Rabou et al. [2006], the key challenge is not to supply biomass for the amounts projected in this study, but the key questions are whether it can be produced sustainably and still be economically feasible. For all scenarios, we found that biomass could be produced at lower cost ranges for the blending targets assumed in this study. Only in the IntHighTech scenario, costs of biomass feedstock are expected to increase as a result of the high demand. It should be noted though that the method used to estimate the share of biomass for the Netherlands is too[52] simple to draw robust conclusions. The impact of high demand on biomass feedstock prices and prices of food and feed are analysed in detail using macro-economic modelling in the follow-up part of this study.

Although important, sustainable production of biomass is not addressed explicitly in this study. Especially in the IntLowTech scenario (where large amounts of palm oil and ethanol from sugar cane are imported), economic, social and environmental impacts are major issues, as described for ethanol from Brazil in Smeets et al. [2008] and for palm oil in Indonesia and Malaysia by Wicke et al. [2008]. Indirect land-use change, for example, could decrease the mitigation potential significantly or even make bioenergy options net producers of greenhouse gases relative to their fossil references.

[52] Share of biomass assumed similar to the ratio of primary energy use in the Netherlands relative to the EU+ and world.

10 CONCLUSIONS

For this study, four scenarios were developed for large-scale deployment of biomass for bioenergy and bio-based materials in the Netherlands for the projected period 2006 to 2030. The four scenarios in this study different with respect to two key uncertainties that, apart from policies, mainly determine the future potential of biomass for bioenergy and bio-based materials. These are international cooperation and related international trade for biomass, and technology development and related commercialisation of advanced biomass conversion technologies. The national scenarios with low- and high-technology development are referred to as NatLowTech and NatHighTech respectively. The scenarios with international cooperation and with low- and high-technology development are referred to as IntLowTech and IntHighTech respectively. Projections other than technological development and biomass availability, such as economic growth, population and final energy demands, were derived from existing scenarios. The scenario parameters and results of bottom-up estimations in this study are used for a top-down macro-economic model in order to analyse the impact of large-scale deployment of biomass in the Netherlands within a macro-economic framework.

If biomass imports for the Netherlands are limited to European resources, we found that the potentials for biomass are limited when low-yield energy crops such as starch and rapeseed have to be cultivated (NatLowTech scenario). The potential increases if oil crops or ethanol are imported from non-EU regions (e.g. palm oil from Indonesia or sugar cane from Brazil) (IntLowTech scenario). Note that especially palm oil and sugar cane ethanol come with major concerns for sustainability due to their impact on food prices, land-use change and labour conditions in these production countries.

If advanced technologies are used, the potential for biomass for bioenergy and bio-based chemicals [CBS, 2008a] increases, even if limited EU sources are available (IntHighTech scenario). High-yield lignocellulosic crops and co-production of electricity using efficient gasification combined cycle technologies results in shares of biomass production that are in range with the PGG targets for bio-based production if global biomass sources are available (IntHighTech scenario).

For the scenarios in this study we found bio-based production to increase from 17 PJ[53] in 2006 to 74 PJ in 2030 for the NatLowTech scenario, 164 PJ for the IntLowTech scenario, 171 PJ for the NatHighTech scenario, 680 PJ for the IntHighTech scenario and 673 PJ in the IntHighTech AC scenario. Neither of these estimations is in line with the goals of the PGG to realise 900 PJ of bio-based production (30% share for 3000 PJ of energy, which was the average 1990-2000 use

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[53] Excluding co-firing of palm oil. This option was abandoned in 2007 due to sustainability issues and was therefore not included in this study.

in the Netherlands). It should be noted though that heat[54] and materials other than chemicals are not included in this study. The replacement of 50% or 33 PJ of cokes with charcoal in the steel industry could be possible according to Rabou et al. [2006]. Furthermore, these results are final energy carriers. Bio-based substitution for the sectors considered in this study results in avoided fossil primary energy ranges from 113 PJ_{prim}. in the IntLowTech scenario to 833 PJ_{prim}. in the IntHighTech scenario.
The costs of substituting fossil-based production with biomass mainly depends on prices for fossil energy carriers. With the assumed oil price of 50 $US\$_{2006}$/bbl in this study, we found that ethanol from sugar cane is already competitive if imported into the Netherlands without trade restrictions. Bio-based production of caprolactam was also found to be competitive with petrochemical caprolactam. If higher oil prices are considered (e.g. 100 $US\$_{2006}$/bbl), then 2nd-generation ethanol and biodiesel also become competitive in the long term, if production costs decrease through technology development (learning).

Greenhouse gas emission reduction from fossil energy substitution by biomass results in 8 Mton CO_2 eq. for the IntLowTech scenario, 15 Mton CO_2 eq. in the IntLowTech and NatHighTech scenario and 56 Mton CO_2 eq. in the IntHighTech scenario in 2030. The high reduction potential in the IntHighTech scenario is the result of the major substitution of transport fuels (60% in 2030) and is lower (53 Mton CO_2 eq.) in the IntHighTech AC scenario as a result of the decreased co-generation of electricity in this scenario. The costs for reducing CO_2 were found to be lowest in the IntLowTech scenario (21 €/tonne CO_2 eq.), mainly as a result of ethanol imports for competitive prices with fossil fuels. The mitigation costs increase when EU 1st-generation fuels are used in the NatLowTech scenario (41 €/tonne CO_2 eq.) as a result of poor mitigation performances and higher production prices. Mitigation costs are highest in the High-Tech scenarios (46-49 €/tonne CO_2 eq.). It should be noted though that the GHG reduction potential is also highest in these scenarios. Furthermore, the added value of importing ethanol and vegetable oils for the Netherlands is limited. If relatively cheap lignocellulosic feedstocks are imported and converted to electricity, transport fuels and chemicals in the Netherlands, this could have a positive effect on the trade balance as a result of the added value created in the Netherlands. This effect is quantified in the follow-up part of this study using macro-economic modelling tools.

Bottom-up (engineering) data was used to set up an Excel spreadsheet model for projecting the impact of large-scale deployment of biomass in the Netherlands. The strength of this method is that technology variation, performance parameters (physical, environmental and economic) and biomass production chains can be modelled in detail. The result of the bottom-up scenarios is a powerful tool to set up

[54] Co-generation of heat for biomass CHP plants (waste incineration and biomass digestion plants) is taken into account.

the parameters of the top-down macro-economic modelling framework in order to quantify the economic impact of biomass deployment in the Netherlands.

The limitations of the bottom-up method used are that no optimisation analyses were performed in order to find the least cost or highest GHG reduction potential for a portfolio of biomass technologies. Furthermore, technological development is assumed exogenous to the model. Technological development could also be modelled endogenously by using the concept of technological learning. However, this requires projections of larger regions such as Europe or the world, as technology development does not take place in a single isolated region such as the Netherlands. Using advanced bottom-up modelling (e.g. with MARKAL) for larger regions (e.g. Europe or the World), could support understanding on technology development, biomass requirements and energy demands from a cross-boundary perspective.

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APPENDIX I: SCENARIOS (WLO)

In the WLO scenarios, the electricity production sector consists of central units, large-scale CHP for district heating, industrial CHP installations and other small-scale decentralised CHP installations, MSW incineration plants and renewable plants such as wind and PV. Large-scale power plants and decentralised small-scale plants are modelled in different models. The electricity production mix differs per scenario.

In the Global Economy scenario, on which we based the IntHighTech scenario, pulverised coal plants are projected to be built in order to meet the increasing electricity demand. In the Transantlantic Market scenario (NatHighTech) nuclear power is reintroduced to secure future energy supply. In the Strong Europe scenario, newly built capacities are mainly NGCC (Natural Gas Combined Cycle) plants. After the year 2025, Combined Cycles with Coal gasification (IGCC) plants in combination with Carbon Capture and Storage (CCS) are also introduced. In the Regional Communities scenario (NatLowTech) scenario IGCC plants are also introduced for security of supply (coal), while it is also relatively clean compared to conventional PC plants.

Global Economy scenario
- Low-carbon policies
- Large-scale deployment of wind energy (no problems with regulations);
- Steep learning curve, low production costs for new, renewable technologies (but lower in Strong Europe scenario);
- Lowest cost for base-load electricity generation.

The Transatlantic Market scenario
- Renewable energy has a higher share compared to the Global economy scenario due to high oil prices and insecure (fossil) energy supply;
- Because of the high progress ratio (thus little learning potential) for renewable technologies, investment costs remain high.

Strong Europe
- High economic growth with stringent climate policies;
- More offshore wind (ambitious climate policies), but lower deployment on land (people’s well-being);
- The technological development is the highest in this scenario (cumulative growth in combination with low progress ratios).

Regional Communities
- Less interest in renewable technologies compared to the SE scenario, but otherwise comparable to the SE scenario.

Biomass in the WLO scenarios

Although wind and biomass are the most important renewable technologies for electricity generation in the WLO scenarios, power production from wind (especially offshore projects) dominate the renewable portfolios of the scenarios.

Biomass is used for co-firing in coal-fired power plants because this has the best economic performance. In all scenarios, 20% of the electric capacity of coal plants is produced from co-fired biomass. In the Global Economy and Transatlantic Market scenarios, co-firing of biomass stagnates after 2020 because the MEP subsidy expires after 2020.

Other biomass options are water treatment sludge, organic household waste, and manure digestion and landfill gas recovery, but these options have a minor and stable share in all scenarios.

Table 17 Overview of the WLO scenarios and figures used for this study (blue)

Strong Europe		Global Economy	
(IntLowTech)		(IntHighTech)	
Global trade with environmental restrictions **Effective international climate policy**		**Global trade (no barriers)** **No international climate policy**	
Population 2040 (mln)	18.9	Population 2040 (mln)	19.7
GDP/cap. (2001 = 100)	156	GDP/cap. (2001 = 100)	221
Energy consumption NL	+10%	Energy consumption NL	+55%
Energy consumption/cap.	-5%	Energy consumption/cap.	+30%
Coal consumption	+40%	Coal consumption	+195%
Oil consumption	+35%	Oil consumption	-90%
Natural gas consumption	-25%	Natural gas consumption	+5%
Domestic gas resources	-85%	Domestic gas resources	-95%
CO_2 emissions	-20%	CO_2 emissions	+65%
Capacity nuclear (MWe)	0	Capacity nuclear (MWe)	0
Share renewable energy	14%	Share renewable energy	1%
Share renewable electricity	34%	Share renewable electricity	1%
Regional Communities		Transatlantic Market	
(NatLowTech)		(NatHighTech)	
Maintained international trade barriers **Effective national environmental policies**		**Maintained international trade barriers** **Weak environmental policies**	
Population 2040 (mln)	15.8	Population 2040 (mln)	17.1
GDP/cap. (2001 = 100)	133	GDP/cap. (2001 = 100)	195
Energy consumption NL	-5%	Energy consumption NL	+40%
Energy consumption/cap.	- 5%	Energy consumption/cap.	+35%
Coal consumption	+35%	Coal consumption	+155%
Oil consumption	+10%	Oil consumption	+65%
Natural gas consumption	-35%	Natural gas consumption	-25%
Domestic gas resources	-75%	Domestic gas resources	-85%
CO_2 emissions	-10%	CO_2 emissions	+30%
Capacity nuclear (MWe)	0	Capacity nuclear (MWe)	6000
Share renewable energy	9%	Share renewable energy	1%
Share renewable electricity	24%	Share renewable electricity	2%

(Similar in this study)

Figure 41 and Figure 42 display the projected energy consumption and CO_2 emissions from energy consumption in the Netherlands for the historic situation [CBS, 2008a] and as projected for the WLO scenarios [Janssen, Okker et al., 2006]. Note that although energy requirements are higher in the Strong Europe scenario than in the Regional Communities scenario, CO_2 emissions in the Strong Europe scenario decrease rapidly after 2015, mainly as a result of diffusion of CO_2 capture and storage technologies.

Figure 41 Current and projected primary energy consumption in the Netherlands for the WLO scenarios [Janssen, Okker et al., 2006; CBS, 2008a]

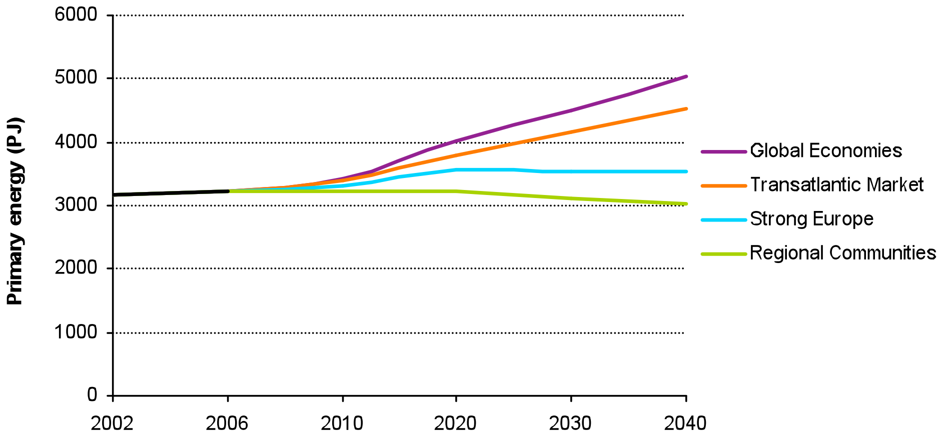
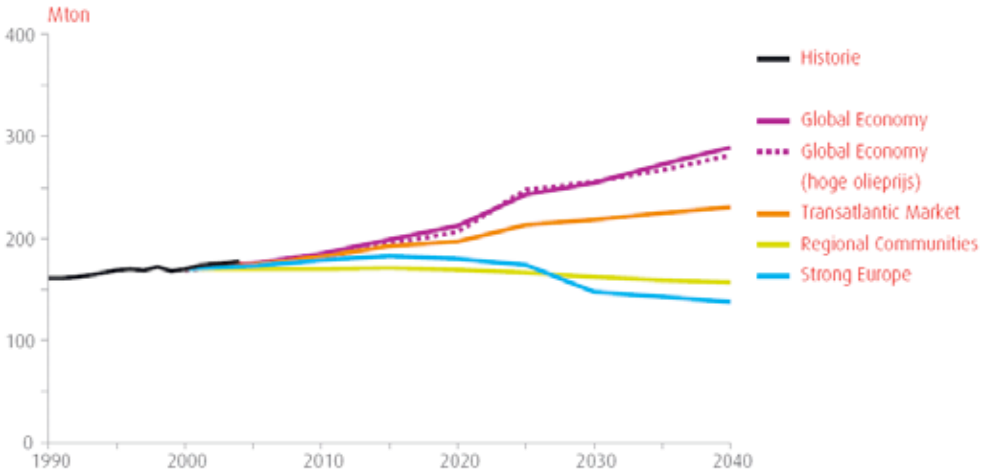


Figure 42 CO_2 emissions from energy consumption [Janssen, Okker et al., 2006] (Future projections exclude non-energetic emissions of limestone consumption, cement production, flue gas desulphurisation and anode consumption in the aluminium industry (around 2.5 mton in 2002).



APPENDIX II : BIODIESEL PRODUCTION CAPACITY

Table 18 Estimated production capacity of biodiesel in the Netherlands [MVO, 2008]

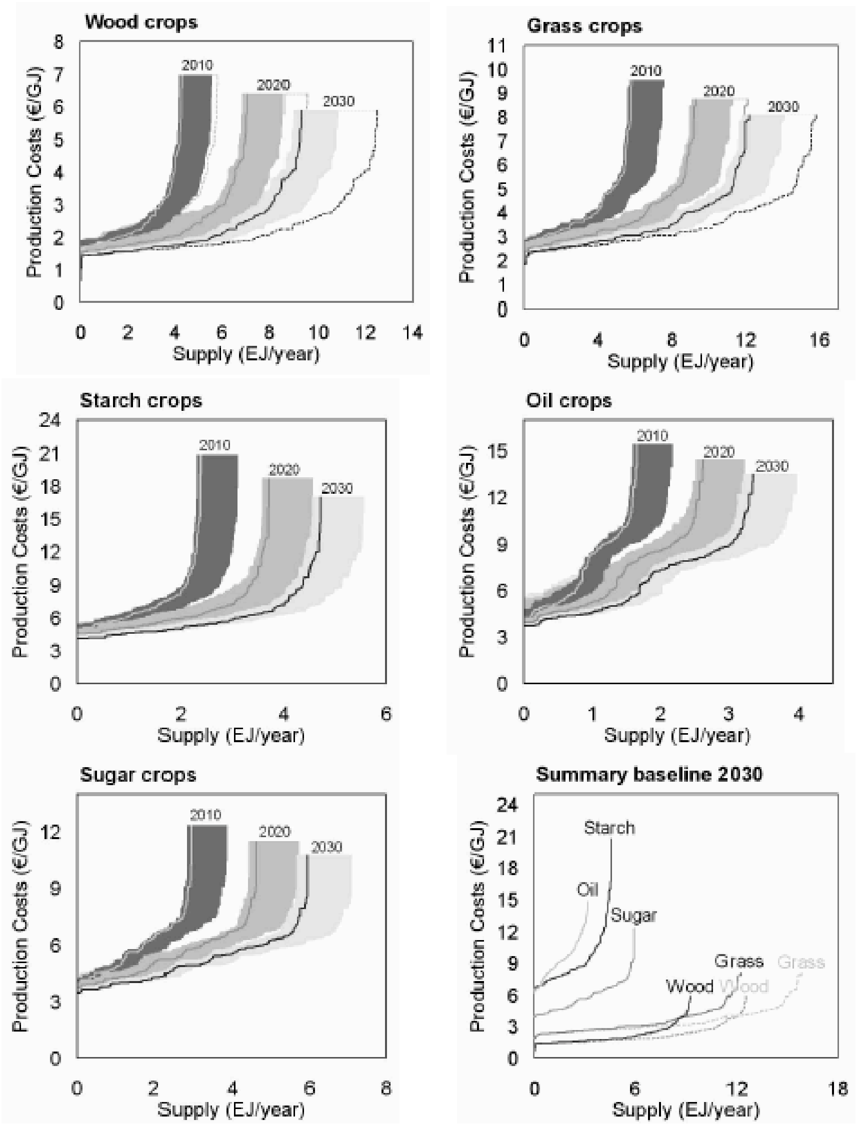
Location, company name	Start production	Yearly capacity**			Resources, more information
	(estimated)	(tons/a)	(mln l/a)	(PJ/a)	
Bewa	2006/2007	15,000	13.5	0.6	used frying oil
Biodiesel Kampen*	2007	60,000	54	2.2	used frying oil
BioDsl	2007	6,000	5.4	0.2	used frying oil
Biofueling*	2008	200,000	180	7.5	multi resources
Biovalue*	2007	240,000	216	9.0	rape and soya
Clean Energy*	2007	250,000	225	9.3	multi resources
DutchBioDiesel	2008	200,000	180	7.5	rape oil
Ecoson (Rendac)	2007	4,000	3.6	0.1	animal fat
Greenmills	2009	200,000	180	7.5	used frying oil
Mercuria Energy Group*	2008	200,000	180	7.5	multi resources
Rosendaal Energy and Heros*	2008	250,000	225	9.3	multi resources
SunOil*	2006	60,000	54	2.2	multi resources
Biopetrol*	2007	400,000	360	14.9	rape and soya
WHEB	2009	400,000	360	14.9	multi resources
Total	2007	300,000	270	11.2	
Total	2009	2,485,000	2237	92.7	

* Member of the Association of the Dutch Biodiesel Industry

** Estimates, based on publicly available information such as websites and press releases

APPENDIX III: BIOMASS COST AND SUPPLY CURVES FOR THE EU27+

[Wit, Faaij et al., 2007]



APPENDIX IV: BIOMASS TRANSPORTATION

The cost and environmental performance of biomass transport are based on data from Dornburg et al. [2007] and Hamelinck et al. [2005]. The costs for biomass transport are calculated using equation V.1. Transport routes include local transport from domestic sources (route A), regional transport from European resources (route B through D), and transatlantic transport of liquids (ethanol and palm oil) and solids (woody crops) in the international scenarios.

$$C_{tr} = \frac{spt + \sum_{i=1}^{n} d_i \times stc_i}{LHV}$$

Eq. V.1 [Dornburg et al., 2007]

C_{tr}: cost of transport [€/MJ_{bio}]
n: number of transport steps
spt: specific cost of pelletising (if applicable) [€/tonne dm]
stc_i: specific transport cost of transport mode used in step I [€/tonne dm*km]
$stc_i = (ec_i + mc_i) + lc_i/d_i$
ec_i: specific energy cost of transport mode used in step i [€/tonne dm*km]
mc_i: management costs of transport mode used in step i [€/tonne dm*km]
d_i: distance in transportation step i [km]
lc_i: specific loading/unloading costs of transport used in step I [€/tonne dm]

Biomass transport chains

The domestic supply of biomass in the Netherlands is limited and large-scale deployment of biomass can only be realised with imports of biomass. It depends on the scenarios what the sources of biomass are (EU27+ for the national scenarios and global for the international scenarios). The additional costs and energy requirement for biomass transport depend on the transport chain. We selected five transport chains as described below. Biomass transportation chains and their cost and their efficiency are derived from Dornburg et al. [2007] and Hamelinck et al. [2005].

Local transport (A)

Domestic bio-energy resources have to be transported to the conversion installations. Similar to Dornburg et al. [2007], we assume domestic biomass to be produced at an average distance of 100 km from the conversion plant and to be transported by truck.

EU transport (wheat/sugar beet) (B)

Sugar and starch crops from EU sources are assumed to be transported locally by truck to a gathering point (50 km). Here it is loaded onto trains and transported to the Netherlands, with an average distance of 800 km.

EU transport (lignocellulosic biomass) (C)

For larger distances, densification of biomass is advantageous. We assume biomass produced in the European region to be transported by truck to a local pre-treatment plant. Here, (woody) biomass is pelletised (densification) and loaded onto trains. Transport to the Netherlands is assumed to take place by rail transport with an average distance of 800 km. Cost and energy requirements for biomass densification are allocated to biomass production and pre-treatment.

EU transport (liquids) (D)

Transport of liquid biomass concerns crude rapeseed oil that is produced from rapeseed in Europe. Rapeseed pre-treatment and crushing takes place close to the production side and no additional transport is required. The cost and energy requirement of rapeseed crushing are allocated to crop production. Rapeseed oil is transported similar to chain B.

International (long-distance) transport of solids (E)

In the international scenarios (low- and high-tech), intercontinental resources become available. Intercontinental transport is assumed to take place by large ships with low specific transport costs. To improve transport efficiency, biomass is densified (pelletised) at local plants before it is shipped to the Netherlands. We assume that biomass is transported by truck to a local pre-treatment plant (50 km) where it is converted into pellets. These pellets are transported by truck (100 km) to the harbour and loaded onto large ocean ships (e.g. Panamax, 50-80 kton dm). Pellets are shipped to the Netherlands (11,000 km) and distributed locally by trucks (50 km).

International (long distance) transport of liquids (F)

For imports of vegetable oil (jatropha and palm oil), we assume that oil extraction takes place close to the production side. Vegetable oil is transported by truck to the harbour (100 km) and shipped to the Netherlands by large ocean ships (11,000 km). In the Netherlands, vegetable oil is refined into biodiesel close to the harbour. We assume 50 km of transport by truck from the harbour to the biodiesel production side.

Pelletising (woody and agricultural residues)

This study includes four types of lignocellulosic biomass: woody crops (SRC) from EU and tropical regions, domestic clean wood residues and domestic residues from agriculture.

For woody biomass, we assume biomass to be harvested and converted into wood chips directly at the source of production. Wood chips from domestic sources (clean wood residues) are transported to the conversion plant (e.g. PC plant with co-firing). Wood from international sources is first densified by pelletising at the central gathering point to improve transport, handling and conversion efficiency. These process steps are based on Hamelinck et al. [2005].

Before pelletising, wood chips need to be sized to 3-10 mm and dried to increase its heating value and decrease decomposition and weight. The biomass is sized using a hammermill to wood chips of about 10 mm and dried in a rotary drum. The hammermill consumes electricity. The heat for drying in the rotary drum comes from partly combustion of the biomass feedstock. After drying, the biomass is pressed to pellets in the pellet press. The total fossil energy requirement for these processes is estimated to be 37.4 kWh_e/odt biomass. The conversion efficiency from wood chips to wood pellets is estimated to be 0.85 kg/kg dm, mainly as a result of biomass requirements for drying of wood chips (2.5 GJ_{hhv}/tonne water evaporated [Hamelinck, Suurs et al., 2005]).

Table 19 Cost, fossil energy requirements and GHG emissions of biomass transport chains

Biomass feedstock	Transport type	Distance	Cost	Energy for transport	GHG emissions
		[km]	€/Gjbiomass	GJp/GJbiomass	kg CO_2 eq./GJ-biomass
Domestic sources					
Agro residues	Pelletising	0	0.6	0.107	0.002
	Truck	100	1.2	0.005	0.362
Total			1.8	0.111	0.364
Woody residues	Truck	100	1.3	0.007	0.499
Sugar beet	Truck	100	0.8	0.004	0.311
EU sources					
Wheat	Truck	50	0.8	0.006	0.458
	Train	800	0.9	0.078	0.006
Total			1.7	0.084	0.464
Vegetable oil (rapeseed)	Truck	50	0.3	0.001	0.114
	Train	800	0.6	0.012	0.001
Total			0.9	0.014	0.115
SRC (e.g. willow)	Truck	50	0.6	0.002	0.146
	Pelletising		0.4	0.065	0.001
	Train	800	0.8	0.019	0.001
Total			1.8	0.085	0.149
Global sources					
Vegetable oil (palm, jatropha)	Truck	100	0.5	0.002	0.172
	Ocean ship	11000	2.9	0.013	1.055
	Truck	50	0.3	0.001	0.086
Total			3.7	0.016	1.313
SCR (e.g. eucalyptus)	Truck	50	0.6	0.003	0.205
	Pelletising		0.4	0.065	0.001
	Truck	100	0.3	0.003	0.220
	Ocean ship	11000	0.7	0.027	2.158
	Truck	50	0.2	0.001	0.110
Total			2.2	0.099	2.694
Sugar cane	Truck	100	0.7	0.003	0.229
	Ocean ship	11000	3.8	0.017	1.407
	Truck	50	0.4	0.001	0.115
Total			4.9	0.022	1.750

APPENDIX V : PRIMARY ENERGY AND GHG EMISSIONS

Introduction

This appendix describes the methodology and data used for estimating the energy and greenhouse gas (GHG) balance and avoided primary energy and GHGs of the biomass conversion routes in this study and their fossil references. In order to estimate the GHG emission-saving potential of the selected biomass conversion options in this study, data from existing LCA (Life Cycle Assessment) studies on fossil and bioenergy were used. The results, as used for this study, are also summarised in the main text of this report (section 7.2).

Methodology

Instead of conducting a full LCA on fossil and bio-based systems, this study uses state-of-the art LCA data from recent publications in order to quantify the environmental performance of the systems included. Impacts of the first and second order, i.e. the energy and GHG emissions of crop production including the production and transportation of agricultural inputs such as fertilisers, transportation of crops, conversion and distribution, are taken into account. Energy and GHG emissions from construction or dismantling of decommissioned plants (3rd-order data) are not taken into account because of limited data available and limited impacts on the total life-cycle chains [Hamelinck and Hoogwijk, 2007; JRC, EUCAR et al., 2007]. Also other environmental performance parameters other than GHG emissions and fossil energy requirements, such as eutrophication and acidification, are beyond the scope of this study.

Reference systems and technologies

For each bio-based system, the conventional (fossil-based) reference system it replaces is defined. Note that in some of the production chains, more than one product is produced, e.g. the transesterification process of vegetable oil produces FAME and glycerine. Allocation of energy and GHG emissions to these by-products are done based on substitution bases, i.e. credits are given to the main product for energy and GHG avoided by substitution of conventional products by co-products. Note that the selected co-product can have a major influence on the performance of the overall production chain. In this study, single co-products and reference systems were selected. The motivation for these selections is given in the footnotes of the result tables. The motivation for land-use reference systems is described below followed by a description of the reference technologies.

Reference systems for land use

In order to quantify GHG emissions from biomass production, the reference land-use system (i.e. the situation if energy crops would not be produced on the same land), has to be determined. The selected reference system has a major influence on net GHG emissions allocated to energy crop production, mainly due to the difference in N_2O emissions from the reference system and bioenergy crop [Smeets, Bouwman et al., in progress]. If, for example, cropland is taken as a reference system, the difference between GHG emissions of the reference and energy crop production system could be relatively small due to comparable fertiliser use in both systems. Effects of land-use change, caused by changing grassland or forests into arable land either directly or indirectly[55], could have a larger effect on GHG emissions from crop production as described by, amongst others, for palm oil [Wicke, Sikkema et al., 2008] and EU biofuels [RFA, 2008]. This study does not take into account changes in under- and above-ground soil organic matter as a result of land-use change by bioenergy crop production, but could potentially decrease the GHG mitigation potential substantially [RFA, 2008]. By excluding effects of land-use change, we implicitly assume that all bioenergy crops produced will be produced on specifically allocated or marginal land, not used for either food or fodder production or natural vegetation. If specifically allocated land is replaced, the reference type land should be set-aside as also assumed by JRC, EUCAR et al. [2006][56]. If food or fodder crops are replaced, the 'no reference' system is best applicable, which implies that all GHG emissions from the land are allocated to bioenergy crop cultivation.

Table 22 and Table 23 display the results for GHG emissions for three reference systems (No reference, Zero N input and Set-aside land) for 1st-generation biofuel production. The results in the main report include the 'Zero N input' reference system. This reference system is also implicitly used for the tier 1 method used by the IPCC fertilised-induced emission (FIE) calculation [Smeets, Bouwman et al., in progress]. Please note that Smeets et al. [in progress] does not include biofuels from lignocellulosic biomass (advanced biofuels). For woody biomass and residues, we used the results of the WTW study. The results for woody crops production are therefore more conservative on N_2O emissions.

Indirect land use change

For this study, we assumed all biomass to be produced on land that was formerly used for the production of other crop types or on set-aside (specifically allocated) land. We did not take indirect land-use change into account. Unless yield

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[55] Direct environmental effects include the destruction of habitats by converting natural vegetation into arable land and local effects on air, soil and water quality and quantity. Indirect environmental effects include displacement of agricultural activities by bioenergy crop production to uncultivated areas (indirect land-use change) [RFA, 2008].

[56] The WTW study [JRC Eucar et al., 2007] assumes set-aside land as reference in the second edition [2006]. Note that for the first edition, 'no-reference crop' was selected as reference system. The reasoning for selecting 'no-reference crop' was that bioenergy crops were expected to be produced on land that would otherwise be used for food crops that would be exported from the EU. For the second edition, the reference system was changed because bioenergy crops are expected to be grown on set-aside land in the EU. Less exports of cereals and more set-aside land is expected as a result of changes in agricultural subsidy and agricultural markets in the EU [JRC, Eucar et al., 2007].

improvements are sufficient to increase land availability for energy crop production, shifts in land-use prior to the energy crops can be expected. The production of palm oil for biodiesel could for example shift the production of vegetable oil for food purposes to new production land to maintain supply. This could lead to deforestation or conversion of other natural areas to cropland [RFA, 2008]. The release of above- and below-ground carbon that was previously stored in these areas could decrease the mitigation potential of biomass substantially or even make it a net carbon [Fargione et al., 2008; RFA, 2008; Searchinger et al., 2008; Wicke et al., 2008].

For the national scenarios, we used data for the EU27+ on potentials for biomass production from REFUEL [Wit, Faaij et al., 2007]. This study does not include a detailed module for the demand of biomass for animal feed. Large-scale production of energy crops within Europe could displace the production of crops for animal feed and negative effects of indirect land-use change or increasing food prices by competition.

A recent study by MNP [Eickhout et al., 2008] indicates that the 10% target for 2020, as proposed in the LowTech and NatHighTech scenarios consistent with the EU targets, is only possible when biomass is imported from outside the EU. This could imply that biomass production in the national scenarios (NatLowTech and NatHighTech) result in imports of food or feed crops as a result of displacement.

Reference technologies

In order to estimate the avoided GHG emissions and avoided primary energy by substitution of fossil energy and materials by bioenergy and bio-based materials, reference technologies are selected to estimate the amount of fossil energy require to generate the same amount of energy or produce the same amount of products. This method is described in Bosselaar and Gerlagh [2006].

For substitution of fossil-based transport fuels, conventional fuels (petrol and diesel) are substituted by bio-based alternatives that can be used in internal combustion engines. The substitution method is therefore straightforward: biodiesel replaces diesel and ethanol replaces petrol on an energy basis. For electricity and heat generation, different reference technologies are selected depending on the conversion technology and the expected conversion option it substitutes. The selected chemicals in this study (ethylene, caprolactam and hydrogen) are similar to the bio-based substitutes. The petrochemical production routes of the fossil references are the main production routes used in the Netherlands. The fossil reference technologies are given in the results tables (Table 21 through Table 27). The performance of fossil energy carriers are displayed in Table 20.

Table 20 Fossil energy use and GHG emissions of primary and secondary fossil fuels

Biomass option	Fossil reference technology		Reference
Biodiesel	Diesel		
- Energy (MJ_{ex}/MJ_f)		0.16	JCR et al. (2007)
- GHG emissions prod. (g CO_2/MJ_f)		14.2	JCR et al. (2007)
- GHG emissions end use (g CO_2/MJ_f)		74.7	JCR et al. (2007)
Ethanol	petrol		
- Energy (MJ_{ex}/MJ_f)		0.14	JCR et al. (2007)
- GHG emissions prod. (g CO_2/MJ_f)		12.5	JCR et al. (2007)
- GHG emissions end use (g CO_2/MJ_f)		73.7	JCR et al. (2007)
	Natural gas		
- Energy (MJ_{ex}/MJ_f)		0.10	Fraunhofer (2006)
- GHG emissions prod. (g CO_2/MJ_f)		3.3	Fraunhofer (2006)
- GHG emissions end use (g CO_2/MJ_f)		56.1	Fraunhofer (2006)
	Hard coal		
- Energy (MJ_{ex}/MJ_f)		0.04	Koorneef (2008)
- GHG emissions prod. (g CO_2/MJ_f)		10	Koorneef (2008)
- GHG emissions end use (g CO_2/MJ_f)		94.6	Fraunhofer (2006)

For transport fuels, we assumed direct substitution of the conventional fossil transport fuels diesel and petrol by biodiesel and ethanol respectively. The efficiencies for use in internal combustion engines are thereby assumed to be similar to their fossil references. Energy and GHG emissions from the production of biofuels are taken into account.

By-products from biomass feedstock and conversion

For the majority of biomass conversion options in this study more than one product is produced from biomass. Ethanol from wheat also includes the production of bran and DDGS (dried distillers' grain wit solubles). Allocation of GHG and energy to these by-products will change the environmental and energetic performance of biofuel production considerably.

This study does not review the impact of various allocation methods explicitly, but uses data from existing LCA studies taking their allocation assumptions into account. Because the majority of data on GHG emissions and primary energy is derived from JRC et al. [2006] and Smeets et al. [in progress], we made consistent assumptions on accounting for by-products. In all cases, the energy requirement and GHG emissions of replaced products are by-products from bioenergy production. In the case of ethanol produced from wheat, DDGS is a protein-rich substance that can be used for animal feed replacing soybean meal. DDGS could also be co-fired in a coal-fired power plant. In case of co-firing, the energy credit would be considerably larger [JRC, EUCAR et al., 2007].

Farming, collection of residues, pre-treatment and transport
The energy requirement and GHG emissions for farming or collection, pre-treatment and transport to the conversion plant can have a major impact on the overall performance of the bio-based production chain. Figure 43 displays the primary energy requirement of biomass feedstock production (cradle to factory gate) including feedstock production, pre-treatment (pelletising) and transport to the conversion plant in the Netherlands. Data for feedstock production is derived from JCR, EUCAR et al. [2006]. Data for pelletising and for transportation of biomass is derived from Hamelinck et al. [2005].

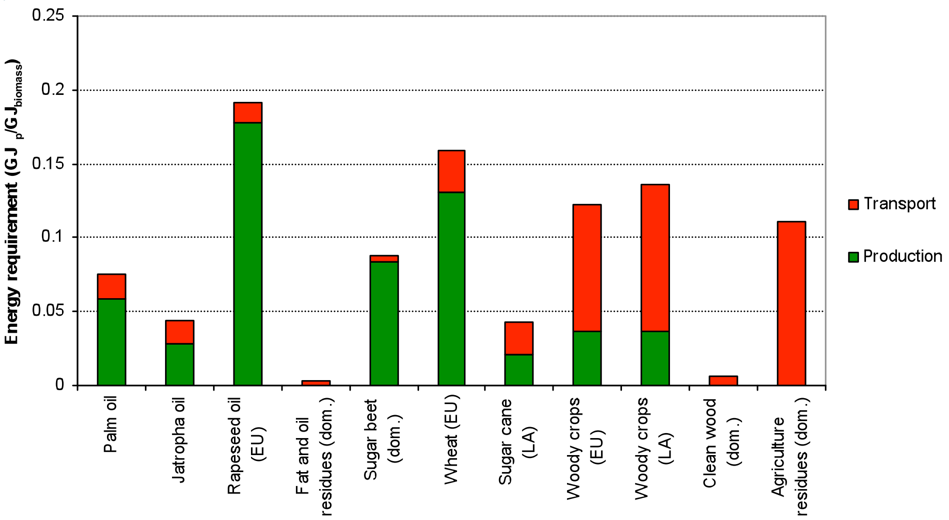
The energy requirement for production of energy crops includes energy requirements for farming processes and indirect energy requirements for e.g the production of fertilisers. Transportation energy include energy for transport to central gathering points, densification (for woody biomass and agricultural residues) by pelletising and local transport to the conversion plants as described in the previous section.

The energy requirement for transport of woody crops and agricultural residues is largest for woody crops and agricultural residues as a result of energy requirement for pelletising. Woody crops are pelletised before transport to the Netherlands, agricultural residues are pelletised close to the source of production to improve transport and handling, conversion efficiency and to avoid fire hazards.

Transport energy of other domestic sources (fat and oil residues, sugar beet and clean wood residues) is marginal due to the average short transport distance assumed (100 km). Production of rapeseed oil is relatively energy-intensive as a result of upstream energy requirement for the production of fertilisers.

Energy requirements and GHG emissions related to biomass transports to the Netherlands depend on feedstock properties (e.g. specific weight, moisture content etc.), transportation methods and distance. To estimate the impact of biomass transportation, we used a simplified version of the transportation model from Hamelinck et al. [Hamelinck, Suurs et al., 2005]. A detailed description of the transportation routes and related energy requirements and GHG emissions can be found in Appendix 5.

Figure 43 Energy consumption for biomass feedstock production and transport (fossil energy per unit of biomass)



Conversion

The conversion of biomass feedstocks to final energy carriers and bio-based chemicals include the consumption of raw materials and process utilities. The performances of the technologies considered in this study are presented in the main text of this report.

Distribution

Energy requirements for distribution of biofuels to the refuelling stations are derived from JCR Eucar et al. [2007]. It is assumed that transport fuels have to be transported over a distance of 150 km to the refuelling stations by truck.

Distribution losses of electricity are not taken into account as we considered direct substitution of electricity before grid distribution. It should be noted that for some biomass digestion technologies, grid losses could also be taken into account [Bosselaar and Gerlagh, 2006].

Results

For all fossil and bio-based routes in this study, the fossil primary energy and GHG emissions are given. The sources are given in the table. Specific assumptions on by-product allocation are given in the footnotes of the result tables.

Transport fuels

This study includes wheat grain, sugar beet and sugar cane for ethanol fermentation, rapeseed, palm fruit and jatropha for biodiesel production (FAME) and woody crops from EU and tropical regions for 2nd-generation biofuel production, electricity generation and gasification for synthesis of chemicals.

Table 21 Fossil primary energy and GHG performance of fossil-based transport fuels (petrol and diesel)

	Prim. energy		GHG		References
	MJ$_{prim}$ x/MJ$_{final\ product}$		g CO$_2$ eq./MJ$_{final\ product}$		
Conversion option					
Process	**Best estimate**		**Best estimate**	**Range**	
Petrol (fossil reference)					
Production (refining)	0.08		7		JRC et al. 2007
Transport and distribution	0.06		5.5		JRC et al. 2007
End use	1.00		73.3		JRC et al. 2007
Total	1.14		85.8	84.8 - 87.9	Calc
Diesel (fossil reference)					
Production (refining)	0.1		8.6		JRC et al. 2007
Transport and distribution End use	0.1		5.6		JRC et al. 2007
	1.00		73.2		JRC et al. 2007
Total	1.20		87.4	85.8 - 89.2	Calc

Table 22 Fossil primary energy and GHG performance of ethanol production from conventional crops

	Prim. energy		GHG		References
	MJ$_{prim}$ x/MJ$_{final\ product}$		g CO$_2$ eq./MJ$_{final\ product}$		
Conversion option					
Process	**Best estimate**		**Best estimate**	**Range**	
EtOH from wheat EU25					
Cultivation (no reference)[a]	0.24		55	33 - 62	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (set-aside land)[a]	0.24		49	27 - 56	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (zero N input)[a]	0.24		37	-30 - 44	JRC et al. 2006, Smeets et al. (in progress)
Feedstock transport	0.05		0.2	0 - 0	Hamelinck 2005
Conversion[b]	0.59		25	25 - 25	JRC et al. 2006, Smeets et al. (in progress)
Transport final product	0.03		1.54	2 - 2	JRC et al. 2006
Total (no reference)	0.92		82	60 - 89	Calc
Total (set-aside land)	0.92		76	54 - 83	Calc
Total (zero N input)	0.92		64	-3 - 71	Calc
EtOH from sugar beet NL					
Cultivation (no reference)[c]	0.16		33	18 - 38	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (set-aside land)[c]	0.16		30	15 - 35	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (zero N input)[c]	0.16		22	-39 - 22	JRC et al. 2006, Smeets et al. (in progress)
Feedstock transport[d]	0.01		0.3	0 - 0	Hamelinck 2005
Conversione	0.65		33	33 - 33	JRC et al. 2006, Smeets et al. (in progress)
Transport final product	0.03		1.54	2 - 2	JRC et al. 2006
Total (no reference)	0.85		68.08	52 - 73	Calc
Total (set-aside land)	0.85		65.19	49 - 70	Calc
Total (zero N input)	0.85		56.36	-4 - 57	Calc

	Prim. energy		GHG		References
	MJ_{prim} x/$MJ_{final\ product}$		g CO_2 eq./$MJ_{final\ product}$		
EtOH from sugar cane LA					
Cultivation (no reference)[f]	0.058		24	17 - 26	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (set-aside land)[f]	0.058		23	15 - 25	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (zero N input)[f]	0.058		17	9 - 19	JRC et al. 2006, Smeets et al. (in progress)
Feedstock transport	0.022		1.7	2 - 2	Hamelinck 2005
Conversiong	-0.141		-10.39	-10 - -10	JRC et al. 2006
Transport final product	0.02		6.81	7 - 7	Hamelinck 2005
Total (no reference)	-0.04		22	15 - 25	Calc
Total (set-aside land)	-0.04		21	14 - 23	Calc
Total (zero N input)	-0.04		15	7 - 17	Calc

a) The cultivation process also includes energy for storage (cooling) and drying. GHG emissions from cultivation (mainly N_2O) are derived from Smeets et al. (in progress).

b) The production of ethanol from wheat is an energy intensive process which consumes natural gas for drying, hydrolysis, fermentation and distillation processes [Hamelinck and Hoogwijk, 2007]. Heat is assumed to be produced by a conventional natural gas boiler with an efficiency of 90%. Note that the efficiency of ethanol production could increase significantly if heat is produced in a CHP plant using straw for fuel as described in JRC et al. [2007].

c) Sugar beet leaves are assumed to be ploughed under in the field to maintain nutrient levels which is the common practice in the EU [JRC, EUCAR et al., 2007].

d) Transport energy requirements are limited as we assume only domestic production of sugar beets. Due to the relatively high moisture content of fresh sugar beets, imports of sugar beets would be costly and energy intensive.

e) Pulp and other by-products from ethanol fermentation are assumed to be sold for animal feed. Process heat is assumed to be generated by a conventional natural gas-fired boiler with an efficiency of 90%.

f) Sugar cane production in Brazil includes relatively low fertiliser use and resulting GHG emissions. Apart from fertiliser-related emissions, combustion of foliage to improve harvesting efficiency, results in CO_2, CH_4 and NOx emissions.

g) Co-production of electricity and heat from bagasse results in surplus energy as credited for. Credits are given for bagasse sold to nearby factories that use it for heat production replacing diesel [JRC, EUCAR et al., 2007].

h) Transport of ethanol to the Netherlands is assumed to take place per ocean ship and is requires less energy than transport of biomass feedstocks prior to conversion.

Table 23 Fossil primary energy and GHG performance of biodiesel production from conventional crops

	Prim. energy		GHG		References
	MJ_{prim} x/$MJ_{final\ product}$		g CO_2 eq./$MJ_{final\ product}$		
Conversion option					
Process	**Best estimate**		**Best estimate**	**Range**	
FAME from palm fruit					
Cultivation (no reference)[a]	0		22	12 - 24	Smeets et al. (in progress)
Cultivation (set-aside land)[a]	0		17	8 - 20	Smeets et al. (in progress)
Cultivation (zero N input)[a]	0		14	-22 - 16	Smeets et al. (in progress)
Feedstock transport	0.02		1.30	1 - 1	Hamelinck 2005
Conversion	0.212		17	17 - 17	JRC et al. 2006, Smeets et al. (in progress)
Transport final product	0.02		1.26	1 - 1	JRC et al. 2006
Total (no reference)	0.25		42	32 - 44	Calc
Total (set-aside land)	0.25		37	28 - 40	Calc
Total (zero N input)	0.25		34	-2 - 36	Calc
FAME from jatropha					
Cultivation[b]			0	0 - 0	?
Feedstock transport	0.02		1.26	1 - 1	Hamelinck 2005
Conversion	0.212		17	17 - 17	JRC et al. 2006
Transport final product	0.02		1.26	1 - 1	JRC et al. 2006
Total	0.25		20	20 - 20	Calc
FAME from rapeseed					
Cultivation (no reference)[c]	0.30		101	55 - 115	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (set-aside land)[c]	0.30		92	46 - 106	JRC et al. 2006, Smeets et al. (in progress)
Cultivation (zero N input)	0.30		67	-6 - 70	JRC et al. 2006, Smeets et al. (in progress)
Feedstock transport	0.01		0.1	0 - 0	Hamelinck 2005
Conversion[d]	0.12		-7	-7 - -7	JRC et al. 2006, Smeets et al. (in progress)
Transport final product	0.02		1.26	1 - 1	JRC et al. 2006
Total (no reference)	0.46		95	50 - 109	Calc
Total (set-aside land)	0.46		86	41 - 101	Calc
Total (zero N input)	0.46		61	-12 - 64	Calc
FAME from dom. oil and fat residues					
Oil and fat, dom. resourcese	0		0	0 - 0	JCR et al. 2006
Feedstock transport	0.00		0.2		Hamelinck 2005
Conversion (including refining)	0.212		-7		
Transport final product	0.02		1.26		JCR et al. 2006
Total	0.23		-5		Calc

a) For biodiesel from palm oil, data on primary energy requirements are derived from Hamelinck et al. [2007]. GHG emissions from biodiesel production are derived from Smeets et al. [in progress].

b) Emissions from jatropha cultivation are derived from Struijs [2008], who conducted research on the sustainability of electricity generation in the Netherlands from jatropha produced in Tanzania. We used similar assumptions on primary energy and GHG emissions from cultivation and oil extraction of jatropha.

c) GHG emissions from rapeseed production are relatively large compared to e.g. palm oil due to large amounts of fertiliser usage. Rapeseed straw is ploughed back into the soil to increase the organic content of the soil.

d) The press cake from the oil extraction process is used for animal feed. Credits are given for substitution of soy bean meal. Conversion of rapeseed oil to biodiesel does not add to the GHG balance because the process requires little energy and credits are given for glycerine production which is assumed to be used for chemicals. Note that if glycerine is used for animal feed, the GHG mitigation performance of RME will decrease [JRC, EUCAR et al., 2007].

e) For biodiesel production from fat and oil residues from domestic resources, only GHG emissions and energy use for transportation to the conversion plant, pre-treatment and refining and conversion to biodiesel (transesterification) are taken into account.

f) We assumed that refining and transesterification processes are comparable to biodiesel production from rapeseed. Note that certain fat or oil residues might be more difficult to process than crude rapeseed oil resulting in optimistic estimates. The produced biodiesel might also be of lower quality. Biodiesel from animal fat is more viscous than biodiesel form vegetable oil with a higher cloud point [JRC, EUCAR et al., 2007]. These issues are not addressed in this study.

Table 24 **Fossil primary energy and GHG performance of biodiesel production from lignocellulosic crops**

	Prim. energy		GHG		References
	MJ_{prim} x/$MJ_{final\ product}$		g CO_2 eq./$MJ_{final\ product}$		
Conversion option					
Process	**Best estimate**		**Best estimate**		
EtOH from agro residues (straw)					
Agro residues (collection)[a]	0.05		3		JRC et al. 2006
Pelletising + transport[b]	0.02		1		Hamelinck 2005
Conversion[c]	-0.11		73.3		Hamelinck 2007
Transport final product	0.03		1.54		JRC et al. 2006
Total	-0.01		5.98		Calc
EtOH from woody biomass					
Wood residues (collection + chipping)[d]	0.013		1.021		JRC et al. 2006
EU wood (farming)[e]	0.108		15		JRC et al. 2006
Trop. Wood (farming)[f]	0.108		15		JRC et al. 2006
Transport woody residues	0.02		1		Hamelinck 2005
Transport EU wood	0.25				Hamelinck 2005
Transport trop. wood	0.29				Hamelinck 2005
Conversion					Hamelinck 2006
Transport final product	0.03		1.54		JRC et al. 2006
Total wood residues	0.06		3.99		Calc
Total EU wood	0.39		16.24		Calc
Total trop. wood	0.43		16.24		Calc

a) Ethanol production from domestic residues from agriculture includes the collection of residues from the field and distribution to a central gathering point. GHG emissions from agricultural production are allocated to crop production.

b) The residues are pelletised at the central gathering point explaining the relatively high energy requirements and GHG emissions from transport.

c) Lignin, which cannot be converted to ethanol, is assumed to be combusted for generation of electricity and process heat. Credits are given for surplus electricity produced with an NGCC plant as reference. For ethanol from agro residues we assumed similar performance of the conversion plant to conversion of ethanol from woody biomass. Note that grasses or straw contain less lignin than woody biomass which would result in lower amounts of electricity co-generated compared to ethanol from woody biomass [Hamelinck, Van Hooijdonk et al., 2005].

d) Domestic wood residues include energy requirements for collection and chipping.

e) Woody biomass from dedicated energy crops (SRC) includes GHG emissions and the energy requirement for wood farming derived from JRC et al. [2007] for cultivation of SRC (poplar or willow) on agricultural land in Europe.

f) We used data for cultivation of EU SCR production for SRC production in tropical regions although energy requirements and GHG emissions might be considerably less as a result of e.g. higher yields.

Table 25 Fossil primary energy and GHG performance of biodiesel production from lignocellulosic crops

	Prim. energy		GHG		References
	MJ_{prim} x/$MJ_{final\ produc}$t		g CO_2 eq./$MJ_{final\ product}$		
Conversion option					
Process	**Best estimate**		**Best estimate**		
FT-diesel agro residues					
Agro residues (collection)	0.00		0		JRC et al. 2006
Pelletising + transport[a]	0.29		1		Hamelinck 2005
Conversion[b]	-0.137		0		Hamelinck 2007
Transport final product	0.03		1.54		JRC et al. 2006
Total	0.19		2.48		Calc
FT-diesel woody biomass					
Wood residues (collection + chipping)[c]	0.005		0.350		JRC et al. 2006
EU wood (farming)[e]	0.037		13		JRC et al. 2006
Trop. Wood (farming)[c]	0.108		15		JRC et al. 2006
Transport woody residues	0.02		1		Hamelinck 2005
Transport EU wood	0.23		0		Hamelinck 2005
Transport trop. wood	0.26		7.0		Hamelinck 2005
Conversion[b]					Hamelinck 2006
Transport final product	0.03		1.54		JRC et al. 2006
Total wood residues	0.05		3.19		Calc
Total EU wood	0.29		15.22		Calc
Total trop. wood	0.33		21.82		Calc

a) Collection, pre-treatment and transport of agro residues are similar to ethanol from agro residues
b) The conversion process generates a surplus of energy by electricity generation from off gas from the FT-synthesis process. Credits are given using with electricity produced with an NGCC plant as reference.
c) Cultivation and pre-treatment of woody biomass are similar to ethanol production from woody biomass.

Electricity generation

Biomass co-firing in coal-fired power plants is assumed to have no influence on the performance of the power plant, which implies that 1 GJ biomass replaces 1 GJ of coal. Note that biomass co-firing could have a negative impact on the net efficiency of the power plant as described in section 5.1.3 of the main text in this report.

The energy penalty of an NGCC plant by co-gasification of biomass is allocated to biomass. We assume digestion plants and waste incineration plants to replace electricity produced by conventional energy carriers in the Netherlands (coal, oil, gas and nuclear). Heat production replaces heat produced in a conventional natural gas boiler (ηlhv = 0.90) as described in Bosselaar et al. [2006].

Table 26 Reference technologies for electricity generation and their performance

Biomass option	Fossil reference technology	Reference year				References
		2006	2010	2020	2030	
Co-firing	Pulverised Coal plant[a]					Bosselaar et al. 2007
- Efficiency (%)		40	46	49	52	van den Broek et al. 2008
- Primary energy (MJp/MJe)		2.6	2.3	2.1	2.0	Calc
- GHG emissions (g CO_2 eq./MJe)		261	227	213	200	Calc
Co-gasification	Natural Gas CC plant[b]					Bosselaar et al. 2007
Co-production (chemicals and biofuels)	Natural Gas CC plant[c]					Bosselaar et al. 2007
- Efficiency (%)		56	58	60	63	van den Broek et al. 2008
- Primary energy (MJp/MJe)		2.0	1.9	1.8	1.7	Calc
- GHG emissions (g CO_2 eq./MJe)		106	102	99	94	Calc
Electricity from waste (combustion and digestion)						
Electricity	National production mix[d]					Bosselaar et al. 2007
- Efficiency (%)		43	45	46	48	Bosselaar et al. 2007
- Primary energy (MJp/MJe)		2.5	2.5	2.4	2.3	Calc
- GHG emissions (g CO_2 eq./MJe)		164	152	162	154	Calc
Heat	Conventional boiler NG[e]					Bosselaar et al. 2007
- Efficiency (%)		90	90	90	90	Bosselaar et al. 2007
- Primary energy (MJp/MJh)		1.1	1.1	1.1	1.1	Calc
- GHG emissions (g CO_2 eq./MJh)		66	66	66	66	Calc

a) Biomass replaces coal directly if co-fired in a PC plant.

b) Co-gasification of biomass replaces natural gas directly. Note that the substitution factor is <1 because the efficiency of the NGCC plant decreases by co-gasification of biomass as explained in section 4 of the main report.

c) Co-production of electricity in advanced biofuel production and synthesis gas for chemicals is expected to replace electricity generated in NGCC plants as we assumed coal to be phased out in the high-tech scenarios.

d) Electricity generated from MSW and WOW is assumed to replace domestic electricity production [Bosselaar and Gerlagh, 2006].

e) Heat production in MSW incineration and digestion plants is assumed to substitute heat produced in conventional natural gas fired boilers. Note that the GHG emissions are higher than in Bosselaar and Gerlagh [2006] since we accounted for emissions that occur from extraction and transport of natural gas.

Chemical production

The GHG emissions, fossil primary energy requirements and the production of bio-based and petrochemical based ethylene, caprolactam and hydrogen are summarised in Table 27.

The bio-based substitutes for chemicals in this study are similar to their fossil references. Energy requirements for the production, usage and waste processing phase (from cradle-to-grave) are taken into account assuming waste incineration with energy recovery [Patel, Crank et al., 2006]. Co-produced electricity from bio-based hydrogen production is assumed to replace electricity generated by an NGCC plant as available in the High-Tech scenarios.

Table 27 Fossil primary energy and GHG performance of petrochemical and bio-based production of chemicals

Conversion option	Primary energy				GHG				References
Process	GJ$_{prim}$ x /t $_{final\ product}$				t CO$_2$ eq./t final $_{product}$				
	2006	2010	2020	2030	2006	2010	2020	2030	
Ethylene									
Fossil based[a]	59.5	59.5	59.5	59.5	4.4	4.4	4.4	4.4	Neelis, 2006, Patel et al. 2006
Bio-based									
Ethanol production[b]	-0.59	-0.74	-0.78	-0.83	0.65	0.65	0.65	0.65	Smeets et al. (in progress), JRC et al. 2007
Conversion[c]	1.94	1.94	1.94	1.94	0.02	0.02	0.02	0.02	Patel et al. 2006
Total	1.36	1.21	1.16	1.12	0.67	0.67	0.67	0.67	Calc.
Total avoide[d]	58.1	58.3	58.3	58.4	3.7	3.7	3.7	3.7	Calc.
Caprolactam									
Fossil based[d]	43.1	43.1	43.1	43.1	2.7	2.7	2.7	2.7	Patel et al. 2006
Bio-basede	27.3	27.3	27.3	27.3	0.07	0.07	0.07	0.07	Patel et al. 2006
Total avoide[d]	15.8	15.8	15.8	15.8	2.6	2.6	2.6	2.6	Calc.
Hydrogen									
Fossil based[f]	186	186	186	186	10.1	10.1	10.1	10.1	NREL, 2008
Bio-based									
Agro residues (collection and transport)[g]	43.4	43.4	36.9	36.6	0.14	0.14	0.12	0.12	Hamelinck, 2005, JRC et al. 2007
Wood residues (collection and transport)[g]	4.3	4.3	3.7	3.7	0.19	0.19	0.16	0.16	Hamelinck, 2005, JRC et al. 2007
EU wood (production and transport)[g]	47.8	47.8	40.6	40.3	2.02	2.02	1.72	1.70	Hamelinck, 2005, JRC et al. 2007
Trop. Wood (production and transport)[g]	52.9	52.9	44.9	44.5	3.00	3.00	2.54	2.53	Hamelinck, 2005, JRC et al. 2007
Conversion[h]	-173.6	-173.6	-171.8	-170.5	-11	-11	-11	-11	Hamelinck et al. 2002
Total agro residues	-130.2	-130.2	-134.9	-133.9	-11.25	-11.25	-11.15	-11.07	Calc.
Total wood residues	-169.3	-169.3	-168.1	-166.9	-11.2	-11.2	-11.11	-11.03	Calc.
Total EU wood	-125.8	-125.8	-131.2	-130.3	-9.367	-9.367	-9.552	-9.483	Calc.
Total trop. wood	-120.8	-120.8	-126.9	-126	-8.392	-8.392	-8.725	-8.661	Calc.
Total avoided agro residues	316	316	321	320	21	21	21	21	Calc.
Total avoided wood residues	355	355	354	353	21	21	21	21	Calc.
Total avoided EU wood	312	312	317	316	19	19	20	20	Calc.
Total avoided trop. wood	307	307	313	312	19	19	19	19	Calc.

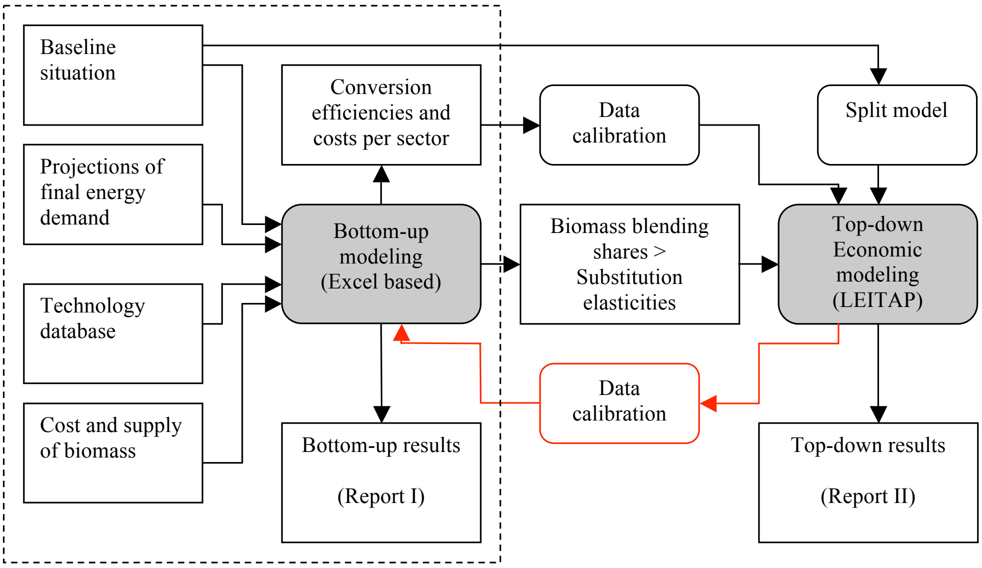
a) Ethylene from steam cracking of naphtha, GHG emissions from waste incineration without energy recovery.
b) Ethanol production from sugar cane in Brazil + transport of ethanol to the Netherlands (similar to transport fuels).
c) Process energy (natural gas for steam and electricity).
d) Caprolactam via phenol hydration. Data in BREW converted from HHV to LHV.
e) Caprolactam from sugar fermentation to lysine.
f) Hydrogen from steam methane reforming of natural gas. Fossil primary energy requirements and GHG emissions calculated from the Excel model provided by NREL [2008].
g) Collection, pre-treatment and transport routes similar to biofuel production from lignocellulosic biomass (FT-diesel and EtOH).
h) Efficiency assumed similar for all lignocellulosic biomass feedstocks. Credit for co-production of electricity (reference = NGCC).

APPENDIX VI: BOTTOM-UP AND TOP-DOWN MODEL INTERACTION

In order to quantify the macro-economic impact of large-scale deployment of biomass in the Netherlands, a macro-economic top-down model was used supported by inputs of bottom-up information. The use of bottom-up information in top-down models is not a standard process and in order to understand the limitations to this method, it is important to understand the main differences between bottom-up and top-down models. Whereas bottom-up models include detailed characteristics (cost and performances) of technologies, these models are often limited in modelling economic behaviour. Final energy demands and fuel prices, for example, are often exogenous parameters in these models (e.g. assumed to change constant in time) [Schäfer et al., 2005]. Top-down economic models, on the other hand, include technologies in aggregated production functions for each sector. Technology change in these models is often presented by substitution between different production functions [McFarland et al., 2004].

The main challenge for this study is to use the strength of top-down economic modelling to quantify the multi-sectoral impact of substituting fossil energy by biomass. For example, bio-based production of transport fuels results in decreased imports and refining of crude oil, but increases the production or imports of agricultural goods (energy crops) and use in the petroleum sector. In order to do so, the model requires adjustments and inputs of bottom-up information of the current and projected technology mix in the Netherlands. Figure 44 describes the process system steps of bottom-up data used for the top-down macro-economic model LEITAP.

Figure 44 Model system for macro-economic modelling using bottom-up input data for bioenergy and bio-based chemicals



The dashed boundary on the left marks the bottom-up part of this study as presented in report I. This figure is partly based on Schäfer et al. [2005].

The methodology as displayed in Figure 44 includes the bottom-up work on the left (in frame) and the top-down work on the left. This report presents the results of the bottom-up scenario work. The bottom-up model consists of physical as well as economic data, the top-down modelling work consists of an economic framework without physical units, but US$ weighted indices. In order to interpret the results and calibrate the economic model, the economic indices are converted into physical units (e.g. PJ or kg) using equation VI.1. Note that this equation only applies to one single region. If multiple regions are considered, the function will be specific per region r.

$$\frac{E_{output,b}}{E_{fuel,b}} = \frac{Y_{output,b}\frac{1}{p_{output}}}{X_{fuel,b}\frac{1}{p_{fuel}}S_{fuel,b}M_b}$$

Eq. VI.1 [McFarland, Reilly et al., 2004]

$E_{output,b}$ = Energy output of technology b.
$E_{fuel,b}$ = Energy input (fuel) of technology b.
$Y_{output,b}$ = Output (dollar weighted index) of technology b.
p_{output} = $p_{e}{}^{*}{}_{lec,r}$ *is an average price of electricity, constructed so that the supplementary physical data are consistent with the economic data base*
$X_{fuel,h}$ = fuel input (dollar weighted index)
$S_{fuel,b}$ = production share of fuel for technology b
M_b = mark-up ratio (cost compared to the reference technology if using the same fuel).

Bottom-up work

Baseline situation

The baseline situation includes a detailed assessment of current biomass use for bioenergy. It was not feasible to quantify the current use of biomass for bio-based chemicals as these statistics are not reported. The baseline situation also includes information on the structure of the electricity sector (vintage). This data is used to model the replacement rate of retired capacities in the electricity generation sector.

Final energy demand per scenario

Projections of final energy demand for electricity, transport fuels and chemicals are used to estimate the demand for primary fossil energy carriers and the substitution potential of biomass. The bottom-up projections include final energy demand projections from the WLO scenarios [Janssen, Okker et al., 2006]. The final energy demands in the LEITAP projections are modelled endogenously.

Technology characterisation and aggregation

The technology database includes the technology characterisation and aggregation per sector and commodity. A selection of representative technologies was made for the current situation and for the near future until 2030. This implies that also technologies were considered that are not yet commercialised. Data on cost and performance of these technologies was collected from bottom-up engineering studies. Future projections of cost were made using economies of scale, technological learning and innovation factors. The Excel model includes a detailed database of these technologies, but in order to assess the results for the data calibration process with the production functions in the top-down model, the technologies in this study are aggregated to single commodity options.

Biomass cost and supply

For the bottom-up estimations of cost and supply of biomass in the scenarios, existing studies were used that estimate the cost and supply relations for biomass energy crops produced in the EU27+ region [Wit, Faaij et al., 2007] and the global supply potential [Hoogwijk, Faaij et al., 2005]. Furthermore, domestic supply of primary, secondary and tertiary residues are taken into account. The projected supply of residues are based on PGG publications [Rabou, Deurwaarder et al., 2006; Kip, Lammers et al., 2007] and [Koppejan and Boer-Meulman, 2005]. For evaluation, the results are compared with the cost and supply of biomass that result from the top-down model outcomes.

Model interaction

As shown in Figure 44 there are three interaction processes between the bottom-up and the top-down models. Blending shares of biomass for biofuels, bio-based chemicals and bio-based electricity, based on the bottom-up projections, are used as input for the top-down model (method described in report II). The second process includes a continuous iteration process in which results of the bottom-up and top-down models are calibrated[57]. The key features for these calibration processes are the relation between energy and dollar indices (eq. VI.1) and the assumed technological change in both model structures.

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[57] Note that the bottom-up data was not calibrated for feedstock prices or changes in demand for energy or chemicals. The required steps should be to use the final demands for electricity, transport fuels and chemicals, as projected wit LEITAP in the bottom-up model. This could change the blending shares of electricity and chemicals as they are based on total final demands in the considered sectors.