Platform Biobased Raw Materials

Potential of Coproduction of Energy, Fuels and Chemicals from Biobased Renewable Resources

Transition Path 3:
Co-production of Energy, Fuels and Chemicals

November 2006

Creatieve Energie
EnergieTransitie

WISEBIOMAS

Working group for Innovative and Sustainable BIObased Energy and MAterialS

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Table of Contents

Preface

This summary report goes into detail about the transition path "Co-production of chemicals, transport fuels, electricity and heat". A Working Group under the chairmanship of Luuk van der Wielen of Delft University of Technology has elaborated this transition path, acting on request of the Platform Biobased Raw Materials.

The umbrella report of the Platform Biobased Raw Materials "30% replacement of fossil-based raw materials in 2030" is based on the elaboration of the five transition paths. Reports for the other individual transition paths are also available.

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Management summary

This report shows how in 2030, biobased alternatives can potentially cover up to 30% of the Netherlands' domestic energy and chemicals demand, effectively reducing CO_2 emissions. Maximizing the economical potential of biobased alternatives seems the most attractive strategy. The method to compare various routes has been highly simplified and the conclusions of this report are only valid within the limitations of the underlying assumptions. Nevertheless, the Working group WISE BIOMAS of the Platform Biobased Raw Materials feels that the conclusions are valuable for Dutch policy makers and others interested in the use of biobased raw materials.

In 2030, biobased alternatives are expected to be sufficiently competitive to fossil-based alternatives, even without subsidies. They are expected to play a significant role in an energy mix comprised of other renewables as well as 'clean' fossil energy sources. Presently, however, the Netherlands needs to step up its stimulation of biobased applications, through substantial investments in R&D programmes, demonstration plants, as well as measures to stimulate implementation. The whole package of tax reductions, local government purchases etc. as well as direct financial support should amount to approximately 500 M€ per year.

The simplified study presented here provides input for more realistic macro-economic scenario analysis taking actual and updated cost-availability relations including 2nd generation biofuels and biochemicals, land use, international trade etc into account. Initial discussions with for instance the Netherlands Bureau for Economic Policy Analysis (Centraal Plan Bureau or CPB) have taken place, but are not covered in this report. It is urgently suggested to update macro-economic scenarios for securing the best Netherlands' position among the accelerating global development towards biobased resources.

Background

The Platform Biobased Raw Materials (Platform Groene Grondstoffen - PGG) is an advisory committee to the Dutch government on biobased solutions for the energy, fuels and chemicals sectors. It has identified five transition paths, jointly leading to a 30% replacement of fossil fuels by biobased alternatives.

The Working group WISE BIOMAS (*Working Group for Innovative and Sustainable BIObased energy and MAterialS)* has elaborated the third transition path *"Co-production of chemicals, fuels, electricity and heat".* This transition path includes the following processes:

- fractionation of biomass (biorefinery)
- fermentation, enzymatic/chemical conversion of biomass into chemicals and/or biofuels and other types of energy (electricity, heat)
- thermochemical conversion (gasification, pyrolysis, co-combustion) of biomass for chemicals and/or biofuels and/or other types of energy (electricity, heat).

WISE BIOMAS unites experts on the biobased economy (biorefinery, fermentation and thermochemical conversion) from academia, research institutes and industry:

Prof.dr.ir. Luuk A.M. van der Wielen, Delft University of Technology (Chair)
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Targets for WISE BIOMAS

The targets for WISE BIOMAS have been:

- to consider what biobased pathways have most potential to fulfill our environmental obligations in an ecologically and economically attractive way;
- to recommend what should be done **today** to realise the foreseen environmental and economic benefits in the future.

WISE BIOMAS has detailed the ambition of PGG, which considers that biobased alternatives should replace 667 PJ of fossil fuels or 35% of the demand for electricity, transportation fuels and chemicals together in 2030. The demand for heat was covered by another working group. The overall platform ambition (including heat) is 30% replacement of fossil feedstocks.

Integral perspective
The PGG ambition only covers the domestic use of energy for electricity, heat, transportation fuels and chemicals/materials. However, the Dutch energy situation is much more complex. The total energy imports of the Netherlands are 2,5 times larger than domestic use due to the Netherlands' trade and transport position. These economic sectors are major contributors to the GDP and will be impacted by a transition to a biobased economy in the Netherlands, but also in adjacent countries.

Methodology
WISE BIOMAS has set out to compare various pathways for domestic application of biomass for energy and chemicals/materials. The Dutch energy situation and the potential role of biomass have been rigorously simplified to allow a quantitative comparison.

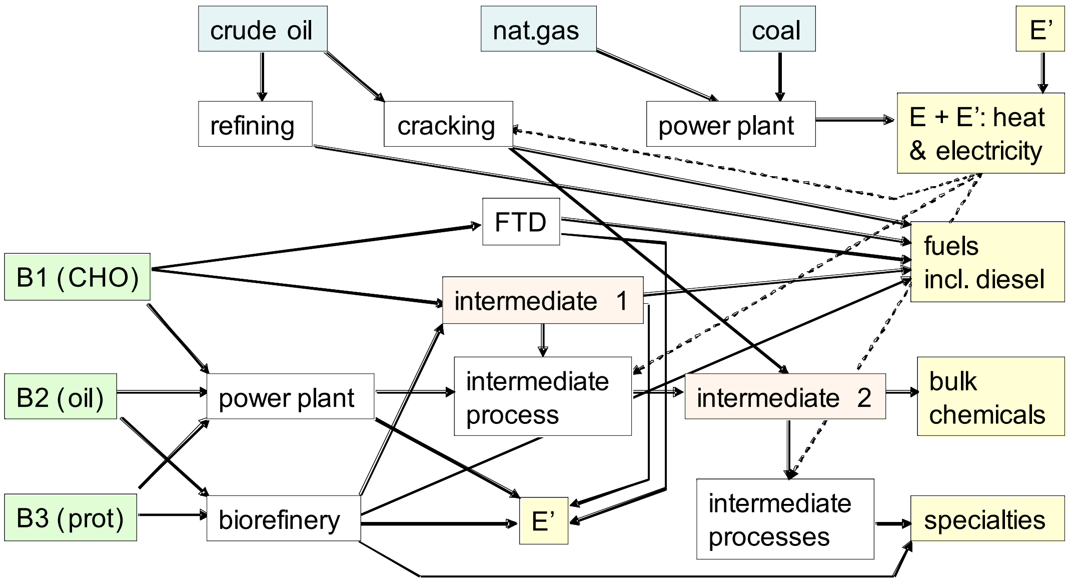

Figure S1. Schematic overview of the simplified Dutch energy situation, converting renewable and fossil feedstocks into desired product classes. B1 corresponds to carbohydrate-rich biomass, B2 to oil-rich biomass and B3 to protein-rich biomass. For reasons of overview, (co)produced electricity has been marked as *E*'.

The leftmost part of Figure S1 shows that three types of biomass have been considered as raw materials: B1, which is lignocellulosic or CHO-rich biomass; B2 which is oil-rich biomass, and B3, which is protein-rich biomass. The top of the figure shows the fossil fuels: oil, natural gas and coal. The rightmost part of the figure shows the products: Electricity, transportation fuels and bulk and specialty chemicals. The conversion routes include biorefinery, fermentation, and thermochemical routes for biomass, and conventional routes (refinery, cracking, power production) for fossil fuels. All has been brought to 2030 standard.

WISE BIOMAS has then quantitatively evaluated the the potential of the network of routes to fulfill several environmental and economic policy targets. After analysis of the results, the working group has come to a set of conclusions and recommendations for the transition path *"Co-production of chemicals, fuels, electricity and heat".*

Cases for 2030

Five optimization Cases have been developed which correspond to possible policy targets. The Cases were:

1. Minimum area for biomass production
2. Maximum margin for Dutch industry
3. Minimum investment for the conversion processes
4. Restricted area, minimum depletion (depletion as a measure of the rate of consumption of scarce fossil fuels. Oil has the highest depletion value, coal the lowest)
5. Restricted area, minimum CO_2 emissions

The results were:

- All cases show comparable environmental results, even when optimized for pure ecological targets (Case 5). There are no clear winning pathways with respect to ecology. This corresponds roughly with the constraint of 35% replacement of fossil fuels for electricity, transportation fuels and chemicals.
- Generally, replacement of fossil oil (for fine chemicals, base chemicals and transportation fuels, in this order) by biomass is economically more attractive than replacement of coal (for electricity), when potential CO_2-sequestration costs are not taken into account. The only exception –with clear negative economic impact- is Case 5 (minimum CO_2 emissions), where the optimum situation consists of replacing coal-fired power production capacity by biomass combustion.
- The differences between the environmental parameters (required area, CO_2 emissions, rate of depletion of fossil fuels and CO_2 emissions per hectare biomass) are relatively small between the various Cases.
- All Cases except Case 5 have a positive economic margin and therefore seem economically viable. The "maximum margin" case has a slightly higher margin than the base case, where no biomass is used. This implies that this route would add to the GDP of the Netherlands.
- The differences between most pathways in ecological impact are small, within the accuracy of the calculations and assumptions. WISE BIOMAS therefore considers it important to leave technical options open for the future. The real attractive pathways will compete on the basis of their economic benefits. Technology development will remain crucial.
- Nevertheless, it is possible to identify candidate pathways with good chances for success. These are mentioned below. Further technology development (when required) as well as demonstration at a technically relevant scale is urgent, since part of the technology development coincides with the larger scale of application.

Implementation

WISE BIOMAS considers that the quantitative results show that more use of biobased raw materials will add to the Dutch GDP by 2030. However, in this early stage, governmental support will be required.

The knowledge position of the Netherlands is very good, and implementing demonstration projects for the main co-production options is well possible. Investments in such demonstrations by industry-based consortia are crucial and urgent, to realise the benefits of the transition to biobased in the long run.

WISE BIOMAS suggests that the following demonstrations could be realised on a short term. The first three are the main co-production pathways, and the fourth recognises the importance of small-scale conversion plants, with additional advantages concerning the co-production of electricity and heat:

- Production of transportation fuels and other products from lignocellulosic and agricultural residual flows through fermentation or thermochemical conversion.
- Co-production of fuels and chemicals with power (and heat) in a large-scale coal/biomass fired IGCC (integrated gasification combined cycle)-concept.
- Improving utilisation of current agro-food (residual) streams through biorefinery and subsequent conversion processes.
- Small-scale biomass conversion into base products, with involvement of the agricultural, energy and chemical sectors. This should involve the development of a buffering network structure and other infrastructural measures.

Conclusions

- Biobased alternatives can potentially cover up to 30% of the Netherlands' domestic energy and chemicals demand, effectively reducing net CO_2 emissions, provided sufficient sustainable biomass or biomass derivates can be made available.
- Maximizing the economic potential of biobased production methods seems an attractive strategy. The environmental targets in reducing CO_2 emissions can be fulfilled by all "Cases" elaborated in this report.
- Biobased raw materials have a positive economic impact and will add to the GDP in 2030. To realise this, a joint effort by industry, research community and government is needed. Initially public R&D has to be carried out, co-financed by the government, to extend the existing knowledge position. Industry will participate financially in pilots and demonstration plants. In a Public Private Partnership there will be a swift transfer from public to private R&D.
- At this stage, a flexible strategy for the further development of biobased process routes for the production of chemicals is required. This should keep the major technical co-production options open. To capitalise on the strong knowledge position of the Netherlands, it is urgent to realise the following demonstration projects:
    - Production of transportation fuels and other products from lignocellulosis and agricultural residual flows through fermentation or thermochemical conversion.
    - Co-production of fuels and chemicals with power (and heat) in a large-scale coal/biomass fired IGCC (integrated gasification combined cycle)--concept.
    - Improving utilisation of current agro-food (residual) streams through biorefinery and subsequent conversion processes.
    - Small-scale biomass conversion into base products, with involvement of the agricultural, energy and chemical sectors.

  In a later stage, investment support will be necessary.
- The cross-sectoral value chains, including the agricultural, fuels, energy and chemical sectors, are a challenge and governmental stimulation to facilitate cross-sectoral collaboration is required.
- Increased action to realise 30% biobased in 2030 is urgent. Other countries are stepping up their activities, and the Netherlands' position as a distribution hub, with a strong agricultural and chemical sector, allows no further delay.

Recommendations

- Large scale imports by the Netherlands as well as international trade partners requires substantial attention for the position of the ports (Rotterdam, Amsterdam, Eemshaven, Gent). Major investments from the public and private sector are required for initiatives such as BioPort, a Rotterdam Harbour-based consortium preparing large scale experiments and implementation in import, trade, processing and communication. Alliances and networks with the industries and governments in adjacent countries should be investigated (German, Belgium, France, UK).
- Small scale conversion of biomass close to the production location is often important for efficient transport. Small-scale installations that are suitable for 3rd World rural communities are a priority.
- Dedicated crops and specialised biorefinery technologies offer an important potential, but a broader-based activity to involve the chemical industry in biorefinery is required. In this respect, it is important that in 2006 the Dutch Platform on Biorefinery has been initiated by WUR and ECN (www.biorefinery.nl). IEA Bioenergy Task 42 "Biorefinery" has established in international Platform, too. Both Platforms join representatives of all stakeholders and aim to speed up biorefinery technology deployment.
- Recycling of minerals (N, K, P, etc.) needs attention. Small-scale pre-conversion in Third World countries would be helpful in this respect as well.
- A continuous monitoring body from relevant stakeholders should advice and decide about the path to follow. All options are open now, but this situation may change. The monitoring body could be staffed from PGG, provided that it will have a serious voice in the decision making.
- Large-scale R&D investments should have continuity. Successful programmes should have successors before the specific programme finalises.
- The governmental investments in an integrated package should be of the order of M€ 500 per year in the first five years for all transition paths of the Platform Biobased Raw Materials. This includes:

- M€ 40 per year for R&D on the transition path *Co-production of chemicals, fuels, electricity and heat* , including pilot plants
- M€ 40 per year for demonstrations on the transition path *Co-production of chemicals, fuels, electricity and heat*
- An additional M€ 250 per year for implementation, such as through a venture capital fund, support of SMEs, local government purchases, tax reductions, and accompanying measures for all transition paths of the Platform Biobased Raw Materials.

A similar or larger budget is expected from industry: to be able to take over and implement the results of R&D on a commercial scale, and as investors in demonstrations and implementations of plants for *Co-production of chemicals, fuels, electricity and heat.*

1. Introduction

1.1 Platform Biobased Raw Materials

Increasing wealth and a rapidly expanding human population cause an increasing demand on energy and raw materials. Fossils reserves are steadily drained and environmental (e.g. "Katrina") and geo-political (e.g. Iraq) disturbances impact price and security of delivery substantially. Furthermore, emission of CO_2 from fossil resources has a substantial impact on climate change. Availability of sustainable, renewable resources for energy and chemistry are of tremendous societal urgency. Possible solutions may be originating from biobased, renewable resources, in Dutch "Groene Grondstoffen", which are essentially created from solar energy and CO_2. Using these results in lower (towards zero) CO_2 emissions and a reduced dependence on fossil resources, such as crude oil, natural gas and coal. Moreover, while solving the major technical challenges, also new biobased, economic opportunities are created, for the Dutch agro, energy and chemicals industry, as well as for the trade and transport sectors.

The Platform Biobased Raw Materials (in Dutch: Platform Groene Grondstoffen PGG) is an advisory committee to the Dutch government on biobased solutions for the energy and fuels sectors, with members from all relevant economic sectors. PGG operates as a platform within the Netherlands Energy Transition activities, under the Task Force Energy Transition. Under several constraints, a 30% replacement of fossil resources by biobased alternatives in the year 2030 seems feasible for the Netherlands. An important constraint is a zero growth scenario in energy consumption relative to the level of 3000 PJ of the year 2000. To realise these goals, a combined package of measures to increase energy efficiency and reduce consumption, as well as to enable a large scale transfer towards biobased (and renewable) resources is necessary. This includes issues such as biomass and its derivatives, as well as improved use of available agro-resources and residue streams. The following four main application areas for biobased resources are distinguished, and the respective estimates of fossil replacement are given in brackets:

- transportation fuels (60% or 324 PJ/a),
- chemicals and materials (25% or 140 PJ/a),
- electricity (25% or 203 PJ/a),
- and heat (17% or 65 PJ/a).

PGG has identified 5 "transition paths" (in Dutch: "transitiepaden") to achieve this situation for 2030:
(1) production of biomass in the Netherlands and abroad
(2) certification of imported biomass
(3) coproduction of chemicals, fuels, electricity and heat
(4) synthetic natural gas (SNG) in natural gas infrastructure
(5) innovative use of renewable resources.

Then, PGG has established working groups to elaborate the transition paths in more detail. WISEBIOMAS covers transition path no 3 "co-production of chemicals, fuels, electricity and heat".

1.2 What is co-production?

WISEBIOMAS considers as "co-production of chemicals, fuels, electricity and heat":

- fractionation of biomass (biorefinery)
- fermentation, enzymatic/chemical conversion of biomass into chemicals and/or biofuels and other types of energy (electricity, heat)
- thermochemical conversion (gasification, pyrolysis, co-combustion) of biomass for chemicals and/or biofuels and/or other types of energy (electricity, heat)

This transition path has an enormous technical potential. Some technologies can be applied today, others are still in their infancy. Integration is a central theme for co-production: A functional and high-quality use of both product and residual streams (material and energy) from a specific sector, within this sector or outside it.

1.3 Targets WISEBIOMAS

The PGG working group WISEBIOMAS has the target to identify and describe attractive techniques on the transition path "Co-production of chemicals, fuels, electricity and heat". Its vision is aimed at policy makers, who have to distinguish between "wise" and "unwise" co-production options.

The quantitative goal for 2030 of WISEBIOMAS follows from the goals of the Platform:

- transportation fuels (60% or 324 PJ/a),
- chemicals and materials (25% or 140 PJ/a),
- electricity (25% or 203 PJ/a),
- and heat (17% or 65 PJ/a).

All these goals fall within the scope of transition path "co-production of chemicals, fuels, electricity and heat". However, during the activities of the working group, it became apparent that the activities within working group 4 on "synthetic natural gas in the natural gas infrastructure" would cover the complete PGG's ambitions for heat. The target for WISEBIOMAS was therefore composed of PGG's targets for transportation fuels, chemicals and materials and electricity together. This adds to 667 PJ and corresponds to 35% of the total foreseen demand for transportation fuels, chemicals and electricity in 2030 of 1910 PJ.

Target Platform Renewable raw materials: 1000 PJ biobased in 2030

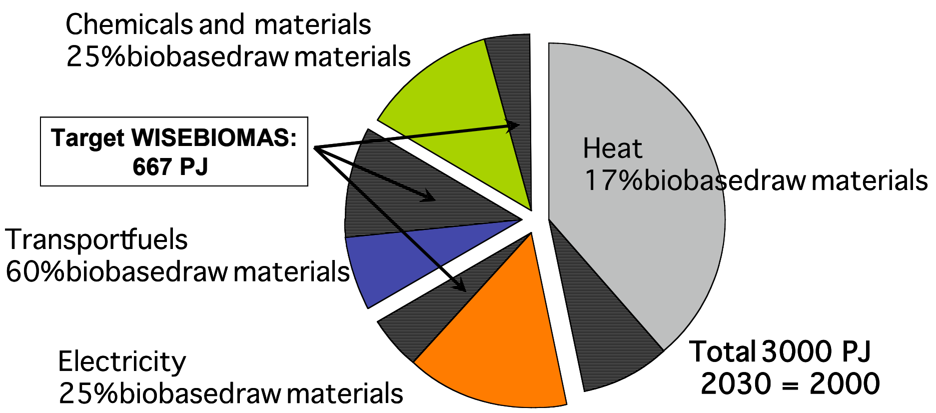

Figure 1 Targets WISE BIOMAS in relation to targets of PGG

WISEBIOMAS found that it was necessary to reconsider the rationale of the distribution of the (approximately) 667 PJ between chemicals, transportation fuels, and electricity. At the start of the working group, there were two main visions on the desired development of co-production activities. These can roughly be described by "focus on the energy sector, and transportation fuels and chemicals will follow suit" and "develop the chemistry, to take more advantage of the functionality of the biomass raw material". WISEBIOMAS has therefore quantitatively compared the expected ecologic and economic benefits of utilisation of biomass and fossil feedstocks for electricity, chemicals and transportation fuels in 2030.

Many excellent studies are available on the potential of biomass to contribute in regional and global energy solutions (Hoogwijk, 2004; Faaij cs), as well as on the potential of specific biobased products (e.g. BREW) to reduce net CO_2 emission and other ecological or economic key numbers. These studies do not or only in part answer important questions such as:

- Assuming a particular policy ambition in terms of sustainability targets, what would be the best combination(s) of fossil and renewable resources in terms of total sustainability impact ?
- Which combination(s) of fossil and renewable resources would give the best economic and innovation options, while optimizing sustainability targets under realistic sets of constraints ?
- What would be the best timing for particular scenarios?
- How much flexibility do these paths allow when certain initial policy choices have been made ? If these choices and flexibilities depend on the price levels of fossil to renewable resources, what mechanisms should be in place to damp undesired dynamics ?
- Would differentiating towards specific demands in terms of crops impact these policy choices, in particular choices in the agro-industries ?
- When import of raw biomass will be restricted and transfer to biobased economy will depend on import of derivative products such as ethanol, how would that challenge the (bio)fuels, energy and chemicals industries ?
- What actions should the government take?

The present report addresses these questions, on the basis of the quantitative data for various fossil/biobased scenarios.

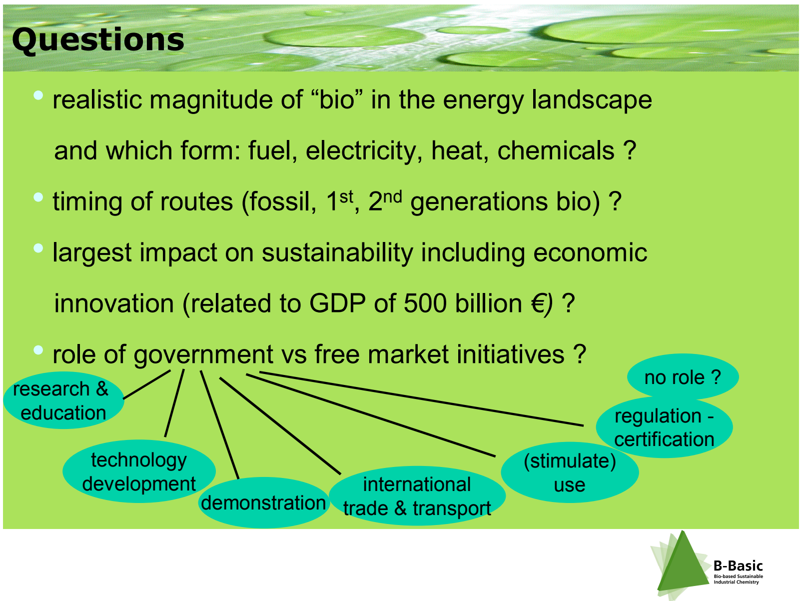

Figure 2 Targets for this report

1.4 Integral perspective

As a reference for the PGG-WISEBIOMAS activities serve the two scenario extremes of the Task Force Energy Transition: "*Global Economy*" and "*Strong Europe*". The *Global Economy* scenario (TF-ET, 2006) describes a continued strong economic growth (2.9% per year) during the period 2000-2050, and a substantial contribution of sustainable energy forms. The overall energy consumption is expected to grow with the economy, despite continued improvements in efficiency (1.3-1.5 % per year). This should be accompanied by increased reductions of CO2 emissions. The Task Force Energy Transition mentions 400 MT/a in 2050. In this scenario, biobased solutions are central and should accommodate approximate 750 PJ/a in 2030 and close to 2000 PJ/a in 2050. This compares closely to the ambition level of PGG, which is 30% biobased solutions for energy and chemistry or roughly 1000 PJ/a in 2030. The main difference between this Task Force Energy Transition scenario and PGG ambition is the perceived economic and energy use growth, which in the Task Force Energy Transition scenario is expected to be covered by other non-renewable (including nuclear) and renewable (wind, solar, geothermal) resources.

The second scenario, *Strong Europe*, emphasizes efficiency improvement, which combined with lower economic growth (and correspondingly lower growth of energy use), should also yield a sustainable future. In this scenario, biobased solutions are practically absent. Interestingly, in both scenarios the use of coal, which is still one of the cheaper (fossil) feedstocks, is kept constant. More details concerning these scenarios can be found in the Task Force Energy Transition's vision document (TF-ET, 2006).

It should be emphasized that Task Force Energy Transition scenarios and PGG ambition only cover the domestic use of energy for industry, households, transport, agro-industries, energy sector etc. All of these are major contributors to the Netherlands Gross Domestic Product (GDP) of approximately 500 billion euro in 2005. Energy security issues, as well as the specific form in which energy is used will impact this value creation factor substantially.

However, the situation in the Netherlands is much more complex. The total energy imports and exports of the Netherlands are substantially (resp 2.5 and 2 times) larger than domestic use due to the Netherlands trade and transport position. The complete Netherlands energy balance is shown as a Sankey diagram (ECN, 2005), reproduced in Figure 3 below. It should be realised that several associated industrial sectors (trade, transport, refineries, part of services, Haven Rotterdam, etc) strongly depend on the transit in terms of crude oil and gas, and their products. These economic sectors are also major contributors to the GDP. Not only the decisions with respect to the Netherlands' situation are crucial for the future of the Dutch energy economy, but also those in the European countries as well as the broader international context. In that sense, this report has to consider the opportunities and challenges of large scale changes in the European energy policies, including variation in the imports of energy carriers (increased biobased carriers relative to crude oil and gas) as well.

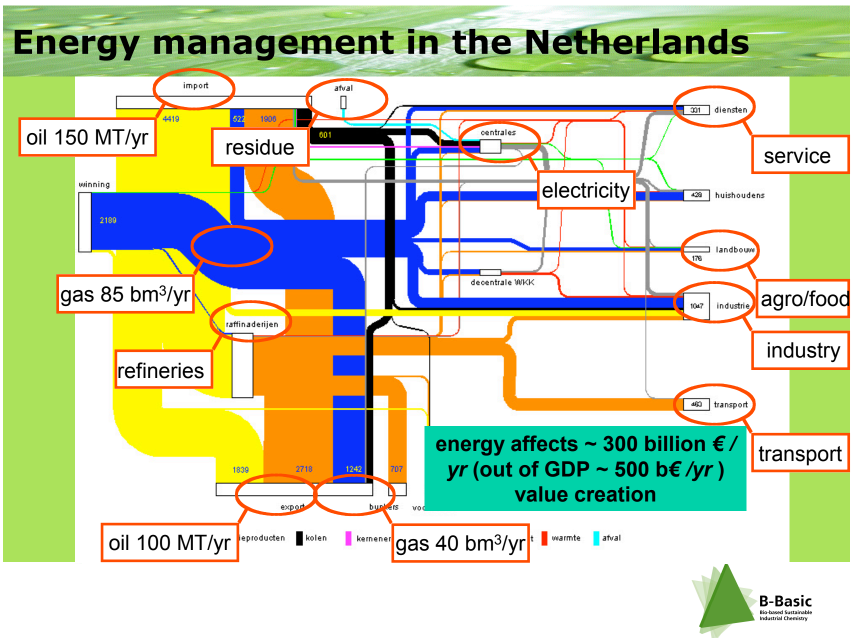

Figure 3 Energy carriers in, to and from the Netherlands according to ECN's Sankey diagram, all contributing the Netherlands' GDP.

Figure 4 shows essentially the same information as in the Sankey diagram above, but in a slightly different way. Diagrams such as figure 4 will be used to present the results of the optimisations that the WISEBIOMAS has done. They are characterised by the following features:

- Just like in Sankey diagrams, the width of the arrows corresponds to the size of the stream, unless explicitly stated otherwise
- Fossil fuel flows enter the system at the top (irrespective of their country of origin)
- Biomass flows enter the system from the left side, irrespective of country of origin

- Domestic use is indicated on the right-hand side of the diagrams
- Exports leave the systems at the bottom of the diagram.
- Colour code: yellow-oil; orange-oil products; blue-gas; black-coal; green-biomass

In the “Sankey-like” diagrams concerning the Dutch energy situation in 2000 some minor flows have been omitted to promote readability.

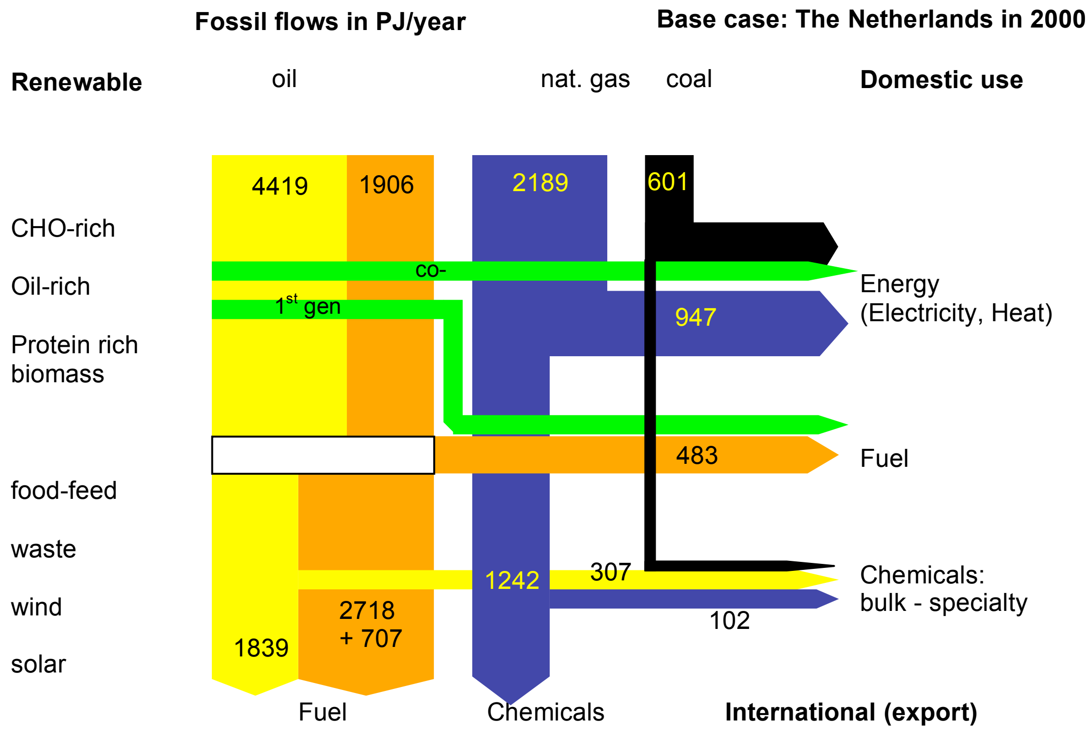

Figure 4 Base case: Domestic energy use and international energy trade position of the Netherlands in 2000 (Biomass flows not to scale, some minor streams omitted).
Legend: yellow-oil; orange-oil products; blue-gas; black-coal; green-biomass

In a comparable manner, the economic, and –to some extent- also the associated mass flows can be visualised as ‘Sankey-like’ flow diagrams. These representations are shown below for the Base case, and provide insight in the economic impact of fossil and biobased resources on economy and logistics. The energy flows are capitalised using the data in Appendix B to yield the economic flows. The mass flows are recalculated from the energy flows, assuming 100% energy yield on mass, using data from Appendix B. Note that the CO_2 streams are not accommodated in this diagram, for reasons of clarity. The electricity flows E indicate the scale of the electricity network. Obviously, it is also relevant to investigate the contributions to CO_2 emissions of the various processes in the network (in MT CO_2 /a).

- In terms of G€/year, the coal flow is marginal in comparison to oil and gas. Coal is significantly cheaper per GJ energy content.
- In terms of Mtons, the picture (figure 5b) is slightly different from figure 4 to reflect the higher energy content of oil compared to both other fossil energy carriers.
- Concerning CO_2 emissions, it should be noted that biomass has no net contribution of the atmospheric CO_2 concentration, and that the emissions of the fossil fuels increase in the order of gas < oil < coal.

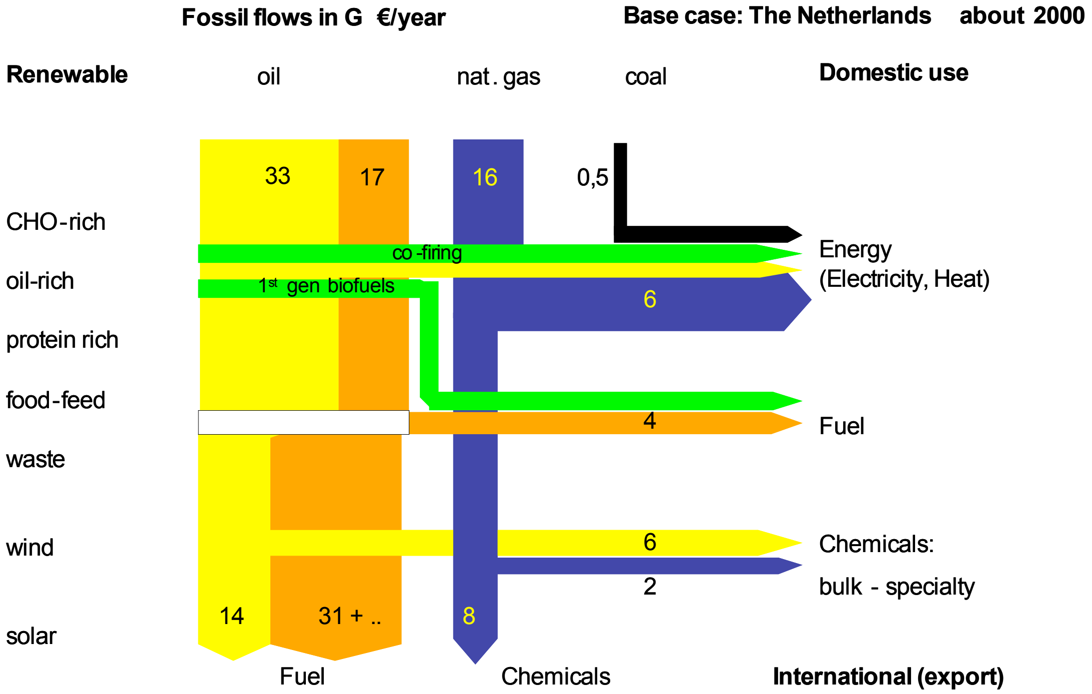

Figure 5a Base case: economic activity related to the domestic energy use and international energy trade position of the Netherlands in 2000 (economic data as used in the calculations). (Biomass flows not to scale, colours as in Figure 4)

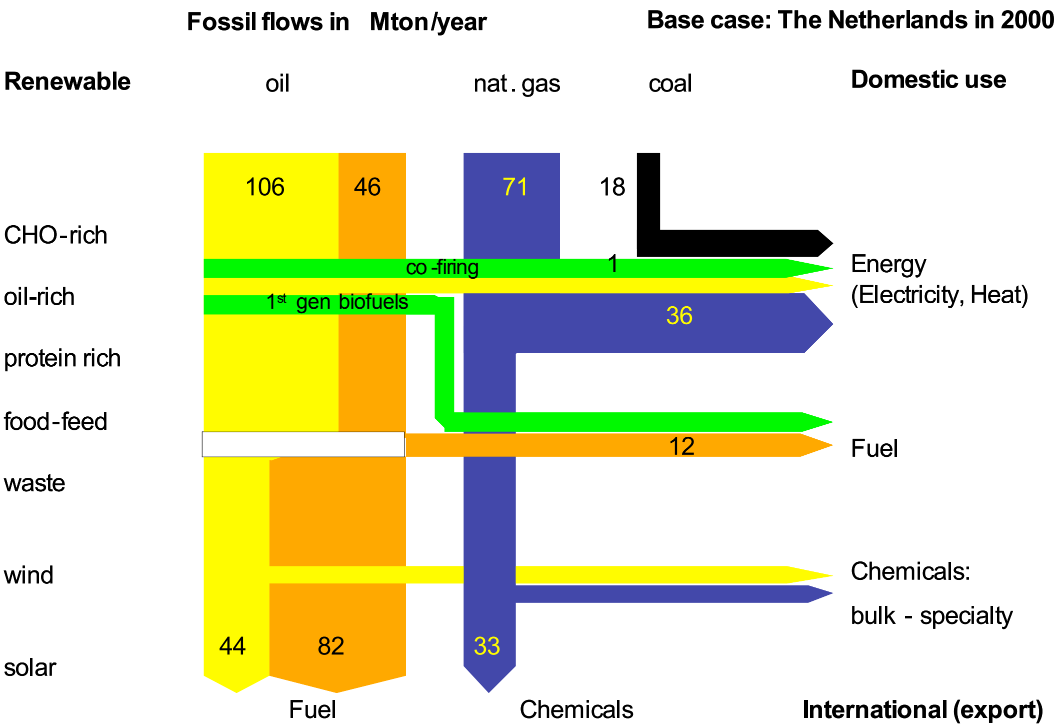

Figure 5b Base case: mass flows related to the domestic energy use and international energy trade position of the Netherlands in 2000. (Biomass flows not to scale, colours as in Figure 4)

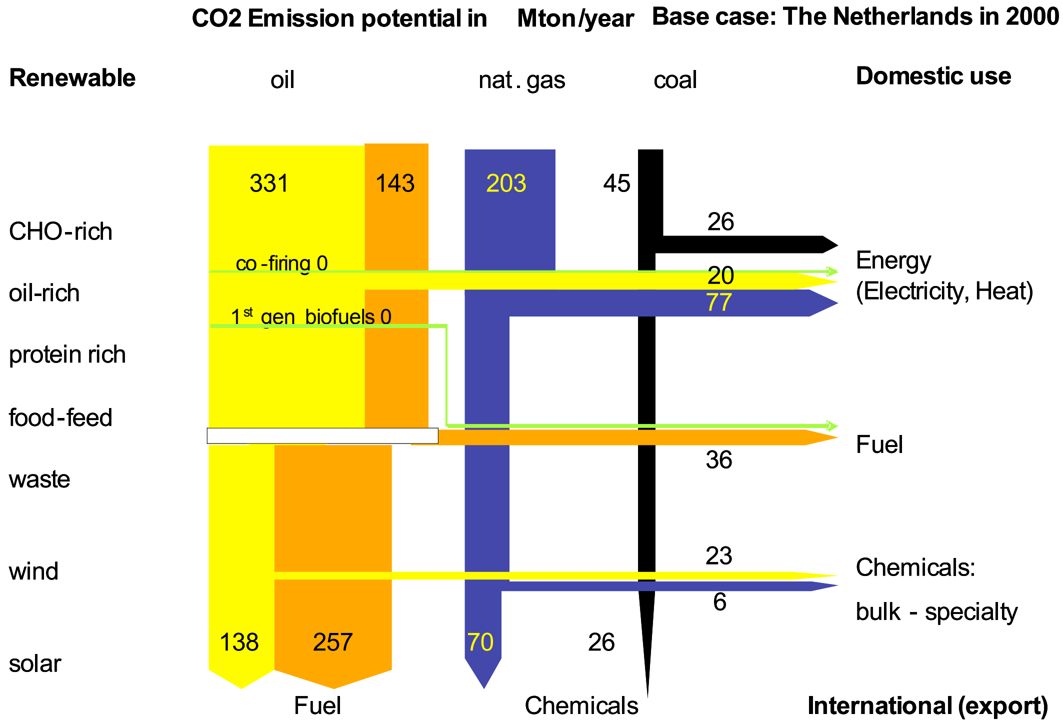

Figure 5c Base case: CO_2 emissions related to the domestic energy use and international energy trade position of the Netherlands in 2000 (Colours as in Figure 4)

1.5 Methodology

Within the theme "co-production of chemicals, transport fuels and energy" a wide range of conversion and fractionation (biorefinery) options may be considered. These include bio- and thermochemical conversions towards fuels and chemicals, with the combined production of other energy forms (electricity and heat). Not all underlying technologies are mature, and particularly their integration is not yet well established. This is clearly a field which is seeing and will see major technological development, and has substantial economic opportunities. A simplified and schematic version of the network of potential conversions towards desired products is shown below.

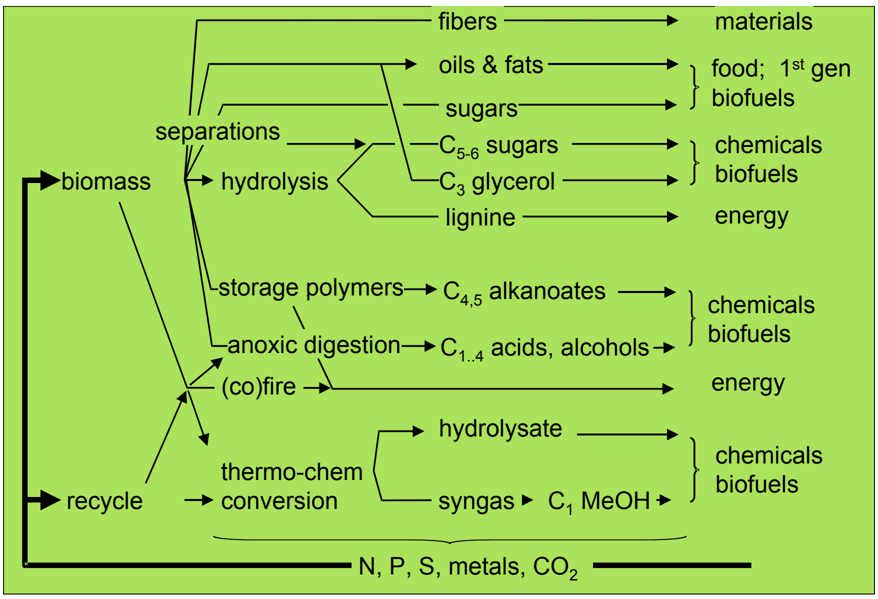

Figure 6 Schematical and simplified overview of fractionation and conversion of biomass in desired industrial and consumer products.

A precise picture of the demand and potential supply routes of all chemicals, transport fuels (and electricity) in 2030 and a subsequent optimisation would be beyond the possibilities of WISEBIOMAS. Therefore, the group has first rigorously simplified the Dutch energy situation and the potential fossil and biobased processes to satisfy the Dutch demand on chemicals and materials, fuels and electricity. Then, the potential routes to satisfy the demand in 2030 have been optimised towards various economic and ecologic criteria with a "linear programming" methodology. Details on the simplification of the Dutch energy situation will be presented in Chapter 2.1 and 2.2. An explanation of linear programming, working from a simple example, is available in Appendix A. After that, conclusions on the most attractive pathways can be drawn. Their implications are discussed in Chapter 4, discussion.

The underlying computations have been implemented by TNO Quality of Life. Full details of the modelling and the assumptions can be found in (Meesters, 2006).

2. Optimal solutions for the "Simplified Dutch Society"

This chapter presents the basic outline of the model that has been used to quantify ecological and economic benefits of various biomass utilisation options. Section 2.1 describes how the Dutch Society has been simplified to six energy inputs, four outputs and a number of conversion processes. Section 2.2 presents the model substances which have been used to specify economic and ecologic parameters for the conversion processes. Section 2.3 introduces the optimization criteria and some important assumptions.

2.1 Resources, products, and conversion processes

Resources

The number of actual available fossil and renewable resources in the real-life Netherlands economy is large, and has a variety of quality, ecologic and economic parameters. WISEBIOMAS has restricted the number of resources to six, three fossil sources and three biomass sources. Non-biobased but also renewable feedstocks such as wind, geothermal and solar energy, as well as nuclear and fusion energy technologies were not taken into account:

- Oil
- Natural Gas
- Coal
- Lignocellulose-rich biomass, which is CHO or carbohydrate-rich biomass, indicated as B1
- Oil-rich biomass, indicated as B2
- Protein-rich biomass with a high N content, indicated as B3

Products

The number of actual available (chemical) products in the real-life Dutch economy is probably even larger than the number of resources, and has a large variety of quality and production volume. WISEBIOMAS has restricted the number of products to four:

- Electricity
- Transportation fuels
- Bulk chemicals
- Specialty chemicals (particularly N-containing products such as antibiotics, caprolactam, amino acids)

The required production volume of these products in 2030 has been taken as the PGG vision, see section 1.3. The ratio between the demand for bulk chemicals and specialty chemicals has been estimated at 80:20.

Conversion processes

Biobased feedstocks can be combusted to produce electricity, (bio)refined and fermented to produce fuels, bulk and specialty chemicals or gasified and synthesized via Fischer Tropsch processes to diesel components. Fossil feedstocks can be refined (oil), directly converted to chemicals and fuels (gas, oil) or combusted in power plants to produce electricity and heat. Obviously, for all cases a wide variety of process options is available, which in reality strongly depend on the exact products manufactured and exact feedstock used.

Figure 7 presents the network of processes that have been analysed by WISEBIOMAS. At the top, the fossil resources crude oil, natural gas and coal are introduced. From the side, three biomass resources are introduced: B1 (lignocellulose/CHO-rich), B2 (oil-rich) and B3 (protein-rich). The figure shows two “intermediates” substances to be processed further to produce a range of chemicals of transportation fuels. Through fermentation of lignocellulose (CHO)-rich biomass, ethanol (EtOH, in the figure) or butanol may be produced, which may be processed further. An example of the second intermediate – a basis for bulk chemicals – is ethene.

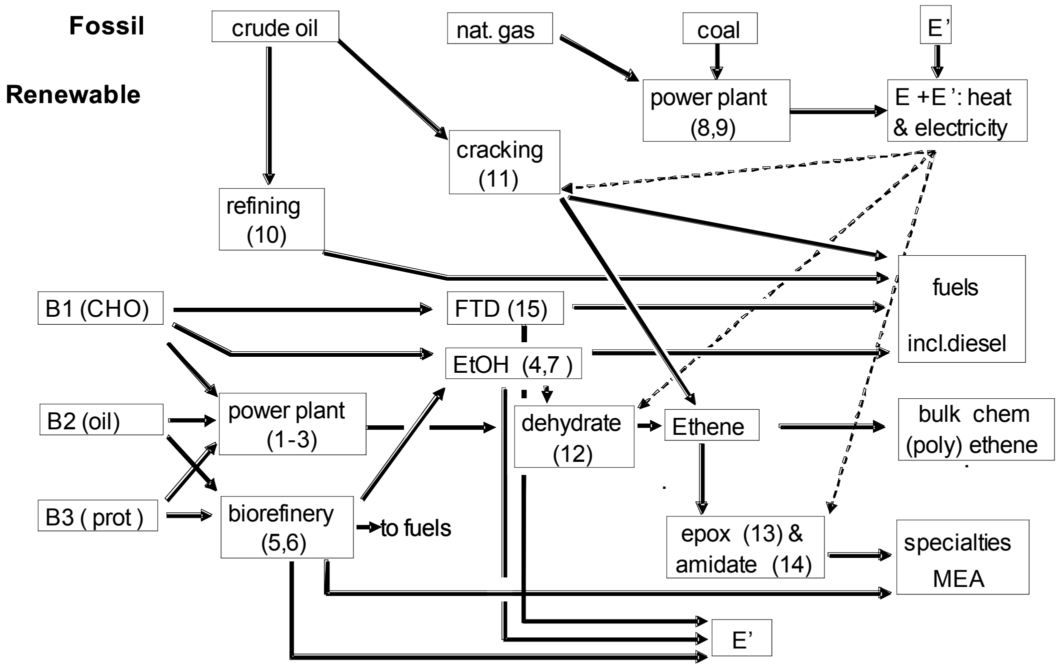

Figure 7. Schematic overview of the lumped processes, converting the renewable and fossil feedstocks into desired product classes.

For reasons of overview in the above figure, several energy flows coproduced in the biomass processing are grouped as ***E'***. *E'* is obviously integral part of the total electricity flow *E*.

An overview of the conversion processes is also given in Table 1.

Table 1 **Selected conventional and biobased processes**

Nr	Process	From	To
1	Combustion	Lignocell. rich biomass	Electricity
2	Combustion	Oil-rich biomass	Electricity
3	Combustion	Protein-rich biomass	Electricity
4	Pretreatment and fermentation	Lignocell. rich biomass	Fuels, Electricity
5	Biorefinery	Oil-rich biomass	Specialties, Fuels, Electricity
6	Biorefinery	Protein-rich biomass	Specialties, Fuels, Electricity
7	Fuel	Intermediate fermentation product	Fuel
8	Combustion	Coal	Electricity
9	Combustion	Natural gas	Electricity
10	Refinery	Oil	Fuel
11	Cracking	Oil	Bulk chem., Fuel
12	Dehydration	Intermediate fermentation product	(Intermediate for) bulk chemicals
13	Epoxidation	(Intermediate for) bulk chemicals	Intermediate for specialties
14	Amination	Intermediate for specialties	Specialties
15	Fischer Tropsch synthesis	Lignocell. rich biomass	Fuel (FT diesel)

The processes 1-7, 12 and 15 are the direct or indirect (7,12) biobased routes, and are at several stages of (early) development. Pathways 8-11 are based on fossil resources, and are currently in use in the petrochemical and energy industry. Pathways 13 and 14 are based on (bio)chemical conversion of intermediate pools which could be bio- or fossil based, depending on which pathways turn out to be the main ones.

Both the biorefinery and the “Pretreatment and fermentation” routes are examples of co-production processes. In the biorefinery process, the plant is fractionated in (feedstock for) specialty and base chemicals, (feedstock for) biofuels. Process heat is converted into electricity. The pretreatment and fermentation process results in an intermediate fermentation product and electricity.

2.2 Model substances

The composition of the feedstocks, the yields, even the required conversion processes are hard to determine if the resources and the converstion processes are not represented by model substances and model processes.

Resources
The model substances for the feedstocks are presented in Table 2. For biomass with a predominant lignocellulosic content, wood would have been another possibility. Palm oil would have been another example of oil-rich crop and soy of a protein-rich crop.

Table 2 **Resources for conventional and biobased processes**

Description	Example
Oil	
Coal	old Australian Drayton coal
Natural gas	
CHO rich biomass	switch grass
Oil rich biomass	rape seed
Protein rich biomass	Grass

Intermediates and conversion processes
WISEBIOMAS has decided to use simulation data (yields, stoichiometry etc) on the basis of products and intermediates from the “C2-family”, (molecules with two carbon atoms). Other choices could have been the C1 family (with methanol) or the C4 family (with butanol). The selected C2 family consists of:

- ethanol (model substance for fuels),
- ethene (model substance for bulk chemicals)
- ethene oxide (intermediate for the production of mono ethanol amine) and
- MEA (mono ethanol amine, model substance for specialties).

As a consequence of selecting the C2 family, most yield or efficiency parameters are readily available, such as for ethanol fermentations from sugars. Those which were not readily available have been estimated on the basis of views of experts, such as the dehydration of ethanol to ethene. We have assumed mature technologies for both biobased and conventional processes.

Table 3 shows an overview of products and intermediates.

Table 3 **Products and intermediates**

Description	Model substance
Electricity	
Transportation fuel	Biodiesel, Bioethanol, FT diesel, Gasoline
Intermediate fermentation product	Ethanol
(Intermediate for) bulk chemicals	Ethene
Intermediate for specialties	Ethene oxide
Specialties	MEA (mono ethanol amine)

Example of conversion process
As an example, the simplified flow diagram as well as mass and energy balances of process route 4 (pre-treatment of lignocellulosic biomass and subsequent fermentation-separation of ethanol and coproduction of energy) are given in Figure 8. In our model, the mass and energy balances are simplified to calculate conversion effiencies of lignocellulose-rich biomass to ethanol and to electricity. In Appendix B, also the other conversion processes are illustrated in terms of mass and energy balances.

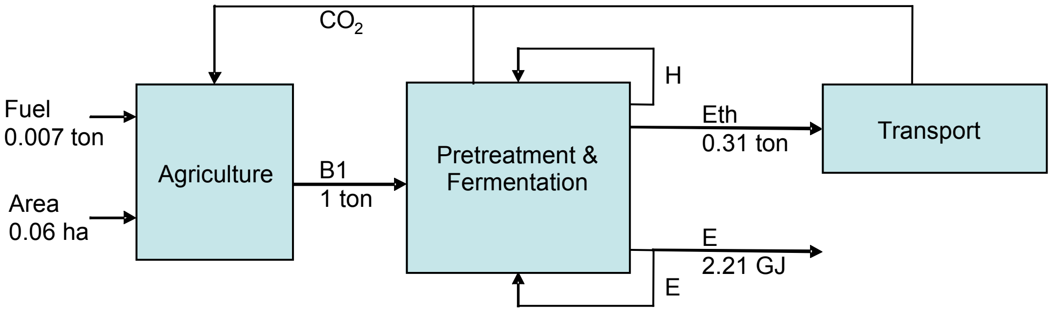

Figure 8 Flow diagram, mass and energy balances and yield parameters of process route 4 *Pretreatment and conversion of biomass B1 to ethanol and electricity*.

In Appendix B, also a simplified cost model is presented to estimate the value of the various (energy and mass) flows, the required capital and the added value ('margin') for the Netherlands economy.

As mentioned before, all process yield and economic parameters have been listed in (Meesters, 2006).

2.3 Optimisation criteria and constraints

In order to answer the earlier questions, and to be able to compare possible answers (transition paths), several (sustainability) criteria and constraints have to be optimized or satisfied. These criteria and constraints were generated and agreed upon in the WISEBIOMAS meetings.

PGG ambition of 35% biobased for electricity, fuels and chemicals
The most obvious **constraint** is that 667 PJ per year of fossil fuels will have to be replaced by biobased energy and materials for chemicals, transportation fuels and electricity, see section 1.3. Furthermore, it is assumed that sufficient sustainable biomass or biomass derivatives can be made available and advanced agricultural technology (including energy efficient nitrogen and minerals recycling) is in place.

Decrease dependence on (foreign) fossil reserves
A criterion to judge the desirability of a specific combination of options could be to judge whether it helps the Netherlands to become less dependent on international fossil fuel reserves. To measure the dependence of imports of (foreign) fossil reserves, the measure "depletion" has been adopted. "Depletion rate" is the rate of consuming a specific fossil feedstock, relative to the reservoir of that feedstock. In this study, "depletion" is the sum of the depletion rates of all fossil feedstocks. Large numbers for depletion indicate a rapid consumption of fossil feedstocks.

Minimise (relative) CO_2 emissions
The Taskforce Energy Transition aims at a reduction of fossil emissions of 50% in 2050 (to 80 MT CO_2 /a) relative to the 1990 production level of 160 MT CO_2/a. Autonomous growth without active measures has lead to 170 MT CO_2/a in 2000, and is expected to lead to 230 MT CO_2/a in 2050. Task Force Energy Transition expects this transition path to contribute approximately 25 MT CO_2/a for biofuels and 10 MT CO_2/a for chemicals and 15 MT CO_2/a for electricity generation.

WISEBIOMAS uses two sustainability indicators of CO_2 emission: the absolute value of MT CO_2/a for a specific set of input and products and a relative value, where the required area for the growth of biomass is taken into account [ton CO_2 reduction/(ha*a)]. Both absolute and relative numbers will be generated .

Economic criteria
Energy use and CO_2 emissions are required for our welfare (and well being), as well as for generating economic benefits. Measures to reduce energy use and CO_2 emissions should be seen as investments as well as economic costs to achieve these, and should be evaluated in this economic sense. The economic contribution to the Gross Domestic Product (GDP) of the industrial sectors

related to the coproduction of fuels, chemicals and energy is substantial. Therefore also the economic impact in terms of costs, benefits and investments, of the processes should be taken into account. Here also, the absolute numbers (in G€/a) are relevant, as well as the number relative to the original biomass production capacity (in hectares) necessary for a particular process to achieve this, so in units of [G€/(ha*a)]. Both are generated.

Qualitative criteria
The different paths have also different additional aspects associated that are more difficult to characterize quantitatively such as risk, robustness, time to develop the technology (maturity), impact on employment, innovation options, relative position in terms of top knowledge infrastructure, etcetera. While more difficult to address, we will still do so. Public perception and willingness to adopt particular solutions are also important factors. Despite the generally positive attitude towards sustainability issues concerning ecology and energy, the general public is often first consumer and then citizen. We will discuss some of the qualitative criteria in the sidelines.

Willingness to implement in industry depends also on flexibility in terms of available or forseseen volume of available resources and the possibility to shift or select between feedstocks. This is important for the biobased routes due to the heterogeneity of many agro-residues and the unclarity about the (market) price development of the feedstocks.

These criteria are summarized in Figure 9 below.

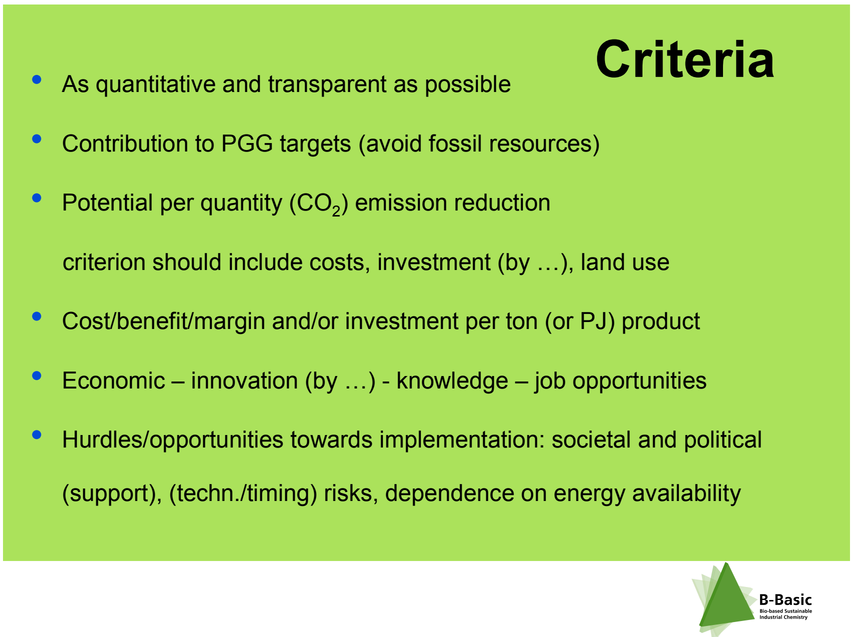

Figure 9 Summary of quantitative and qualitative criteria for comparison of process and feedstock options.

Calculated cases
The following optimisation criteria been used to calculate five "Cases":

1. Minimum area for biomass production
2. Maximum (economic) margin
3. Minimum investment
4. Restricted area (equal to minimum area), minimum depletion
5. Restricted area (equal to minimum area), minimum CO_2 emissions

In the base case, all products are made from fossil fuels. The volumes compare to the situation presented by *Rabou et al.* (2006). In Case 1 (Minimum area), the land use is minimised – while setting the integral 667 PJ biobased resources criterion- to investigate the minimum footprint of such a situation. In Case 2 (maximum margin), the optimal combination is investigated where margin (see

Appendix B for definition) is optimized as a measure for optimizing the total associated added value. Case 3 targets the minimum investment, assuming a green fields situation, for transfer to a 35% biobased economy.
In Cases 4 and 5, the area is restricted to 2.55 Mha. For reference: this area is approximately equal to the size of the arable soils in the Netherlands. Depletion (Case 4) and CO_2 emissions (Case 5) have been respectively minimized under that restriction.

Important assumptions
A complete presentation of the utilised process cost and efficiencies, raw material cost, conversion rates etc. is presented in Meesters (2006). Some important assumptions are presented here:

- All biomass is assumed to cost €100/ton. This implies that oil-rich biomass, which has a higher energy density, is the cheapest biomass in terms of energy. In reality, the many different types of biomass all have their specific prices. The assumed price is rather higher than the current price levels of €25-50 /ton to avoid a too rosy picture.
- Two price levels for oil have been assumed: USD 50/barrel and USD 70/barrel.
- Production of electricity from natural gas is not allowed in 2030 because of the limited resources.
- Production of chemicals and fuels from coal has not been considered.
- CO_2 capture and storage have not been considered.
- In order to compare mature fossil-based technologies to mature bio-based technologies, efficiencies of biobased routes have been assumed at 90% of the theoretical maximum.
- Nitrogen fixation in fertilizer (for biomass growth) or in specialty chemicals has not been taken into account, even though it is an energy intensive process. The validation is, that in both cases the same process (Haber-Bosch) is used.
- All facilities are green field or grass roots situations.
- The model fixes the production volume of specialty chemicals at equal or more than 20% of the total chemical production in the Netherlands.
- The model also fixes the target for biobased at equal or more than replacing 35% of fossil fuels for electricity, transportation fuels and chemicals.

3. Results

As mentioned in Chapter 2 the following five “Cases” have been calculated.

1. Minimum area for biomass production
2. Maximum (economic) margin
3. Minimum investment
4. Restricted area (equal to minimum area), minimum depletion
5. Restricted area (equal to minimum area), minimum CO_2 emissions

In this Chapter, we will first analyse the flows in these specific cases to understand the model and generate a basis for understanding the subsequent choices. Then, we will compare the cases at an oil price of 50 USD/barrel, and discuss the sensitivity to oil to biomass price ratio.

3.1 Five “Cases” at an oil price of USD 50/barrel

Case 1: Minimum area for biomass production
When our criterion is that we want to achieve PGG targets with minimum area for biomass production, the model suggest that we should use Lignocellulose-rich biomass through Fisher-Tropsch for fuel and through fermentation to provide chemicals. The required area for attaining PGGs targets is than 2,55 Mha, which is about 75% of the total area of the Netherlands.

Figure 10 illustrates the flows in this case. The convention is here, that fossil fuels enter the system from above, biomass enters from the left-hand side; domestic use is indicated at the right-hand side and exports are indicated at the bottom. Oil is yellow, gas is blue, coal is black and biomass is green.

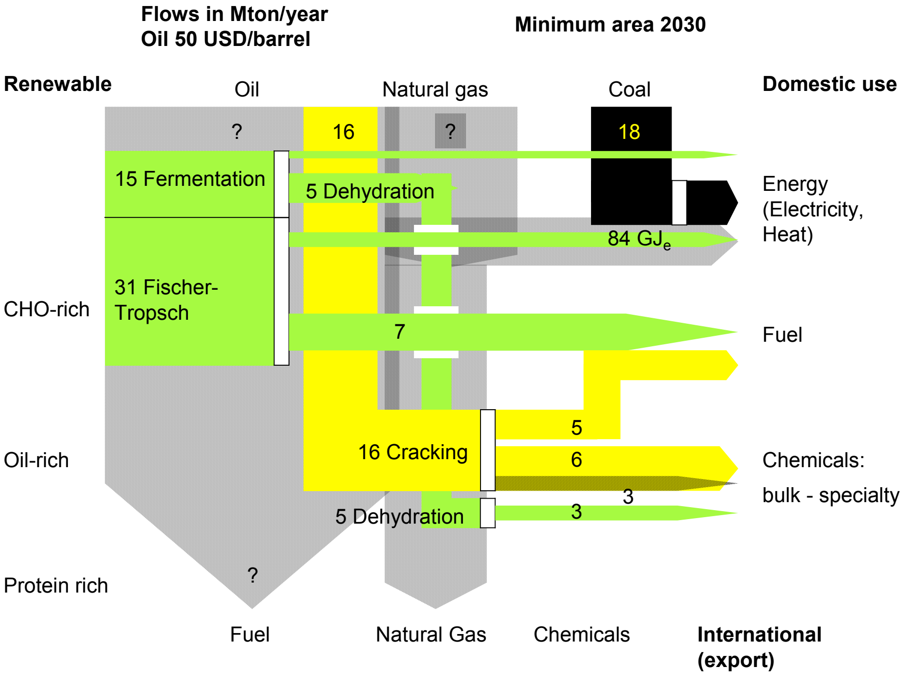

Figure 10: Case 1 - Minimum area for biomass production (Flows in Mton/a)

The figure shows that biomass, oil and coal are used to meet the domestic demand for electricity, fuels and chemicals. Coal is only used for electricity. A large flow of biomass is converted through the Fischer Tropsch process into transportation fuel. A smaller flow is used for the production of bulk chemicals. The choice for the lignocellulose crop stems from the circumstance that the yield of the model substance per hectare is higher than for the other biomass model substances.

The shaded arrows of oil and natural gas at the background of the graph show that there may still be a transit of oil and natural gas through our country, and that natural gas may also be used for the production of heat. These streams were not optimised in the model and their magnitude is therefore marked with “?”.

<u>Case 2: Maximum economic margin</u>

Optimisation according to an economic criterion of maximum margin shows a quite different picture, see Figure 11.

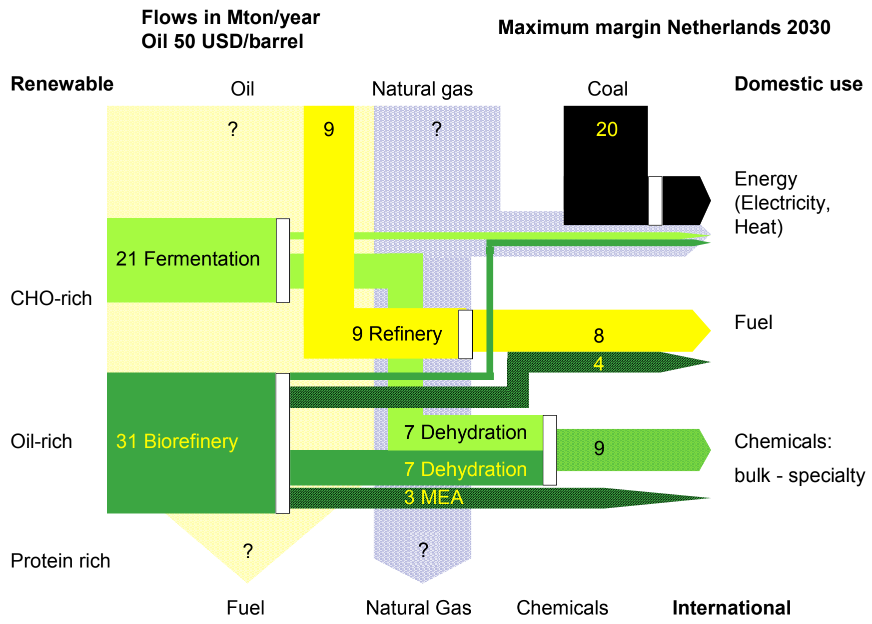

Figure 11: Calculated mass flows for Case 2 - Maximum margin

In this case, lignocellulose-rich biomass and oil-rich biomass are converted to bulk and specialty chemicals, while (cheap) coal contributes to the electricity supply. Specialties come from 100% biorefinery. Furthermore, fermentation of CHO-rich biomass supplies additional base material for the production of chemicals. Electricity has 17% biobased share, fuel has 35% biobased share and chemicals have a 100% biobased share in this Case.

Case 3: Minimum investment

Optimisation toward minimum investment suggests fermentation of CHO-rich biomass, see Figure 12.

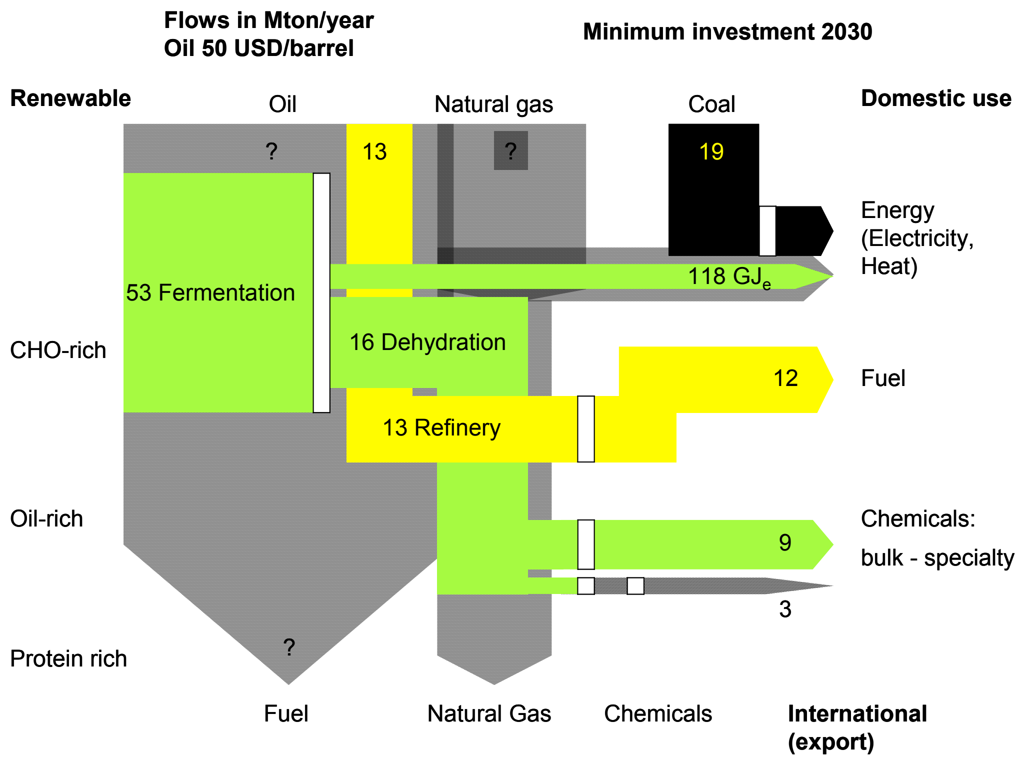

Figure 12 Calculated mass flows for Case 3 – Minimum investment

In this Case, minimum investment (based on grass roots situations) was the optimisation criterion. In this case, CHO-rich biomass is fermented. At the assumed capital charges, it is cheaper to invest in chemicals production capacity than in fuel production capacity, so the Ethanol from fermentation is converted to chemicals instead of fuels. Fuels come 100% from oil. Though this case shows a strength of CHO-rich biomass, it is quite hypothetical, since the real base case is evidently not “grass roots”.

Case 4: Minimum depletion

Figure 13 shows the preferred routes for Case 4 (minimum depletion, fixed area).

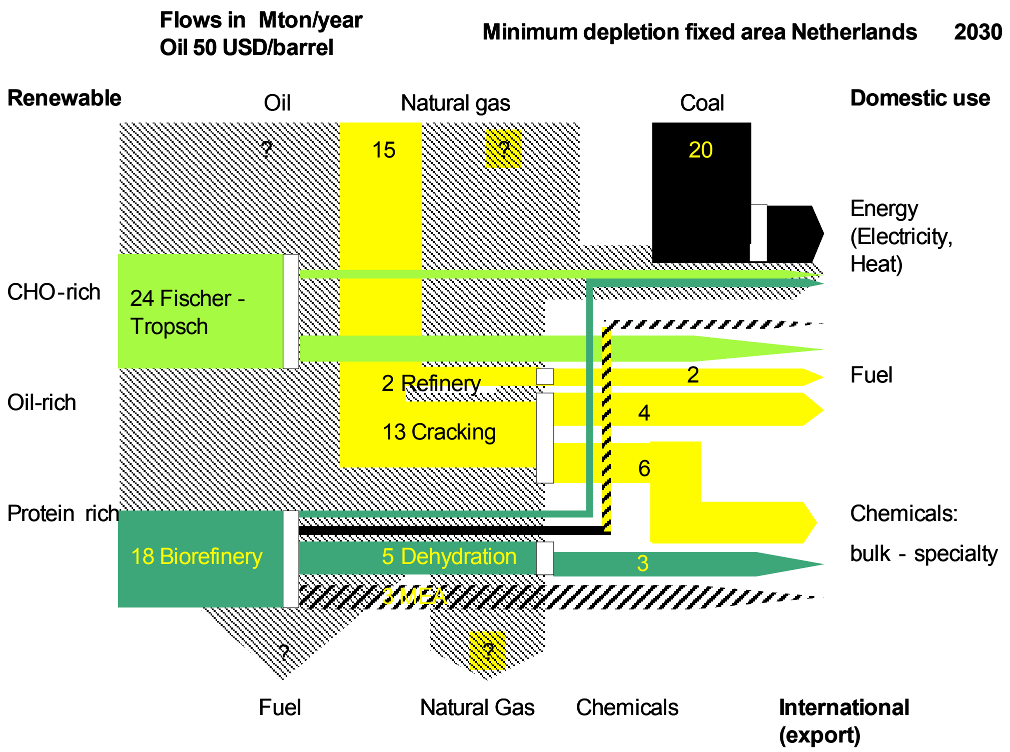

Figure 13 Calculated mass flows for the preferred processes for minimum depletion on restricted area as optimisation criterion (Case 4).

It is clear that in this case, the use of oil is unattractive, since the oil reserves are smaller than those of gas and coal. Biorefinery of protein rich biomass is more attractive than of oil-rich biomass because the products substitute more oil per hectare. In this case, PGG’s target is met by replacing 100% of the fine chemical demand by biobased products, 33% of fossil (oil) -based bulk chemicals by biobased products, and 50% of fossil (oil) -based fuels by biobased fuels. 16 percent of electricity is produced from biobased sources.

When the area restriction to the minimum area necessary for PGG’s targets is released, biorefinery of 31 Mton/year oil-rich biomass can replace even more fossil oil, obviously at the expense of additional (international) production area and large imports.

Case 5 Minimum CO_2 emissions

Figure 14 shows the mass flows when CO_2 emissions are minimised. This is again a different picture. The optimisation is driven by fact that CO_2 emissions from coal combustion are larger than CO_2 emissions from oil combustion, and therefore, coal-fired power production capacity is replaced by lignocellulose-rich biomass in this Case.

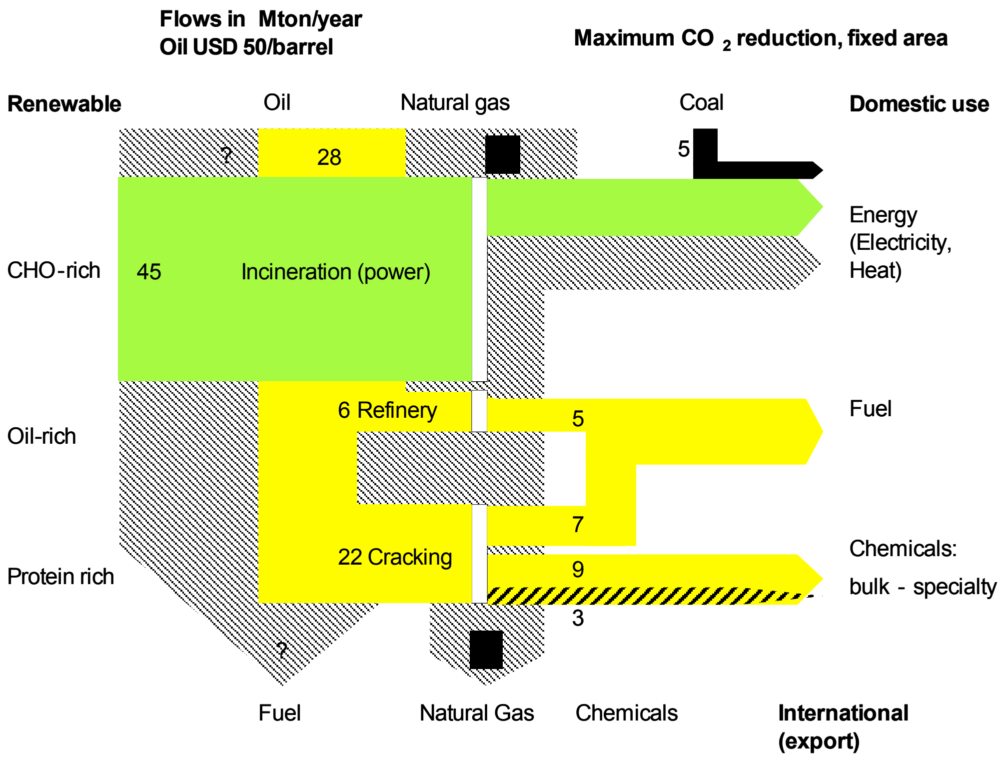

Figure 14 Mass flows for the preferred processes for maximum CO_2 emission reduction and a fixed area as optimisation criterion (Case 5).

The model does not regard CO_2 capture and storage at coal power plants, although this may well concern the majority of the electricity generation capacity in 2030. The impact of CO_2 capture and storage in coal-powered power plants are higher operational cost, lower conversion efficiencies and obviously lower CO_2 emissions. When only part of the power plants is equipped with CO_2 capture techniques, the remainder could be made CO_2 free through utilisation of biomass. When 100% of the power plants has CO_2 capture in place, the model cannot reduce CO_2 emissions from electric power generation and will have to replace fossil oil instead (for fuels or chemicals).

3.2 Comparison of the five "Cases"

Comparing all computational results, the main features of the preferred production chains of the 5 Cases and the Base case are summarized in Table 4.

Table 4 Main features of the preferred production chains for various optimisation criteria.

Criterion	Preferred production chains
1 Minimum area (use for biomass production)	Hydrocarbon-rich biomass B1 through Fisher-Tropsch for fuel and through fermentation to provide chemicals
2 Maximum margin	Oil-rich biomass B2 for fine chemicals, hydrocarbon-rich biomass B1 for base chemicals
3 Minimum investment	Hydrocarbon-rich B1 biomass through fermentation for production of chemicals
4 Restricted area, minimum depletion	Protein-rich biomass B3 for biorefinery and hydrocarbon-rich biomass B1 for Fischer Tropsch
5 Restricted area, minimum CO_2 emissions	All biomass to power plants (to replace coal).

To put these cases in a perspective, Figure 15 shows estimated values of relevant overall environmental criteria in the various optimisation cases:

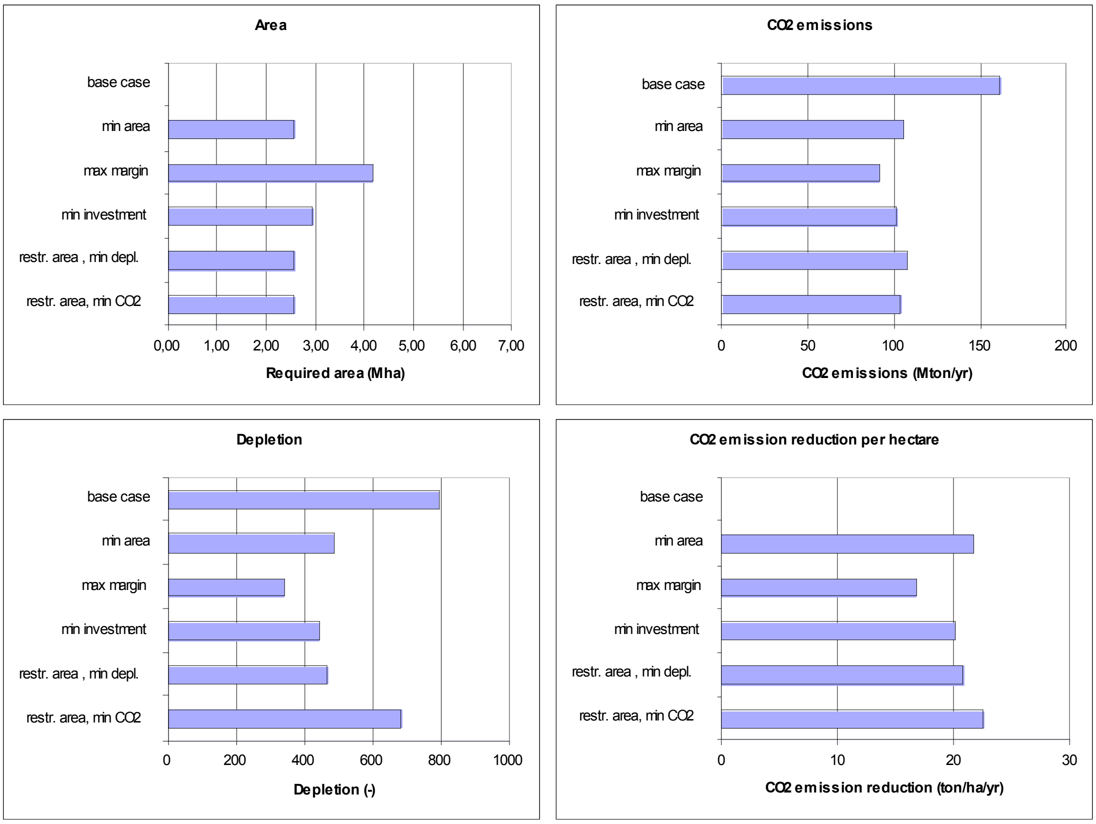

Figure 15 Comparison of the environmental achievements for the base case and the various optimisation cases.

The figure shows that the required area and the depletion are varying considerably if different biobased and fossil resources are used in a different way. Overall CO_2 emissions shows less variation in these scenarios. The CO_2 emissions reduction per hectare varies by 30% between the cases "5 restricted area, minimum CO_2 emissions" and "2 maximum margin".

Figure 16 shows the economic variables for the different optimisation cases:

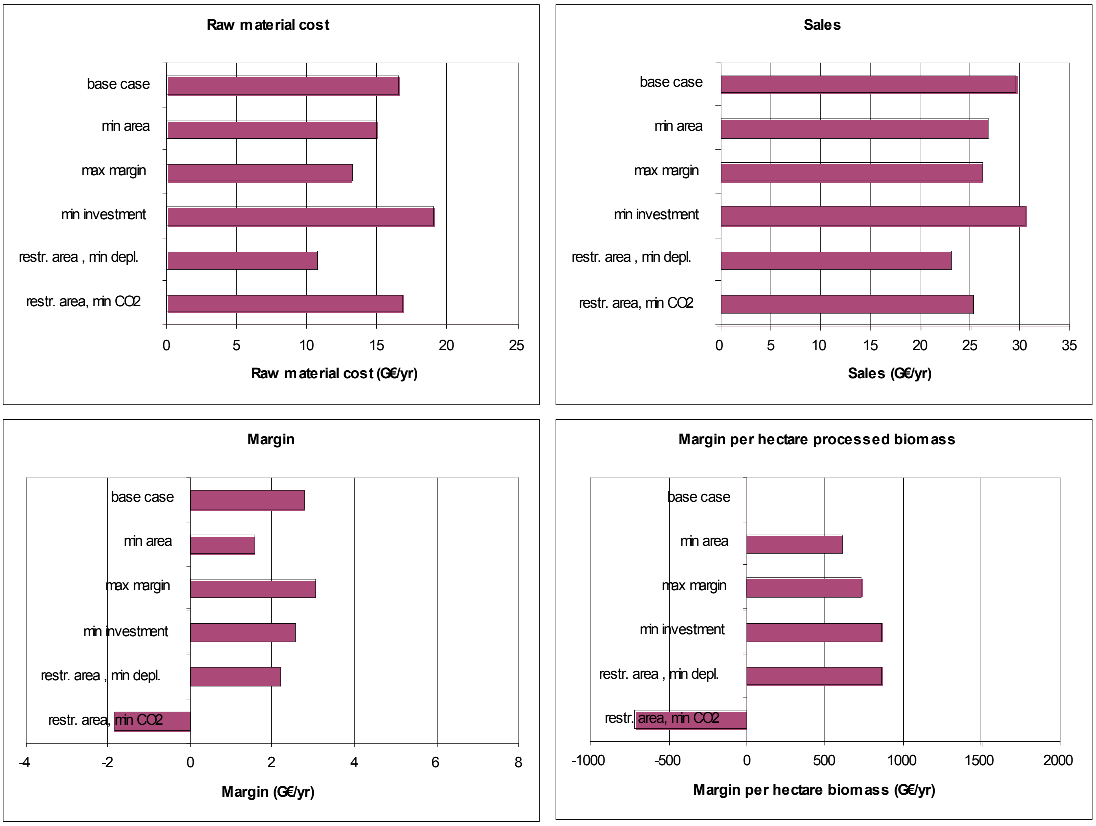

Figure 16: Comparison of the economic achievements of the base case and the various optimisation cases (GDP Netherlands 2003: 480 G€)

The most prominent detail of Figure 16 is that the margin for the Case 5 "Restricted area, minimum CO_2 reduction" is negative. In this case, biomass is combusted in power plants. It should be noted that the economic data were based on a biomass price of € 100/ton, which is significantly more than prices used today for co-combustion of scrap wood or roadside grass (€ 20/ton). This explains the difference with other studies, where co-combustion of biomass in (existing!) power plants emerges as a cost-effective measure to curb CO_2 emissions. It should be noted that co-firing in existing power plants is roughly limited to 25%, and a substantially larger contribution requires dedicated installations and significant input streams.

Furthermore, (not shown in the figure) raw material costs vary considerably depending on the selected optimisation case. Optimisation for minimum investment cost has to be balanced by high raw material cost. It is also striking that the maximum margin per hectare of processed biomass is realised for the minimum investment and minimum depletion scenarios (Cases 3 and 4).

Replacement of expensive fossil oil by biomass (Cases 1-4) has more advantages than replacement of coal.

- Replacement of fossil oil and coal by biomass both contribute sufficiently to CO_2 emission reduction by about 50 Mtons/a, in correspondence with the Task Force Energy Transition targets (see section 2.3).
- Replacement of fossil oil (for chemicals or for transportation fuels) has significant positive economic benefits compared to replacement of coal. Furthermore, replacement of fossil oil will render the Netherlands less dependent on oil supplies and contribute to energy supply security.
- The production of chemicals from biomass is expected to become even more advantageous (once the technology is in place) than the (advanced) production of fuels from biomass.
- The "maximum margin" case (Case 2) shows high CO_2 emissions reductions, a low depletion and the best economic features. The land use is however a factor of 1,6 higher than for the restricted area cases. Therefore, large scale imports are essential to cover the domestic energy demand (in addition to the Netherlands trade position via Rotterdam Harbour). This

Case relates strongly to that of an internationally very active Netherlands and stimulating the development of a Rotterdam BioPort.

- Therefore, an increased impact of the biobased economy fits well in the "*Global Growth*" Scenario of the Task Force Energy Transition (or CPB-Shell). Action is **urgently** required to make sure that the Netherlands reaps these fruits.

3.3 Sensitivity to oil price

The calculations above have been performed with an oil price of USD 50/barrel. The working group choose this conservative scenario to avoid a too rosy picture of the benefits of biomass use. To explore the impact of a higher oil price, the calculations were also performed with an oil price of USD 70/barrel, about the price in the summer of 2006.

<u>Case 2 Minimum margin at an oil price of USD 70/barrel</u>
Figure 17 below shows the flows at an oil price of USD 70/barrel.

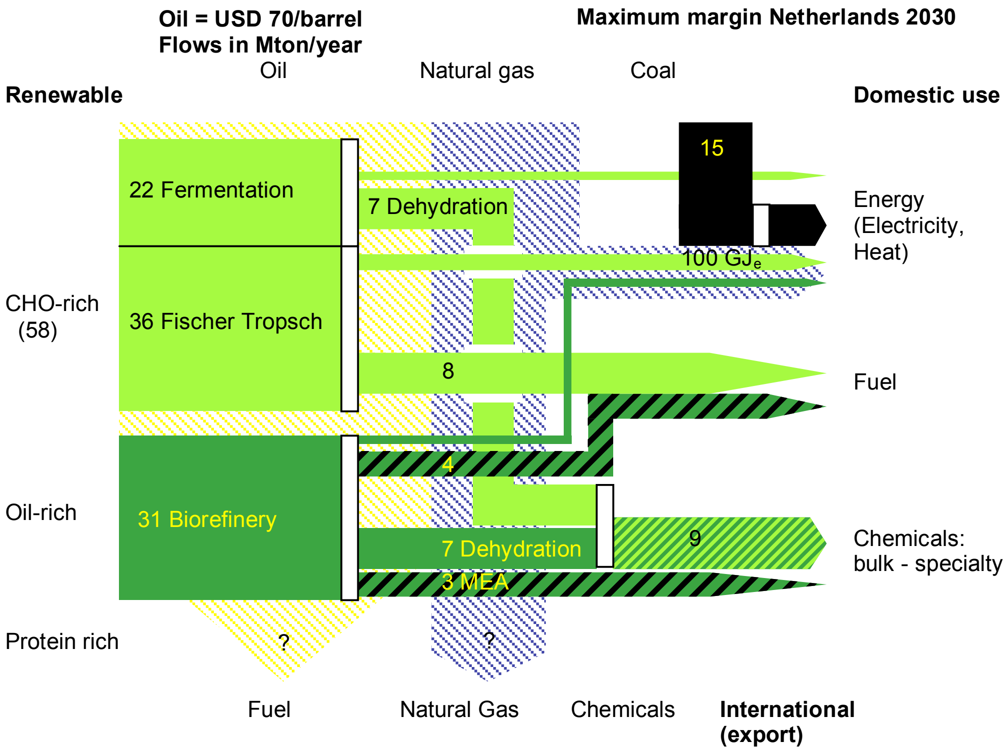

Figure 17 At an oil price of 70 USD/barrel, a maximum margin scenario proposes the production of chemicals and fuels from 100% biomass

In this Case 2 at an oil price of USD 70/barrel, all fossil-oil based products should be replaced by biobased products. In this way, the use of biomass grows above the targets of the PGG. Coal is used to generate the remaining electricity demand.

The results of the other cases are presented in Table 5. It is obvious that in the case of a restricted area, the preferred production chains are identical to the preferred production chains at an oil price of USD 50/barrel.

Table 5 Main features of the preferred production chains for various optimisation criteria at an oil price of USD 70/barrel

Criterion	Preferred production chains
1 Minimum area	As with USD 50/barrel
2 Maximum margin	Fuels and chemicals come from renewable resources, instead of from oil
3 Minimum investment	Hydrocarbon-rich biomass through fermentation for production of chemicals, and through Fischer-Tropsch for fuels
4 Restricted area, minimum depletion	As with USD 50/barrel
5 Restricted area, minimum CO_2 emissions	As with USD 50/barrel

Figure 18 shows the depletion, CO_2 emissions per hectare biomass, the margin, and the margin per hectare processed biomass.

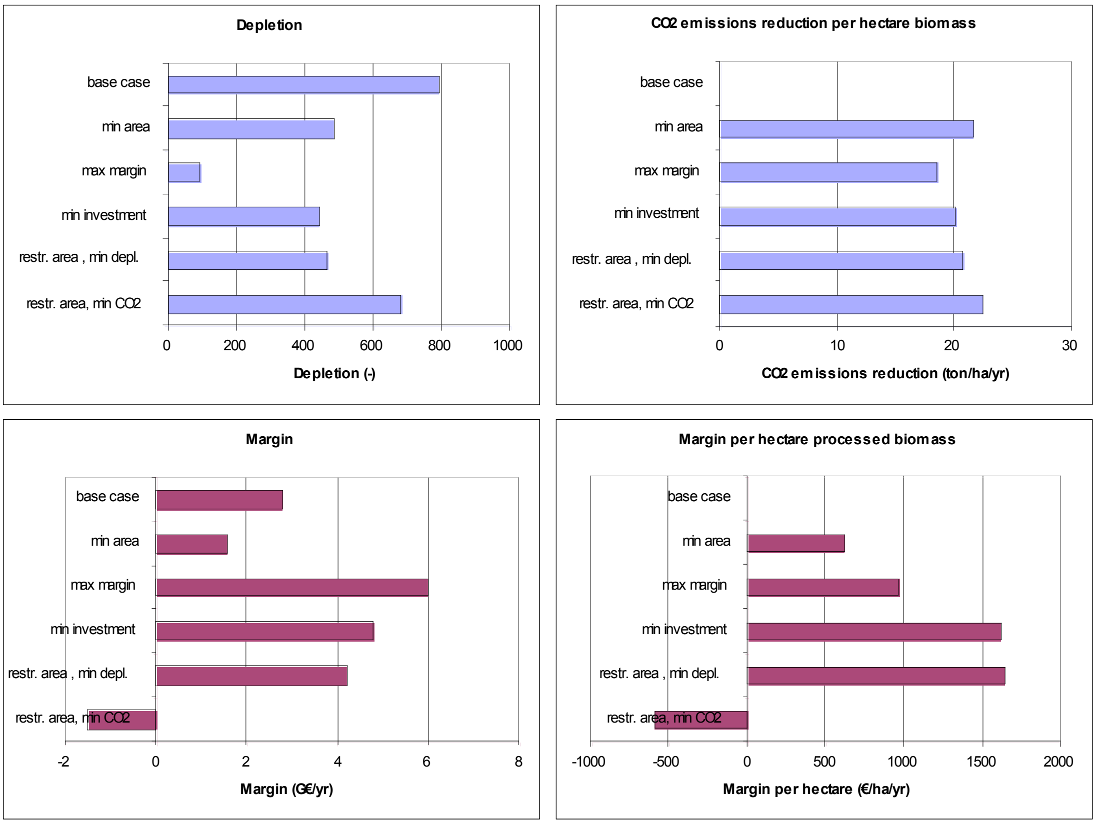

Figure 18 Comparison of environmental and economical features for optimisations with an oil price of 70 USD/barrel.

The graphs present clearly that production of substances with a high added value from biomass becomes highly attractive at high oil prices. Again, this supports a strategy to focus on replacement of fossil oil with biomass. The following comments are relevant:

- The production of specialty chemicals is economically interesting, but the model currently limits the volume because there must be a market for the by-products as well. How this will work out in a real-life situation can probably not be foreseen in this stage.
- The model assumes a (high) biomass price which is insensitive to oil price increases – which is roughly true for the production price, but may be far from true for the market price in 2030.

3.4 Sensitivity to biomass pricing

As pointed out above, the model assumes a uniform biomass price of €100/ton. The current price is closer to €50/ton. But the price for biomass shows an increasing trend, so the choice for €100/ton can be considered conservative. Relevant for the economic choice between biomass and fossil fuels is obviously the ratio between both prices.
Depending on this ratio, our calculations have shown that the first process to become competitive is chemicals manufacturing through fermentation (industrial biotechnology) and biorefineries, the second is the thermochemical production of Fischer Tropsch Diesel from relatively dry biomass flows, the third is fermentation of relatively wet biomass for biofuels production.

The calculations indicate that only production of bulk and specialty chemicals from oil- or protein-rich biomass will be profitable at an oil price of 50 USD/barrel. Production of Fischer Tropsch diesel from lignocellulose-rich biomass will be profitable from an oil price exceeding USD 70/barrel, while the production of ethanol as a transportation fuel from lignocellulose-rich biomass will be profitable from 80 USD/barrel. Figure 19 illustrates this. Above an oil price of USD 50/barrel, and at a biomass price of USD 100/ton, the figure shows a light blue area where production of chemicals from fermentation and biorefinery becomes economically attractive. Above an oil price of 70 USD/barrel, the lilac area shows that the production of (large scale) Fisher Tropsch diesel would become economically attractive as well. Evidently, the production of chemicals from fermentation and biorefinery is still ecomically attractive in these circumstances, too. The lilac area practically coincides with the cherry red area where biofuels from fermentation are economically attractive, along with both other applications. Note that the simulations are based on data for the the large scale implementation of Fisher-Tropsch technology.

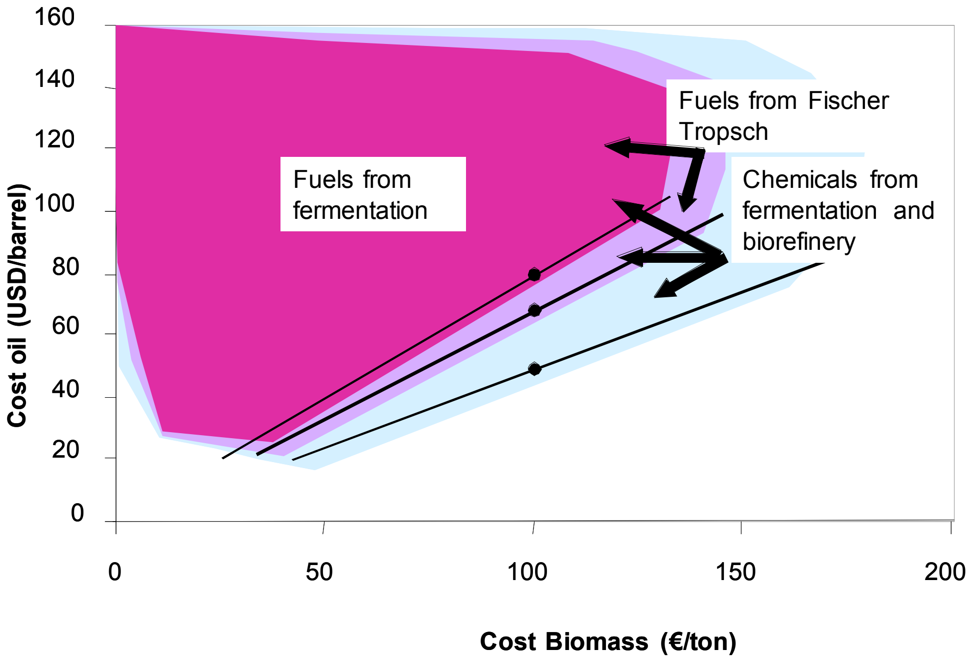

Figure 19 Coloured areas indicate feasible/attractive process routes for various crude oil and biomass price ratios.

It should also be pointed out that it is not realistic that all biomass will be available at the same price per ton. Each separate source of biomass will have its own sales price and its own characteristics. Other criteria will prevail to select among biomass types –such as the versatility and flexibility of use. That directs towards lignocellulosic feedstocks (B1) and appropriate measures to deal with Nitrogen reuse for agriculture and for Nitrogen-based functionalities in chemicals. It should be noted that this last point of view is not supported by all WISEBIOMAS members – some indicate at the potential benefits of direct harvesting relevant chemicals from biorefining protein-rich biomass.

4. Discussion

In this chapter, several results of considerations among WISE BIOMAS or by subgroups of WISE BIOMAS are brought together:

- Section 4.1 is in fact the most important of this Chapter, and describes the results of a WISE BIOMAS meeting where a discussion of the results and required action were on the agenda.
- Section 4.2 discusses some important limitations of the method and the results presented in Chapter 2 and 3, to put the results in perspective.
- Section 4.3 discusses the link with other PGG working groups.
- Section 4.4. presents considerations concerning the timing.
- Section 4.5 presents the results of a discussion with CPB, the Netherlands Bureau for Economic Policy Analysis, which led to the planning of a CPB study for 2007.

4.1 How to act on the results

WISE BIOMAS summarises the results as follows:

- All optimization cases show comparable environmental results, even when optimzed for pure ecological targets (Case 5). There are no clear “winner pathways” with respect to ecology. A constraint which has been met by all cases is 35% replacement of fossil fuels for electricity, tranportation fuels and chemicals.
- Generally, replacement of fossil oil (for fine chemicals, base chemicals and transportation fuels, in this order) by biomass is more attractive than replacement of coal (for electricity) where potential CO_2 sequestration costs have not been taken into account. The only exception –with clear negative economic impact- is Case 5 (minimum CO_2 emissions), where the optimum situation consists of replacing coal-fired power production capacity by biomass combustion.
- The differences between the environmental parameters (required area, CO_2 emissions, rate of depletion of fossil fuels and CO_2 emissions per hectare biomass) are relatively small between the various Cases.
- All Cases except Case 5 have a positive margin and are therefore economically viable. The “maximum margin” case has a higher margin than the base case, where no biomass is used. This implies that this route would add to the GDP of the Netherlands.
- The differences between most pathways in ecological impact are small and the assumptions have been rigorous. WISE BIOMAS therefore considers it important to leave technical options open for the future and compare various “real-life” pathways on the basis of their economic benefits. Technology development will remain crucial.

WISE BIOMAS considers that the quantitative results show that more use of biobased raw materials will add to the Dutch GDP by 2030. However, in this early stage, governmental support will be required.

Though the knowledge position of the Netherlands is very good, we presently lack demonstration projects for the main co-production options. Investments in such demonstrations are crucial and urgent, to realise the benefits of the transition to biobased in the long run.

WISE BIOMAS suggests that the following demonstrations should be realised on a short term. The first three are the main co-production pathways, and the fourth recognises the importance of small-scale conversion plants, with addional advantages concerning the co-production of (electricity and) heat:

- Production of transportation fuels and other products from lignocellulosis and agricultural residual flows through fermentation or thermochemical conversion.
- Co-production of fuels and chemicals with power (and heat) in a large-scale coal/biomass fired IGCC-concept.
- Improving utilisation of current agro-food (residual) streams through biorefinery and subsequent conversion processes.
- Small-scale biomass conversion into base products, with involvement of the agricultural, energy and chemical sectors.

4.2 Limitations of the method

- The results presented in this study can only be used in a comparative way – to compare various Cases amongst themselves. Readers should furthermore be aware that the Cases are built on some rigorous assumptions as to the efficiencies of the biobased processes in 2030 and as to the prices of oil-based and bio-based materials. The most important assumptions were given in section 2.3 and a complete overview of all used assumptions and data is presented in (Meesters, 2006).

- CO_2 capture and storage at coal fired power plants is not taken into account, although it might well be a reality in 2030. If we had considered CO_2 capture and storage, replacement of coal-fired power generation capacity with CO_2 capture by biomass without CO_2 capture might have become less attractive. On the other hand, CO_2 capture could also be installed in biomass-based power plants, which would imply an increase of operational and investment cost for both technologies, and an increase of CO_2 reductions by biomass.

- From the analysis, it can be concluded that the co-production of chemicals, fuels and electricity from various biomass crops by will lead to a large added value. However, at the same time one should realise that actual *biorefinery* processes and the feedstock for the production of (specialty) chemicals must be quite specific. Therefore, a no-regret strategy would be to replace oil in any case, and focus on robust lignocellulosic routes first, and probably at the same time develop more specific routes for specific specialty chemicals.

- The missing international perspective has been hinted at, in the background of Figures 10-14 and 17 with shaded arrows of oil (products) and gas imported and exported. Even when the Netherlands reduces its domestic use of oil in 2030, there is an independent transit of oil through our country, which relates to the demand for oil in adjacent countries. This is also true for natural gas. Additionally, there might be a larger volume of biomass or derivative products imported for conversion to fuels and chemicals for the international market. Due to its key position in logistics (Rotterdam harbour) the Netherlands, should take measures to remain so – for instance through the development of ***BioPort***, focused at a strong biobased industry around Rotterdam Harbour.

  In neighbouring countries, especially in Germany, there is a significant interest in bio-based products. Timely adoption of biobased chemistry and fuels industry would help to obtain market shares in biobased products. A threat to the biobased economy in the Netherlands (and Western Europe as a whole) is that our crowded countries do not have the arable land necessary for large-scale growth of energy crops. The total area (arable and non-arable) in the Netherlands is 3,4 Mha and –according to our model- the minimum area to attain PGG goals is 2,55 Mha. We may consider that there is approximately 2,3 Mha arable land in the Netherlands, which is mostly in use for the production of food, feed or flowers. Evidently, residual streams form these crops are one source of the required biomass.

- As mentioned before, heat has not been regarded in the model: waste (process) heat from biorefinery and fermentation was converted into electricity. But what would be the differences between the application of biomass for heat and the application of biomass for electricity? Biomass for space heating will probably replace natural gas, while biomass for process heating will generally replace oil or natural gas. Both are economically more attractive than replacing coal. Also, the conversion of residual streams into heat can be done with a higher efficiency than the conversion into electricity. On the other hand, heat can only be used close to the site of generation while electricity can be transported. “Wise” co-production of electricity or heat together with the other products must be very site-specific. Small-scale facilities could favour a high waste heat utilisation ratio.

4.3 Link to other PGG Working Groups

WG1 Production of biomass
Working group 1 of PGG has investigated the availability and production potential of biomass. The working group has identified various sources in- and outside the Netherlands to produce the required biomass volume. But not only the volume, also the nature of the biomass is important. Protein rich biomass should be used for biorefinery and the production of specialty chemicals. Lignocellulose-rich biomass should be used for fermentation or combustion.

The working group recognises the following sources of biomass:

- Increasing the efficiency of biomass that is already available in the Netherlands
- Dedicated cropping of existing and/or genetically improved (for non-food application) crops, in the Netherlands, but mainly abroad
- Aquatic cropping using saline soils, and the sea itself.
- Import of primary agricultural raw materials, intermediates and end products

The working group concludes that from these sources, sufficient biomass should become available to meet the demands related to the targets of PGG.

The conclusions of the working group 1 and WISE BIOMAS are in line. Both working groups recognise the various possibilities with biomass. Both working groups have concluded that there are no fundamental hindrances to realise the ambition of the Platform by 2030. However, it should be noted that the model predictions strongly depend on market prices, which are the result of supply and demand. It was also apparent from the model results that the '*optimal'* mix of biomasses (lignocellulose-rich, oil-rich and protein-rich) already strongly depended on the Cases studied. Hence, not a clear choice can be made for a particular biomass scenario, other than a total volume. Two main factors support this statement.

1. Chemical and probably also fuels industry wishes to have a flexibility of selecting feedstocks and will strive to develop general and robust technology. Compare this to the current petrochemical industry that can operate on a wider feedstock range.
2. The availability of biomass is not obvious. In general, the world food situation will have a higher priority than the world energy situation. Mostly the residue streams of agriculture and forestry will be available for energy and chemicals feedstocks. This situation will probably bias lignocellulosic residual flows as a feedstock. At the same time, there is no reason for despair: there is still a lot of arable land available, production can be increased, as well as the efficiency of the food chain.

WG2 Realisation of sustainable biomass import
A constraint to all biobased scenarios is that the biomass should be sustainable. There should not be harmful side-effects to the environment, and to the local communities and their economies.

The project group "Duurzame import biomassa" has developed a number of testable criteria and has started activities for the certification biomass. Two members of PGG are members of the project group.

For co-production of chemicals, fuels, electricity and heat, the development of criteria and certificates is of eminent importance. The project group's report has been published in Dutch and English (Project group sustainable biomass production, 2006).

WG4 "Groen gas"
The working group "Groen gas", a joint working group of the platforms "Groene Grondstoffen" en "Nieuw Gas" has though about ways to reduce CO_2 emissions and the dependence on fossil fuels through the use of green gas. The working group considers that firstly (starting today), biogas from fermentation of manure will lead to an increase of renewable gas for heating purposes. About 2015, large scale production of SNG from biomass will lead to a "greener" gas grid. The SNG route will lead to 20-50% replacement of natural gas. This would satisfy the goals of the Platform Biobased Raw

Materials (PGG) for the production of heat. At the same time, it should be recognised that the demand for biomass to satisfy the Dutch energy demand would increase beyond the values given in this report.

<u>WG5 Innovative use of renewable resources</u>
Also, the working group 5 of the platform “Groene Grondstoffen” has studied what strategic decisions are necessary in order to help the chemical industry to adopt renewable resources. The working group considered the following routes:

- Replacement of 25% of the fossil organic chemical raw materials through biobased resources by 2030. This requires a lasting effort on existing R&D strategies
- Increased recycling of materials (mainly outside the Netherlands). Additional policies required.
- More efficient catalytical (bio)chemical processes – lasting effort on existing R&D strategies required.
- Dematerialisation: materials with a strongly improved functionality - lasting effort on existing R&D strategies required.

WG5 considers the possibilities of biorefinery with reserve. It proposes building blocks from energy for chemical applications. Its spearhead is (bio)catalytical research. WISE BIOMAS also underlines the importance of lasting efforts in R&D on biomass-related topics and (bio)catalysis, since the technologies that should realise our targets of 2030 are not mature yet. However, WISE BIOMAS considers the development and implementation of biofuels and bio-based chemicals as a matter with such urgency, that dedicated long-term programmes and commitments will be necessary.

4.4 Timing

A change to a more biobased economy will not be the work of a few years. Current (petro)chemical plants will have a lifetime of many years more. Development of methods to convert lignocellulosic and other types of biomass efficiently to biofuels and chemicals will also take some time. Firstly, efficient methods for the conversion of lignocellulosic biomass to biofuels will enter the market, in 5 years (2nd generation biofuels). Also, we expect that biorefinery processes will enter, but their market penetration will be slower since the products and processes are more specific.

It is important that governmental support for a selected direction will be effective for a long period - in terms of a decade. And it is urgent. Other countries step up their activities, we must do so as well.

4.5 Comparison to CPB scenarios

The results of the computations have been discussed with CPB (Netherlands Bureau for Economic Policy Analysis). This Bureau makes independent economic analyses that are relevant for policymaking in the Netherlands.

During the discussion, a difference between the views of WISE BIOMAS and CPB became apparent. WISE BIOMAS considered that the societal benefit of biobased production would be positive in 2030 (in terms of economic benefits, but also CO_2 emissions reduction, and other environmental and societal benefits) and CPB considered that there would be a societal cost for the increased application of biomass. CPB could not support the results of the efforts of WISE BIOMAS from their own background and sources. Their views dated from some years back, and there have been many important changes in the meantime.

The consensus was, that it would be worthwhile that CPB would look again into the societal benefits of the biobased economy. This will help the Platform Renewable Raw Materials (PGG) to advise the government, based on current technical insights and current prize predictions, and the superior CPB economic models. Such a CPB study will in principle be scheduled for 2007. PGG will be available for technical advise, price functions, and will incorporate the results in further input for the government.

5. Conclusions and recommendations

Conclusions

- Biobased alternatives can potentially cover up to 30% of the Netherlands' domestic energy and chemicals demand, effectively reducing net CO_2 emissions, provided sufficient sustainable biomass or biomass derivatives can be made available.
- Maximizing the economic potential of biobased production methods seems an attractive strategy for the coming years. The environmental targets in reducing CO_2 emissions can be fulfilled by all "Cases" elaborated in this report.
- Biobased raw materials have a positive economic impact and will add to the GDP in 2030. To realise this, a joint effort by industry, research community and government is needed. Initially public R&D has to be carried out, co-financed by the government, to extend the existing knowledge position. Industry will participate financially in pilots and demonstration plants. In a Public Private Partnership there will be a swift transfer from public to private R&D.
- At this stage, a flexible strategy for the further development of biobased process routes for the production of chemicals is required. This should keep the major technical co-production options open. To capitalise on the strong knowledge position of the Netherlands, it is urgent to realise the following demonstration projects:
    - Production of transportation fuels and other products from lignocellulosis and agricultural residual flows through fermentation or thermochemical conversion.
    - Co-production of fuels and chemicals with power (and heat) in a large-scale coal/biomass fired IGCC-concept.
    - Improving utilisation of current agro-food (residual) streams through biorefinery and subsequent conversion processes.
    - Small-scale biomass conversion into base products, with involvement of the agricultural, energy and chemical sectors.

  In a later stage, investment support will be necessary.
- The cross-sectoral value chains, including the agricultural, fuels, energy and chemical sectors, are a challenge and governmental stimulation to facilitate cross-sectoral collaboration is required.
- Increased action to realise 30% biobased in 2030 is urgent. Other countries are stepping up their activities, and the Netherlands' position as a distribution hub, with a strong agricultural and chemical sector, allows no further delay.

Recommendations

- Large scale imports by the Netherlands as well as international trade partners requires substantial attention for the position of the ports (Rotterdam, Amsterdam, Eemshaven, Gent). Major investments from the public and private sector are required for initiatives such as BioPort, a Rotterdam Harbour-based consortium preparing large scale experiments and implementation in import, trade, processing and communication. Alliances and networks with the industries and governments in adjacent countries should be investigated (German, Belgium, France, UK).
- Small scale conversion of biomass close to the production location is often important for efficient transport. Small-scale installations that are suitable for 3rd World rural communities are a priority.
- Dedicated crops and specialised biorefinery technologies offer an important potential, but a broader-based activity to involve the chemical industry in biorefinery is required. In this respect, it is important that in 2006 the Dutch Platform on Biorefinery has been initiated by WUR and ECN (www.biorefinery.nl). IEA Bioenergy Task 42 "Biorefinery" has established in international Platform, too. Both Platforms join representatives of all stakeholders and aim to speed up biorefinery technology deployment.
- Recycling of minerals (N, K, P, etc.) needs attention. Small-scale pre-conversion in Third World countries would be helpful in this respect as well.
- A continuous monitoring body from relevant stakeholders should advice and decide about the path to follow. All options are open now, but this situation may change. The monitoring body could be staffed from PGG, provided that it will have a serious voice in the decision making.
- Large-scale R&D investments should have continuity. Successful programmes should have successors before the specific programme finalises.

- The governmental investments in an integrated package should be of the order of M€ 500 per year in the first five years for all transition paths of the Platform Biobased Raw Materials. This includes:
    - M€ 40 per year for R&D on the transition path *Co-production of chemicals, fuels, electricity and heat,* including pilot plants
    - M€ 40 per year for demonstrations on the transition path *Co-production of chemicals, fuels, electricity and heat*
    - An additional M€ 250 per year for implementation, such as through a venture capitall fund, support of SMEs, local government purchases, tax reductions and accompanying measures for all transitions paths of the Platform Biobased Raw Materials.

  A similar or larger budget is expected from industry: to be able to take over and implement the results of R&D on a commercial scale, and as investors in demonstrations and implementations of plants for *Co-production of chemicals, fuels, electricity and heat.*

Acknowledgements

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Appendix A Linear Programming

Linear Programming is a method which allows optimisation of a large number of interdepent variables. It has been used by WISEBIOMAS to optimise the Dutch energy economy in 2030 towards several ecologic and economic optimisation criteria. In order to understand how such an optimisation can be done, TNO has worked out a similar optimisation problem, but with less variables: ***The Simple Virtual Society.*** This is presented in this appendix, along with the general principles of linear programming.

A.1 Model of *A Simple Virtual Society* (Meesters *et al*, 2006).

Imagine a civilization with a need for 10 electricity units and 1 product unit. Also there are two resources: oil and renewables. Four conversion processes are known as shown in Table A.1. Only 4 units of renewable are available; which conversion processes should be used when we want to minimise dependence on oil imports or minimise CO_2 emissions, with a given supply of renewables?

Table A.1 Conversion processes known to A Simple Virtual Society.

Conversion	From	To	Needed	Produced
1	Renewable	Electricity	2 renewable	1 electricity
2	Renewable	Product	2 renewable plus 1 electricity	1 product
3	Oil	Electricity	2 oil	1 electricity
4	Oil	Product	2 oil plus 0.5 electricity	1 product

Since conversion 4 is more efficient than conversion 2, it is immediately clear that the lowest need for oil will be reached when the product is made from oil (conversion 4). All renewable should then be converted to electricity (conversion 1) in order to minimise CO_2 emissions. The remaining demand for electricity must be satisfied by conversion 3 (conversion of oil to electricity). In this approach 19 units of oil will be needed (Figure A.1), whereas 20 units of oil would be needed when the product demand was satisfied through product synthesis from renewables (Figure A.2). This example shows that the efficiency of new ‘green’ conversion techniques should somehow be compared to the efficiency of existing ‘black’ processes.

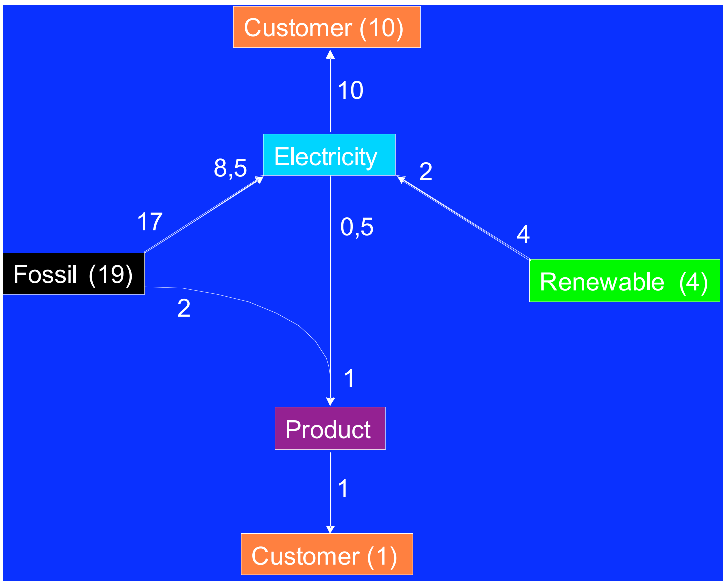


Figure A.1 **Schematic representation of optimal solution for** A Simple Virtual Society

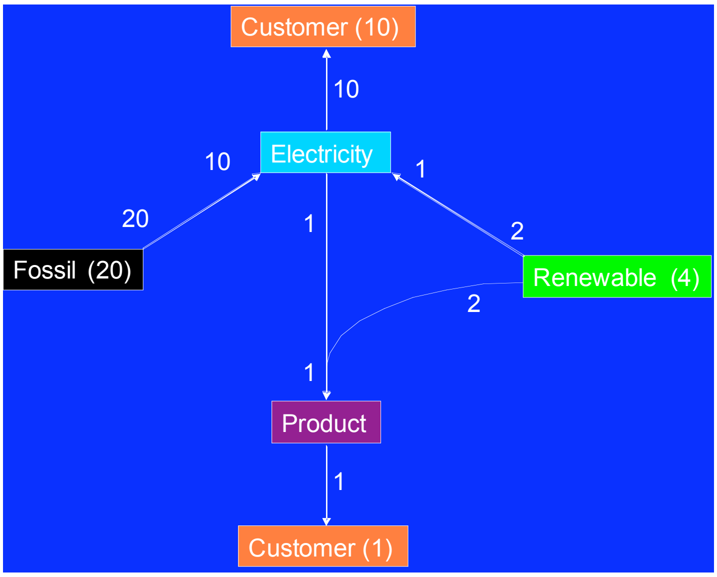


Figure A.2 **Schematic representation of less efficient solution of** A Simple Virtual Society.

Taken from K. Meesters, J. Zeevalkink and J.A.M. de Bont (2006)

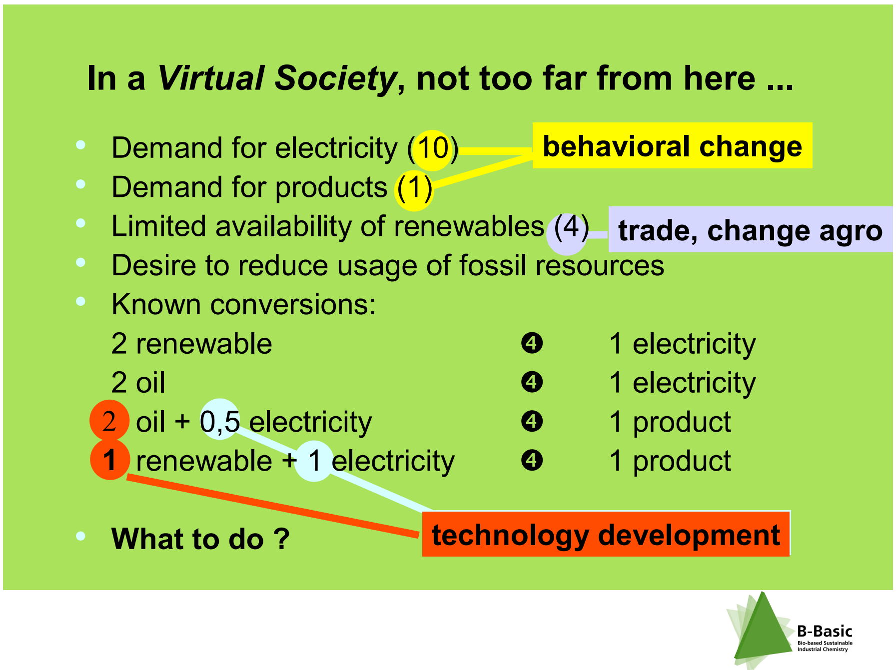
A.2 Technology development

The state of the technology is defined by the (yield) parameters in the model. In this example, the state-of-the-art for electricity production is equal for fossil and renewable technology (2 units). Bio-based manufacturing of products however requires 1 unit of electricity, whereas fossil-based technology needs only 0.5 units of electricity. Technological progress, resulting from R&D programs, is represented by improving the value of the model parameters. Of course, technological progress is constrained by the theoretical (conversion) limits of specific technologies. Impact of R&D programs can therefore be quantified by sensitivity studies ranging from the current state-of-the-art towards the theoretical limits. In this example, the investment in R&D should lead to reducing the electricity demand by at least 0.5 unit for the biobased technology (Scenario 1), in order to make biobased manufacturing economically competitive (at equal price levels). But there are also alternative scenarios:

- improving the efficiency of manufacturing products from fossil feedstocks directly, by using less units of oil for production,
- improving the production efficiency of electricity from either feedstock,
- (in some other cases, because this example did not include cost and had no possibility to attract more renewables) accepting the higher cost level of biobased production by state support (e.g. reduced taxation for biobased electricity). When our Simple Virtual Society has strong competition of other Virtual Societies, this may only be a very temporary measure.

A.3 Economic impact versus other sustainability characteristics.

Obviously, each of these scenarios have different economic impacts when renewables en fossil feedstocks have different price levels. This simple model also describes the societal behaviour in terms of a specific need (10 units electricity, 1 unit product). The impact of behavioural change towards less units of electricity and product can also be quantified.



The relativ… esults of the selected p… :ing (minimizin… ne. At the same time, it is well possible that the solutions are equal. In ***A Simplified Dutch Society*** there will be more feedstock options, fossil and renewable, as well as larger number of products, including intermediate components. This may result in different optimal solutions for several policy targets: ecological, economic and other societal benefits.

A.4 Linear programming for the simple virtual society

Comparison of different processes could be done via linear programming. The problem of our example civilization can be written as in Table A.2. The society's demands (E and P row) and the availability of renewable (R row) are given in a column vector at the right hand side (in red). The process efficiencies are put in columns (in yellow): the R to E column shows that 1 renewable is consumed and 0.5 electricity is produced. A vector with process rates (in green) lies on top of this matrix. Multiplication of the efficiency matrix (in yellow) with this vector will yield the production of electricity (E) and product (P) and the consumption of renewable (R) and oil (O) (in magenta).

An optimum solution is found when all constraints are satisfied (numbers in magenta ≥ numbers in red) and the oil demand is at its lowest (= maximization of negative oil production).

Table A.2 Linear optimisation problem for imaginary civilization.

	R to E	R to P	O to E	O to P			
	c1	c2	c3	c4			
E	0.50	-0.50	0.50	-0.25	x_E	>=	10
P	0.00	0.50	0.00	0.50	x_P	>=	1
R	-1.00	-1.00	0.00	0.00	x_R	>=	-4
O	0.00	0.00	-1.00	-1.00	x_O	maximize	

R to E *renewable to electricity*
R to P *renewable to product*
O to E *oil to energy*
O to P *oil to product*

Linear programming can solve problems like this easily. In this case the maximum solution is found when c1, c2, c3 and c4 equal 4, 0, 17 and 2 respectively (process rates, green blocks in Table A.2). The oil consumption is then equal to 19 (Table A.3) which is consistent with the value presented in Figure A.1.

Table A.3 Optimal solution for imaginary civilization.

	R to E	R to P	O to E	O to P			
	4.00	0.00	17.00	2.00			
E	0.50	-0.50	0.50	-0.25	10	>=	10
P	0.00	0.50	0.00	0.50	1	>=	1
R	-1.00	-1.00	0.00	0.00	-4	>=	-4
O	0.00	0.00	-1.00	-1.00	-19.00	maximize	

R to E *renewable to electricity*
R to P *renewable to product*
O to E *oil to energy*
O to P *oil to product*

Taken from K. Meesters, J. Zeevalkink and J.A.M. de Bont (2006)

A.5 Linear programming for the simplified Dutch society, general principles

Processes in the Netherlands economy to produce desired energy and chemical products are defined by certain demands on resources and efficiencies in the conversion thereof. In the Netherlands environment, these transformation processes are highly coupled, whereby the product of the one process (energy forms or chemical intermediates) are the feedstock for another. Several parthways can be identified, to vary in the degree in which fossil and renewable resources are required, and that also vary in the degree of economic value they generate. WISEBIOMAS –to advise PGG and the Dutch government- investigates those pathways that satisfy the product demands while maximizing sustainability issues and other benefits for the Netherlands society.

A highly simplified mathematical model of the Netherlands is created in which a highly simplified network of process, feedstocks and demands are related. Each process is described by a vector that contains relative[1] CO_2 production, fossil energy demand, depletion rate of fossil resources, electricity demand, heat demand, raw materials consumption, product yield, by-product yields and economical parameters. These vectors are put together in a matrix (*M*).

Multiplication of this matrix *M* with rate vector *r* (containing the process rates) will yield the consumption/production of CO_2, fossil energy, depletion rate of fossil resources, electricity, heat, raw materials, products and by-products: the production vector (*p*).

$M \cdot r = p$ (equation 1)

A demand vector (*d*) is set that gives the desired production. This vector was filled with the numbers that were expected to represent the society's demands in the year 2030 (Rabou *et al.*, 2006).
In order to fulfill all demands, the following equation must hold:

$p \geq d$ (equation 2)

or:

$M \cdot r \geq d$ (equation 3)

Linear programming is used to determine the most efficient pathways to fulfill the future demands with respect to reduced CO_2 emission, fossil energy use and reservoir depletion. If the number of processes is larger than the number of demands (and the matrix contains only independent vectors), a certain degree of freedom is left for vector *r*. Linear programming can find such values for vector *r* that equation 2 is satisfied while optimizing some criterion (*c*) which must be a linear function of *r* ($c(r) = a \cdot r_1 + b \cdot r_2 + c \cdot r_3 + d \cdot r_4 + \ldots$). This criterion can be the minimization of CO_2 exhaust, fossil energy demand, depletion rate of fossil reservoirs, capital charges or the maximization of margin or profit.

[1] The elements of matrix M are "yields" in terms of ton CO2 produced per ton of product, (fossil) energy demand per ton of product, etc

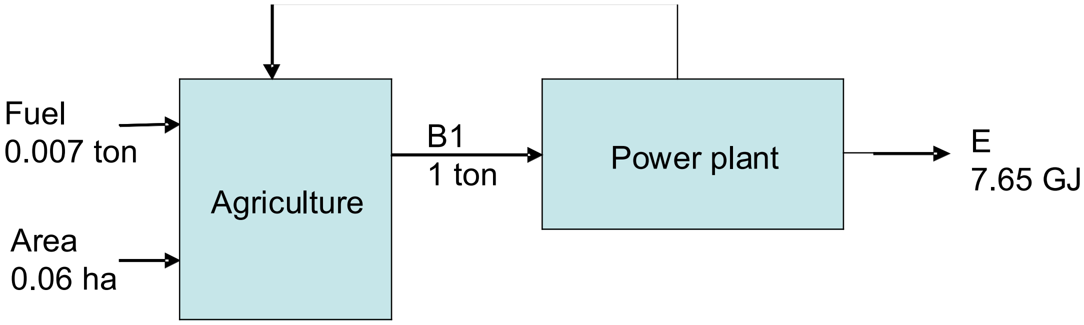
Appendix B Implementation for a Simplified Dutch Society

B.1 Process descriptions and diagrams

The processes discussed in the main text are briefly discussed below. We have used C2-compounds as a model for various classes of products: ethanol, ethene (for bulk chemicals), and ethene oxide and ethanol amine as functionalised specialty chemicals. The dry mass yields are given on a ton/ton conversion basis, and energy yields as GJ/ton. Negative numbers imply conversion, positive numbers production. The yield data given below are also used in the matrix with the process data (see Appendix A: matrix M). It is assumed that plants can recycle their process water to such an extent that the water content of the crop provides sufficient process water. When carbon dioxide is assumed to be fully recycled, it is omitted from the calculation.

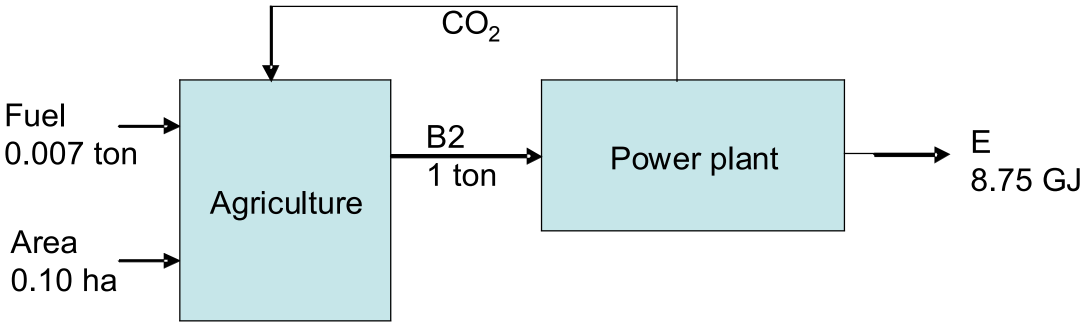
Process 1: electricity from CHO rich biomass (B1)

B1 is grown in a field and then combusted in a power plant. The CO_2 exhaust during combustion is assumed to be equal to the CO_2 uptake during agriculture and omitted from the calculation. Agriculture uses a small amount of fuel for cultivation and harvest of B1.



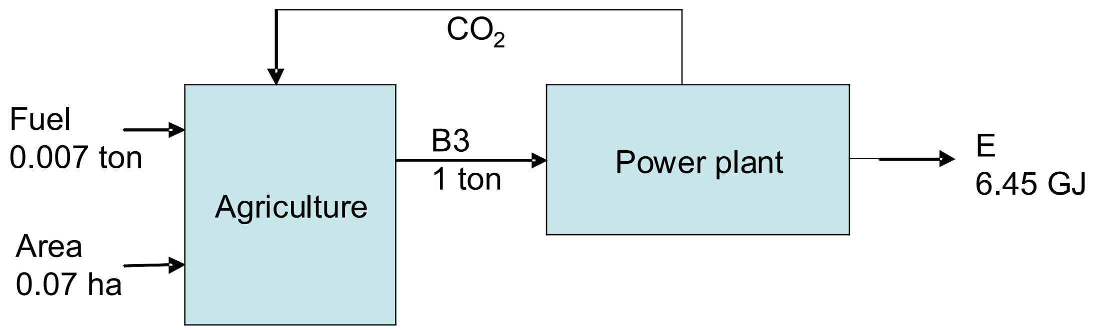
Process 2: electricity from oil rich biomass (B2)

B2 is grown in a field and then combusted in a power plant. The CO_2 exhaust during combustion is assumed to be equal to the CO_2 uptake during agriculture and omitted from the calculation. Agriculture uses a small amount of fuel for cultivation and harvest of B2.

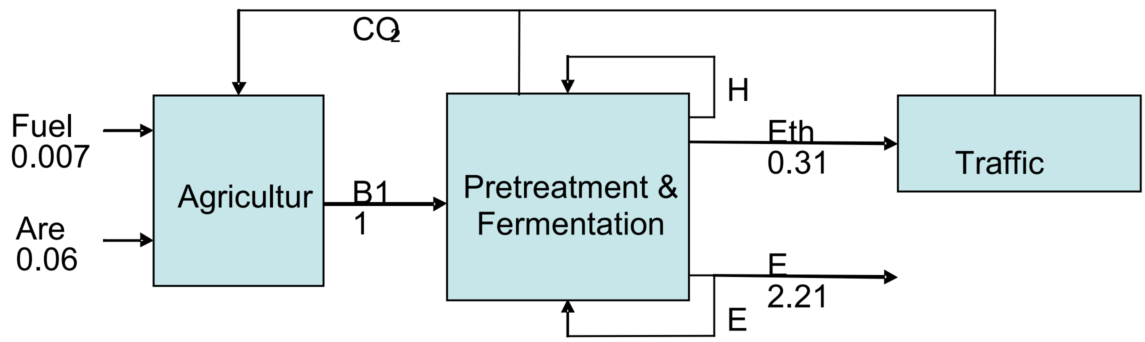


Process 3: electricity from oil rich biomass (B3)

B3 is grown in a field and then combusted in a power plant. The CO_2 exhaust during combustion is assumed to be equal to the CO_2 uptake during agriculture and omitted from the calculation. Agriculture uses a small amount of fuel for cultivation and harvest of B3.



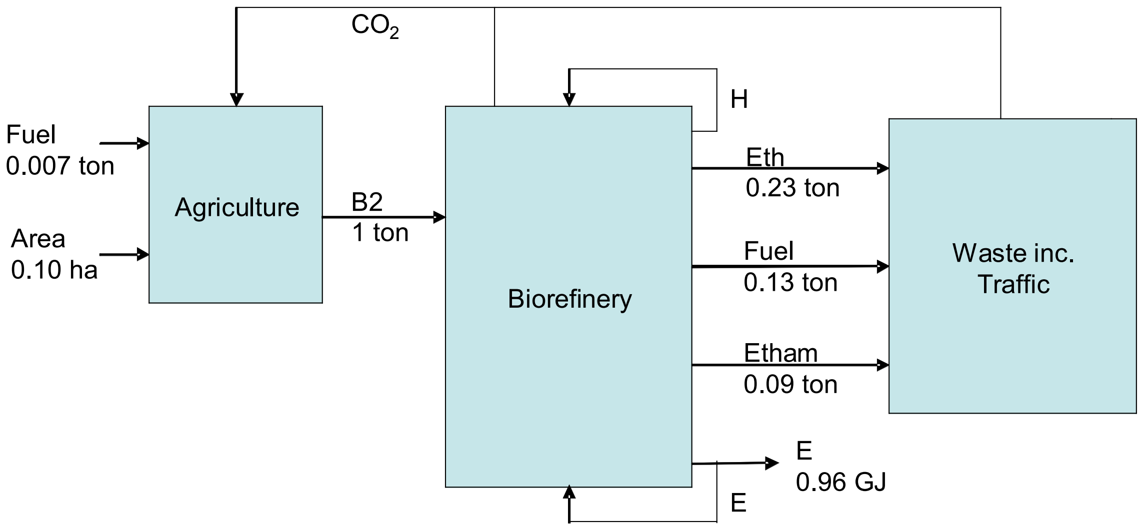
Process 4: pretreatment and fermentation
B1 is grown in a field and then pretreated. The resulting hydrolisate is fermented to ethanol. Ethanol is distilled from the water. The lignin formed during pretreatment is combusted to generate heat for the process. Excess heat is used to produce electricity. A part of the electricity is used by the process; the excess electricity is delivered to the grid. Eventually the ethanol will be combusted as a fuel in cars or it will be used to produce ethylene that in the end is combusted in waste combustors. The CO_2 exhaust of these processes will be equal to the CO_2 uptake in agriculture and omitted from the calculation. It is assumed that the plant can recycle its process water to such an extent that the water content of the crop provides sufficient process water.



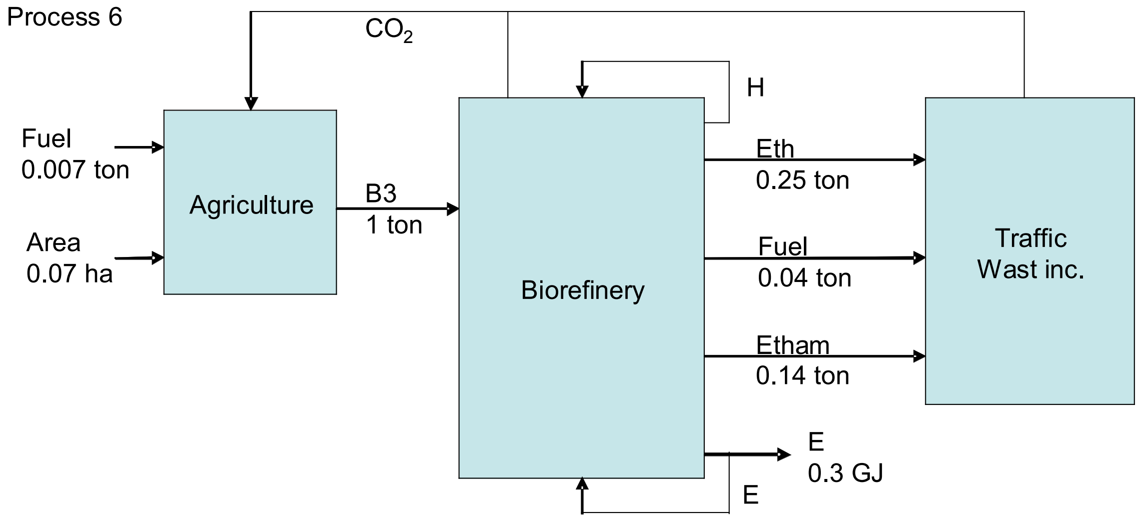
This simplified plant description and data were compared to those of Straathof et al (2006) and underlying reports, who summarize a desk study on the application of the current knowledge in sugar-ethanol industry to investigate the feasibility of sugar and ethanol coproduction from sugar cane, to search for alternative usages for the side products of the sugar production and to improve the existing technology to get more sustainable and environmentally friendly processes. The lignocellulose biomass B1 converting plant was modelled from a current sugar/ethanol plant of current technology (year 2005). Minor raw materials are limestone, sulphur and sulphuric acid, and cellulase for cellulose hydrolysis, and process water is recycled. The cellulose and hemicellulose fractions of lignocellulose are hydrolyzed into hexose and pentose sugars to be used as substrate for ethanol production. In addition, vinasse, filter cake and the genetically modified yeast are combusted, and streams rich in organic materials are treated in a waste water treatment plant. The lignine content is not sufficient to supply the required plant energy, and the current economy would dictate to purchase electricity and fuels for operating the plant. In the future, changes in that economic perspective will probably require to partly convert the biomass into electricity and steam (like in the conventional technology). This is assumed to be indeed implemented in Process 4.

Process 5: biorefinery of oil rich biomass
B2 is grown in a field and biorefined. The proteins are converted to fine chemicals. The oil is purified to produce biodiesel. The CHO rich fraction is pretreated and the resulting hydrolisate is fermented to ethanol. Ethanol is distilled from the water. The lignin formed during pretreatment is burnt to generate heat for the process. Excess heat is used to produce electricity. A part of the electricity is used by the process; the excess electricity is delivered to the grid. Eventually all the products will be burnt as a fuel

in cars or as waste in combustors. The CO_2 exhaust of these processes will be equal to the CO_2 uptake in agriculture.

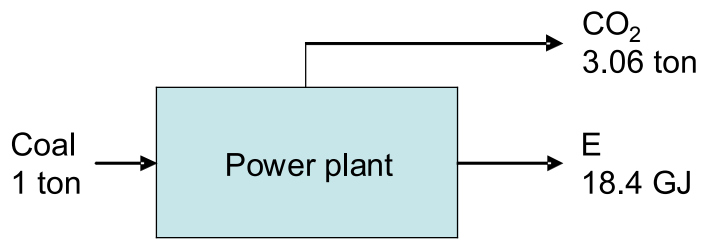


Process 6: biorefinery of protein rich biomass
B3 is grown in a field and biorefined. The proteins are converted to fine chemicals. The oil is purified to produce biodiesel. The CHO rich fraction is pretreated and the resulting hydrolisate is fermented to ethanol. Ethanol is distilled from the water. The lignin formed during pretreatment is burnt to generate heat for the process. Excess heat is used to produce electricity. A part of the electricity is used by the process; the excess electricity is delivered to the grid. Eventually all the products will be burnt as a fuel in cars or as waste in combustors. The CO_2 exhaust of these processes will be equal to the CO_2 uptake in agriculture.

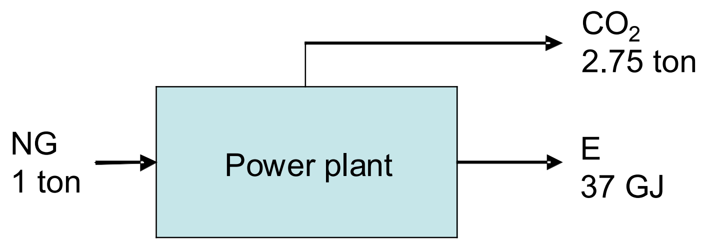


Process 7: ethanol to fuel
This conversion converts tons of ethanol to tons of gasoline equivalent.

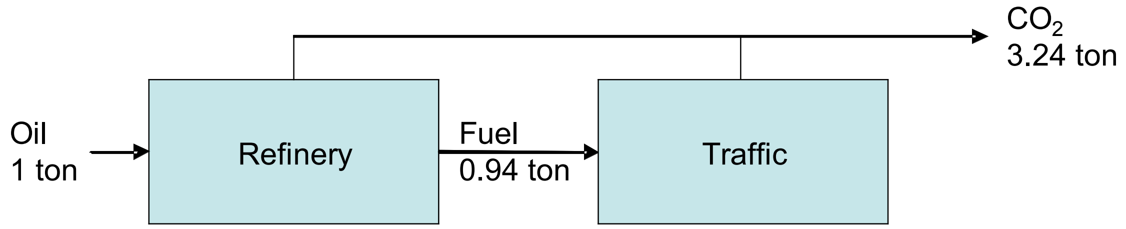
Process 8: electricity form coal
Coal is combusted in a power plant. CO_2 exhausted is released into the atmosphere.



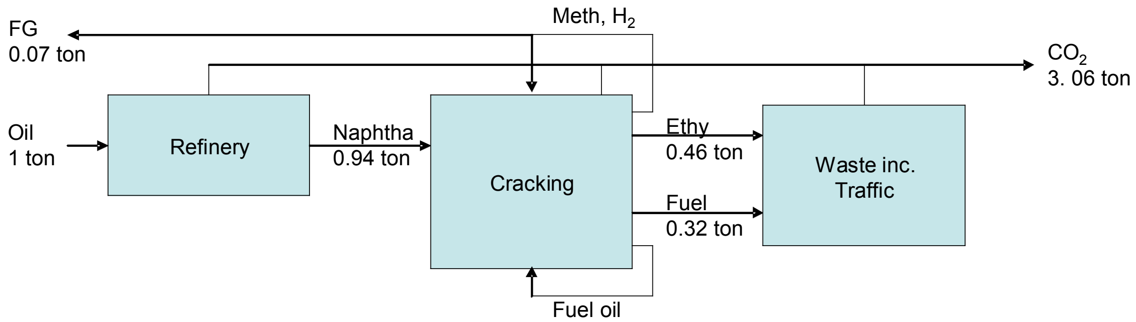
Process 9: electricity form natural gas
Natural gas is combusted in a power plant. CO_2 exhausted is released into the atmosphere.



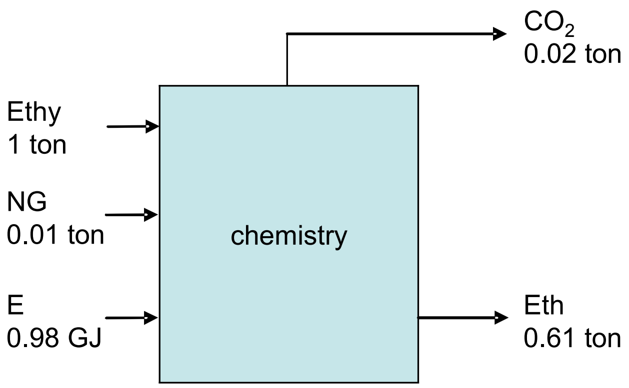
Process 10: fuel from oil via refinery
Oil is refined to produce fuel. The fuel will be burnt in cars. The CO_2 produced in the cars and in the refinery will be exhausted to the atmosphere.



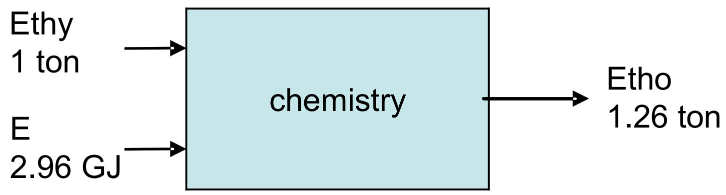
Process 11: ethylene from oil via cracking
Oil is refined to produce naphtha. The naphtha is cracked to produce ethylene and fuel. As side products fuel oil and fuel gas are formed, which are assumed to be used in the process. A small amount of excess fuel gas is delivered to heat consuming processes on the site. The CO_2 produced in the cars and in the refinery, the cracking unit, in cars and in waste combustors will be exhausted to the atmosphere.



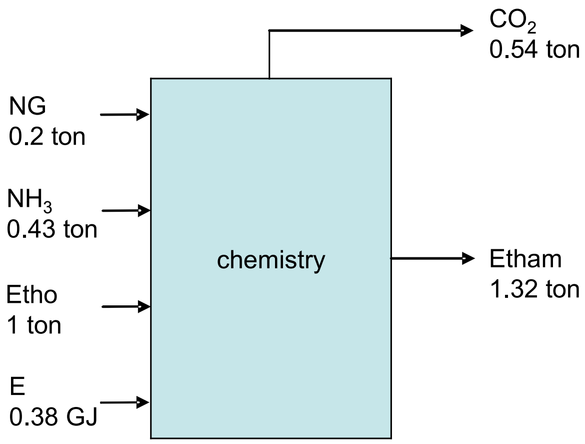
Process 12: ethanol dehydration
Ethanol is dehydrated to form ethylene according to: $C_2H_5OH \rightarrow C_2H_4 + H_2O$. Heat (from natural gas input NG) and electricity are needed for the process.



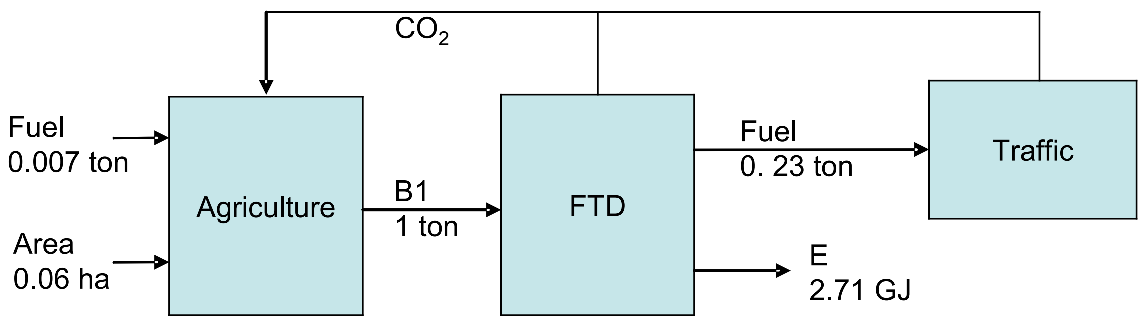
Process 13: ethylene epoxydation
Ethylene is oxidized to form ethylene oxide according to: $C_2H_4 + 0.5\ O_2 \rightarrow C_2H_4O$. Electric energy is needed for pure oxygen production and cooling (to prevent runaway reaction).



Process 14: amination of ethylene oxide
Ethylene oxide is aminated to from ethanolamine according to: $C_2H_4O + NH_3 \rightarrow HOC_2H_4NH_2$. Natural gas and electrical energy are needed to drive the process in the direction of ethanolamine.



Process 15: FTD synthesis from CHO rich biomass
B1 is grown in a field and then converted to synthesis gas. The synthesis gas is used to produce diesel via the Fischer Tropsch process. Excess heat is used to produce electricity, which is delivered to the grid. Eventually, the Fischer Tropsch Diesel will be combusted as a fuel in cars. The CO_2 exhaust from the gasification, the FTD process and the cars will be equal to the CO_2 uptake in agriculture. Hence, CO_2 is omitted from the calculation.



B.2 Consideration of system boundaries

CO_2 emission
Most products will end up as CO_2 at the end of their life cycle. Recalcitrant plastics on a refuse dump or in nature are an exception. It is however questionable that such a waste of energy and environmental pollution should be rewarded with a 'CO_2 neutral' qualification. Therefore any carbon from fossil resources that is used to produce heat, electricity, fuels or products will in the end increase the CO_2 concentration of the earth's atmosphere. Carbon from renewable resources will not. The system boundaries of the CO_2 emission therefore were chosen to be the earth's crust; any fossil resource that is dug up, pumped up or let out of the earth will contribute to the green house effect.

Nitrogen
Nitrogen might be fixed by leguminous plants or via the Haber-Bosch process. The fixation of nitrogen by leguminous plants costs (solar) energy and therefore these plants have lower crop yields than intensified plant cultivations that use ammonia-derived fertilizer as a nitrogen source. Hence, in this report, it is assumed that net biological nitrogen fixation does not occur and that all ammonia is made via the Haber-Bosch process. It is assumed that the plants take up all nitrogen provided by the fertilizer that is spread over the land (no nitrification/denitrification and no wash out). Therefore the demand for ammonia during production of ethanolamine is equal in both the chemical and the biological production chain.
Because both the chemical and the biological production route for ethanolamine use the same amount of nitrogen originating from the Haber-Bosch process, including the Haber-Bosch process does not differentiate between both production routes. Omission of this process will cause a nequally lowered CO_2 exhaust, methane demand, depletion rate of fossil resources and raw material costs for both processes.

B.3 Valid time frame

The outcome of the project will be used to focus the Netherlands research and development strategy on issues that will be relevant during the transition from a fossil based economy to a renewable based economy. This transition has already started at small scale but is expected to be implemented at large scale in the period 2020-2030. Therefore the efficiencies of renewable and conventional processes should represent the expected state of the art technology in that period. It would not make sense to compare current laboratory results and low efficiency trials with lignocellulosic biomass feedstocks to the more or less mature, coal fired (steam and gas turbine) power plants. Therefore efficiencies are used that are 90% of the theoretical maximum, eventhough that is not yet state-of-the-art technology.

B.4 Economics of the individual processes and the integral system.

Based on the simplified flowsheets, the economic impact of each of the processes as well as effect on the integral system can be estimated. The procedure is straightforward: the *manufacturing costs* are composed on variable costs (VC raw materials, energy and other costs that depend directly to production volume) plus fixed costs (FC: all that depend mainly on the investment : interest, personnel). The latter is calculated as a Capital Charge. The capital charges were calculated from the invested capital. The invested capital include interest, depreciation, maintenance, insurance, royalties, rent, labour, laboratory, and costs inside as well as outside of the battery limits.

capital charges = 25%/yr of invested capital

The market or selling price depends on offer and demand, and is dynamic. Particularly for those products that depend strongly on fossil resources, the current dynamics of the crude oil market demonstrate that sensitivity. Industry works with long term contracts to balance part of these dynamics, so we will use a relative conservative estimate of the crude oil (and associated natural gas) price. In order to be able to estimate a sustainable industrial situation, we assume a business-to-

business and final sales price that is (remotely) related to the manufacturing costs plus an industry averaged margin.
We realise the limitations of this approach. Hence:

Margin = Sales – Manufacturing Costs = typically 10..15% van Sales (varies per industry).

Taxation in this model is seen as a response of the government, which serves policy targets. Particularly for the field of fuels, several measures are taken that serve different goals: high taxation of fuels in general to reduce fuel use, and stimulate the use of biofuels via lower taxation. Therefore, the calculations have been performed without taxes.

Raw material costs
The raw (petro)material costs depend on the crude oil price. In Figure A.3, chemicals sales prices from the spot market were plotted against the oil price (CMR 1999, CMR 2004, CMR 2006, CBS 2006, OECD 2004, ICIS 2006). Linear relations were fitted through these points to derive the estimates of chemicals sales prices with the oil price. This dependence has been questioned by some of the working group members, since logic dictates that the price for MEA would show a steeper dependence on oil price than ethene, since more oil is needed for one kilogram of MEA than for ethene. The result of a steeper dependence would most probably be better economic characteristics for the production of fine chemicals from biomass.

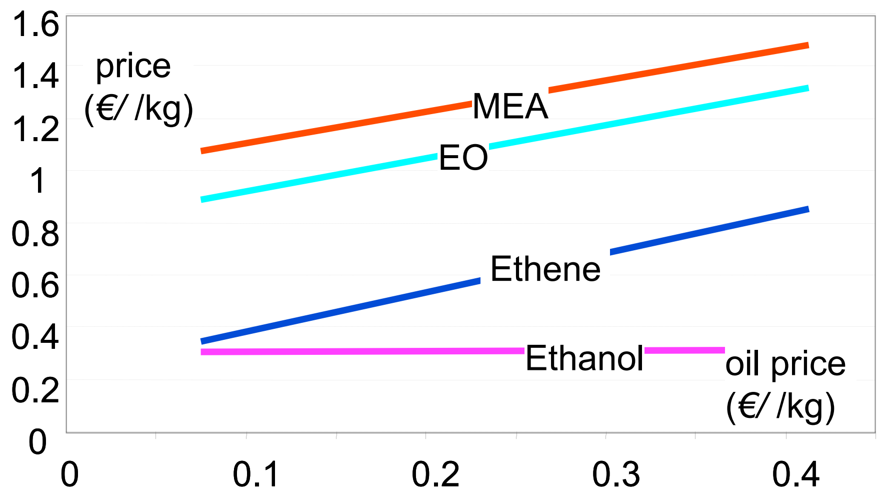


Figure A3 **Estimated sales prices depending on crude oil price for selected C_2-chemicals (MEA is monoethanol amine, EO ethene oxide).**

Sales

Ethanol, Electricity and Ethylene are final products as well as intermediates. Intermediates are included in both product sales and raw material costs (i.e. both product sales and raw material costs increase when intermediates are further processed; the margin is not influenced).

B.5 Process matrix M

Using the previous assumptions, the process vectors were derived. Each vector contains information on the raw material consumption, the needed crop area, the production of (side)products, the consumption of utilities, the exhaust of CO_2, fossil energy usage, the depletion rate of fossil resources rate, the raw material costs, the sales and the capital charge of the process.

The depletion rate of fossil resources is reciprocally related to the depletion time (in short "***depletion***") which is the sum of the known or estimated remaining reservoir divided by the rate of consumption of each fossil feedstock, summed over all fossil feedstocks. A small depletion indicates a high rate of depletion fossil reservoires. These vectors were put together in a matrix as shown in Table A.3 and Table A.4.

Table A.3, process vectors 1 till 7 (all numbers per ton raw material), process numbers as in Section B.1 of this appendix

		Inc. B1	Inc. B2	Inc. B3	P&F B1	BRef B2	BRef B3	Eth-fuel
Process number		**1**	**2**	**3**	**4**	**5**	**6**	**7**
area	**ha/ton**	0,06	0,10	0,07	0,06	0,10	0,07	0
depletion rate	**1/ton**	0	0	0	0	0	0	0
fossil energy	**GJ/ton**	0	0	0	0	0	0	0
renewable energy	**GJ/ton**	-17,27	-19,72	-16,74	-17,27	-19,72	-16,74	0
electricity	**GJ_e/ton**	7,65	8,75	6,45	2,21	0,96	0,30	0
CO_2	**ton/ton**	0	0	0	0	0	0	0
Raw material	**ton/ton**	-1	-1	-1	-1	-1	-1	0
ethanol	**ton/ton**	0	0	0	0,31	0,23	0,25	-1
ethylene	**ton/ton**	0	0	0	0	0	0	0
etho	**ton/ton**	0	0	0	0	0	0	0
etham	**ton/ton**	0	0	0	0	0,09	0,14	0
fuel	**ton/ton**	-0,007	-0,007	-0,007	-0,007	0,13	0,04	0,67
rmc	**€/ton**	-104,06	-104,06	-104,43	-100,00	-100,00	-100,00	-315,29
sales	**€/ton**	127,50	145,88	107,55	134,69	307,49	337,68	406,05
capital charges	**€/ton**	90,90	104,01	76,68	47,53	106,50	106,50	0,00

Table A.4, process vectors 8 till 15 (all numbers per ton raw material), process numbers as in Section B.1 of this appendix

		Coal-E	NG-E	Oil-fuel	Oil-ethy	Eth-Ethy	Eth-Etho	Etho-Etham	FTD
Process number		**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Area	**ha/ton**	0	0	0	0	0	0	0	0,06
depletion rate	**1/ton**	6,3	16	24	22,94	0,09	0	3,17	0
fossil energy	**GJ/ton**	-33,41	-53,17	-41,78	-38,27	-0,29	0	-10,54	0
Renewable energy	**GJ/ton**	0	0	0	0	0	0	0	-17,27
Electricity	**GJ_e/ton**	18,37	37,22	0	-0,07	-0,59	-2,96	0	2,71
CO_2	**ton/ton**	3,06	2,75	3,24	3,06	0,02	0	0,54	0
raw material	**ton/ton**	-1	-1	-1	-1	0	0	0	-1
Ethanol	**ton/ton**	0	0	0	0	-1	0	0	0
Ethylene	**ton/ton**	0	0	0	0,46	0,61	-1	0	0
Etho	**ton/ton**	0	0	0	0	0	1,26	-1	0
Etham	**ton/ton**	0	0	0	0	0	0	1,32	0
Fuel	**ton/ton**	0	0	0,94	0,32	0	0	0	0,23
Rmc	**€/ton**	-25,72	-319,02	-504,67	-484,75	-326,92	-1043,67	-1495,46	-104,06
Sales	**€/ton**	306,24	620,31	569,26	648,10	602,64	1805,93	2104,61	188,69
capital charges	**€/ton**	218,35	221,14	69,09	171,39	45,12	220,68	195,28	58,15

Appendix C Theoretical yields of chemicals and fuels on biomass

(pers. communication A.J.J. Straathof, 2006).

Overview of main C1 to C4 compounds that may be produced from glucose

Functional groups considered: alkene, alcohol, aldehyde, ketone, carboxylic acid

Isomers are usually not given but sometimes indicated by "="

Maximum yields have been calculated assuming glucose is stoichiometrically converted into product

Maximum yields will be lower when microbial growth etc. are taken into account

oxidation level	**-4**		**-3**		**-2**		**-1**		**0**		**1**		**2**		**3**	
(compared to glucose)																
O2 consumed	none		none		none		0.5 O2		none		0.5 O2		1 O2		1.5 O2	
side products	2 CO2 + 1 H2O		1.5 CO2 + 0.5 H2O		1 CO2		1 CO2		none		none		1 H2O		1 H2O	
(mol/mol product)																
		yield		**yield**		**yield**		**yield**		**yield**		**yield**		**yield**		**yield**
Product group		kg/kg		kg/kg		kg/kg		kg/kg		kg/kg		kg/kg		kg/kg		kg/kg
C1					methane	0,27	methanol	0,53	formaldehyde	1	formate	1,53	CO2	1,47		
C2			ethane	0,29	ethanol	0,51	glycol	0,69	acetate = glycolaldehyde	1	glycolate	1,27	glyoxylate	1,23	oxalate	1,5
C2 minus H2O					ethene	0,31	acetaldehyde	0,49								
C3	propane	0,29	propanol	0,44	propanediol	0,63	glycerol	0,77	lactate = dihydroxyacetone	1	glycerate	1,18	malonate = hydroxypyruvate	1,16	tartronate	1,33
C3 minus H2O			propene	0,31	acetone = propanal = allyl alcohol	0,48	propanoate = acetol	0,62	acrylate	0,8	pyruvate	0,98				
C3 minus 2 H2O							acrolein	0,47								
C4	butanol	0,41	butanediol	0,55	butanetriol	0,71	erythritol	0,81	dihydroxybutanoate	1	trihydroxybutanoate	1,13	malate	1,12	tartrate	1,25
C4 minus H2O	butene	0,31	butanone	0,44	butanoate = acetoin	0,59	hydroxybutanoate	0,69	oxobutanoate	0,85	succinate	0,98	fumarate	0,97	oxaloacetate	1,1
C4 minus 2 H2O					butenone	0,47	diacetyl = methacrylate	0,57	crotonate	0,7						

max.carbon yield due to CO2 production

yellow	1
purple	0,8
orange	0,75
light orange	0,73
green	0,67
pink	0,60
grey	0,57
blue	0,5

Appendix D Composition of Working Party WISEBIOMAS

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Evaluation support
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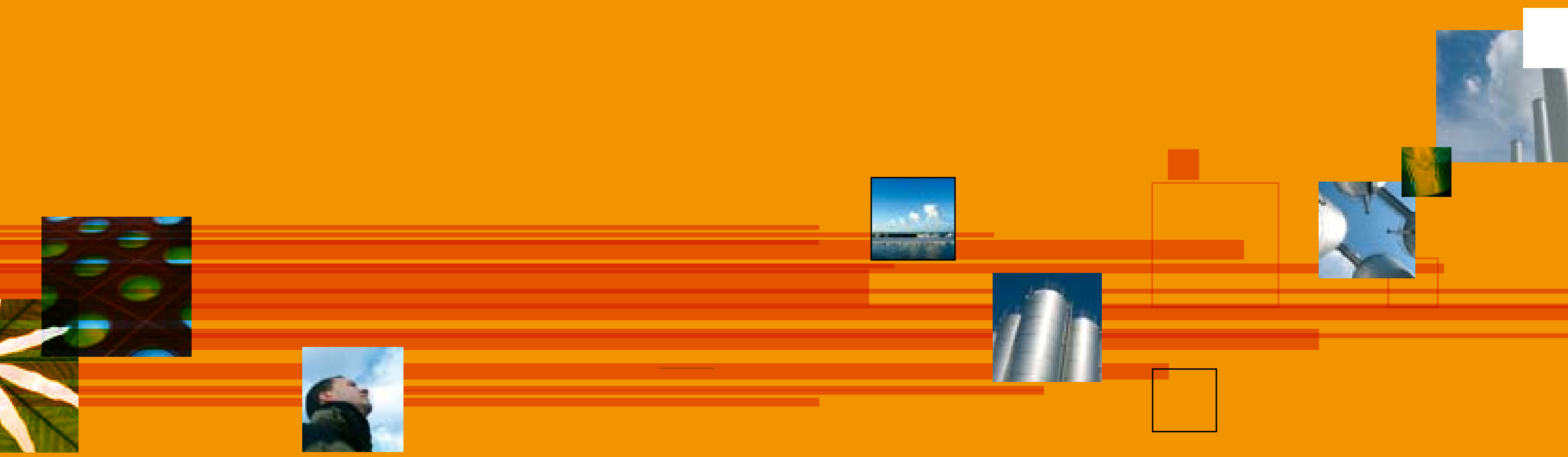
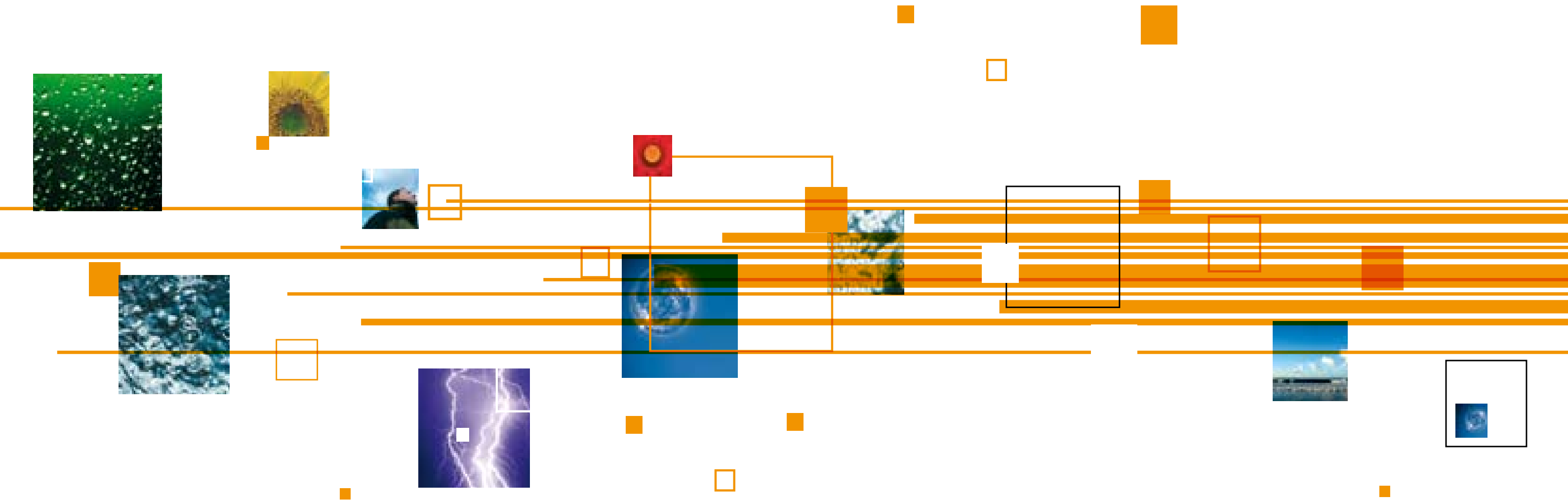
TNO Quality of Life





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For further information:

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