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BIOMASS FOR GREENHOUSE GAS EMISSION REDUCTION

Task 8: Optimal emission reduction strategies for Western Europe

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Abstract

This report discusses optimal use of biomass in Western Europe for greenhouse gas emission mitigation. The analysis is based on the MARKAL MATTER4.2 energy and materials systems engineering model. The results show that biomass strategies can contribute up to 400 Mt CO_2 equivalents of emission reduction in 2030. Biomass use for transportation fuels and feedstocks, energy recovery from waste and afforestation seem the most promising options. Biomass use for energy and materials will increase from 250 Mt in the base case to 600 Mt in case of 75% emission reduction in 2030. Based on the modelling results it is recommended to apply generic pricing instruments, provide a long-term policy target to all market parties and avoid premature technology selection.

CONTENTS

GLOSSARY

B/C	Benefit/Cost ratio
BFH	Bundesforschungsanstalt Für Holzwirtschaft, Hamburg, Germany
BIG-CC	Biomass Gasification Combined Cycle
BRED	Biomass for Greenhouse Gas Emission REDuction
CDM	Clean Development Mechanism
CH_4	Methane
CHP	Combined Heat and Power generation
CO_2	Carbon dioxide, the most important greenhouse gas
dm	Dry matter
DME	DiMethyl Ether
ECN	Netherlands Energy Research Foundation
EFTA	European Free Trade Association (Western European non-EU countries)
EMS	Energie en MateriaalgebruiksScenarios
ETBE	Ethyl Tertiary Butyl Ether
ETSAP	Energy Technology Systems Analysis Programme
EU	European Union
EUR	Euro, European Monetary Union Currency Unit (1 EUR ≈ 1.04 USD)
EQ	Equilibrium
EWAB	Dutch acronym for Energy Recovery from Waste and Biomass
FARM	Future Agriculture Resources Model
FP	Flash Pyrolysis
FT	Fischer Tropsch
GCMs	General Circulation Models
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
H_2O	Water
HTU	Hydro Thermal Upgrading
HFCs	Hydrofluorocarbons
HY	High Yield
IEA	International Energy Agency
IENICA	Interactive European Network for Industrial Crops and their Applications
IGCC	Integrated Gasification Combined Cycle
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Analysis
LCCs	Least Cost Combinations
LFG	LandFill Gas
LHV	Lower Heating Value
LP	Linear Programming
LY	Low Yield
MARKAL	MARKet Allocation
MATTER	MATerials Technologies for greenhouse gas Emission Reduction
MED	MARKAL Elastic Demand
MFA	Material Flow Analysis
MM	MARKAL MACRO
MSW	Municipal Solid Waste
MTBE	Methyl Tertiary Butyl Ether
NO_x	Nitrogen oxide (x = 1, 2)
N_2O	Nitrous oxide
Novem	Netherlands Organisation for Energy and Environment

NPV	Net Present Value
NTUA	National Technical University of Athens, Greece
OECD	Organisation for Economic Cooperation and Development
PEC	Dutch acronym for Product and Energy Plant
PFCs	Perfluorcarbons
PHB	Polyhydroxybutyrate
PHV	Polyhydroxyvalerate
pm	Pro Memoriam
Ppmv	parts per million, volume based
PV	Photo Voltaic
RD&D	Research, Development & Demonstration
RME	Rapeseed Methyl Ester
SD	Sitting Ducks
SF_6	Sulphurhexafluoride
SNG	Synthetic Natural Gas
SO_2	Sulfur dioxide
SOFC	Solid Oxide Fuel Cell
SP	Shadow Price
STAG	STeam And Gas power plant
TE	Total Energy
TID	Time independent
UNFCCC	United Nations Framework of Convention on Climate Change
WEC	World Energy Council
WIR	Wood In the Rough
wt	Weight

PREAMBLE

This report provides the background information and the results for the MARKAL MATTER4.2 model calculations that have been done in the framework of the BRED project. A draft version of this report has been reviewed at an expert workshop in Brussels, 6-7 December 1999. The general feeling regarding the draft report was that it contained a lot of useful information, but it was not sufficiently accessible. On one hand, there was interest in more detail by some experts, on the other hand there was a request for a more comprehensive report by policy makers. It is virtually impossible to accommodate both wishes in one single report.

A two-way approach has been selected. On one hand, this report contains separate summaries for separate target groups. The target groups are: policy makers, industry, farmers and forest industries and scientists. Each summary contains a reader's guideline that indicates the most relevant chapters for the specific target group in the opinion of the authors. Some examples have been added to the discussion of the modelling results, but for a more comprehensive discussion of the model structure and the model input data one is referred to the Internet (http://www.ecn.nl/unit_bs/bred). On the other hand, papers focusing on specific target groups are currently being written by the project team. This report can also be considered as a background document for these separate papers.

SUMMARY FOR POLICY MAKERS

This report discusses the results of task 8 of the BRED project (Biomass for greenhouse gas emission REDuction), funded by the European Commission, DG Research, in the framework of the Environment and Climate Programme. The BRED project focuses on the optimal use of Western European biomass for greenhouse gas emission mitigation on the long term. While the European Kyoto target of 8% emission reduction in the period 2008-2012 will only have limited impact, ambitious long-term emission reduction targets of 50-75% would have a much more significant impact on the economy. This study analyses the impact of such ambitious long-term policy targets.

The increased use of biomass as substitute for fossil energy and materials and the storage of carbon in natural organic materials have been documented extensively in many earlier European studies. This study adds a few elements to the existing body of knowledge. Regarding methodological issues, biomass strategies are compared to other emission mitigation strategies on the basis of discounted costs. Interactions of emission mitigation measures are considered explicitly. Technological change is considered explicitly. The competing land use for food and fodder production is considered in detail. This combination of elements has not been considered in many preceding studies. Regarding scope, this study considers afforestations, carbon storage in soils and the production of materials on top of bioenergy applications. This is a much broader scope than earlier studies that have mainly focused on bioenergy alone.

The results differ considerably from earlier studies. The results indicate a significant land use for afforestations and limited energy and materials crops. Up to 30 Mha land can be made available for GHG policies. However, the results show that it is cost-effective to use three quarters of this land for afforestation, because sufficient cost-effective biomass applications are lacking. Wood recovery from forests can be increased by 30%. Depending on the GHG policy targets, biomass use ranges from 200 Mt dry matter to 650 Mt dry matter. The more ambitious the emission mitigation targets, the higher is the biomass use. This biomass is used for transportation fuels and for feedstocks for plastics and other synthetic organic materials. Energy recovery from waste is also relevant. Electricity production from clean biomass is not an attractive strategy because of the large number of cost-effective competing alternatives for emission mitigation in this market.

The contribution to GHG emission mitigation is elaborated in Table S.1. The table shows that the technical potential is significantly higher than the economic potential. The former one is based on bottom-up estimates, the latter one is based on MARKAL MATTER 4.2 calculations. The difference between both potentials is very significant. This difference can be attributed to the consideration of competing land use options, the consideration of competing emission mitigation options and the consideration of interactions between emission mitigation options (e.g. increased energy efficiency reduces the potential for emission reduction in energy supply). The results show the importance of taking these factors into account. Neglecting these factors results in an overestimation of the emission reduction potential by a factor three.

Table S.1 *The relevance of biomass GHG strategies: techno-economic potentials, 2030*

Strategy	Technological potential[1] [Mt CO_2 eq]	Economic potential[2] [Mt CO_2 eq]
Afforestation/soil carbon	180	150
Carbon storage in products	105	25
Energy substitution	400	100
Materials substitution	500	100
Energy recovery from waste	100	25
Total	1285	400

The economic biomass emission reduction potential of 400 Mt CO_2 equivalents still represents 9% of the 1990 emissions.

A number of cases have been analysed, based on a mix of different policy instruments. The results show that the selection of appropriate policy instruments is a decisive factor with regard to the development of future biomass strategies. Pricing instruments seem more appropriate than specific regulations, given the flexibility but uncertainties with regard to optimal technology selection and biomass availability. Significant costs can be saved and significant efficiency gains are possible in case the appropriate approach is selected. The gains can amount to 100 billion EURO and 500 Mt emission reduction in 2030. According to the model calculations the optimal biomass use for energy and materials ranges from 250-350 Mt dry matter in the base case up to 525-600 Mt at a penalty level of 200 EURO/t CO_2.

Significant efforts have been put into the techno-economic characterisation of the technologies that must be developed in order to develop biomass strategies successfully. The inventory shows that significant technological progress is imminent in a number of biomass supply and demand areas. However, a number of competing technologies are being developed simultaneously. In many cases it is uncertain as of yet which technology will be the best. For this reason it is recommended to apply generic pricing policy instruments instead of regulations that prescribe specific technologies. A clear and reliable long term policy target is recommended in order to enable a timely industrial change to appropriate GHG extensive production tech-nologies. Moreover the international carbon leakage problem must be solved before these policies can be applied in practice.

Biomass strategies are influenced by many conflicting policy areas. In this case it involves GHG policies, other environmental policies, agricultural policies and industry policies. For example the European agricultural subsidy scheme, currently representing half of the annual budget, will be significantly affected by GHG policies. If 20% of the agricultural land area would be afforested, as the model calculations suggest, this would have major impacts on rural development, especially in Southern Europe. Integrated policy development is recommended in order to prevent undesirable side effects.

[1] Estimated on the basis of 10 Mha biomass crops, current reference system, not considering costs or interactions.
[2] Characterised by the GHG emission mitigation contribution at a permit price of 200 EUR/t CO_2.

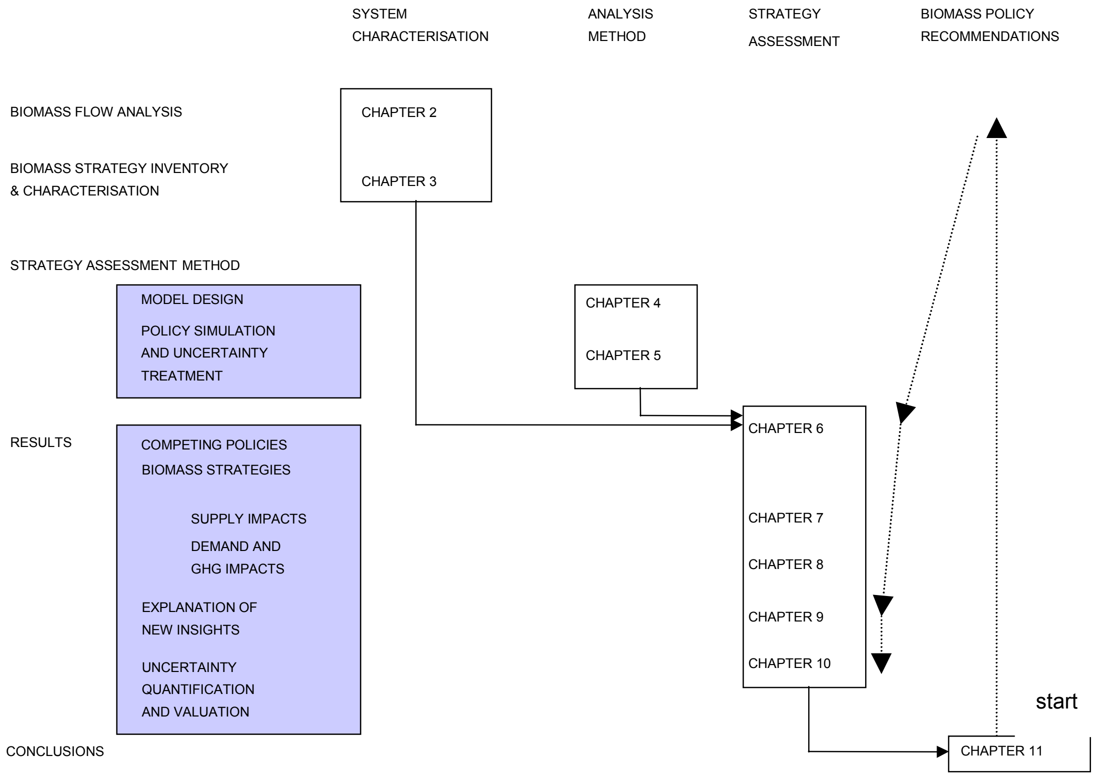


Figure S.1 *Recommended reading scheme for policy makers*

SUMMARY FOR INDUSTRY

Greenhouse gas (GHG) emission mitigation is currently one of the main environmental policy problems. While the actual dangers of climate change are still unclear as of yet, policies are currently being developed to reduce GHG emissions in order to decrease the risk of undesirable environmental impacts on the long term. While the European Kyoto target of 8% emission reduction in the period 2008-2012 will only have limited impact, ambitious long-term emission reduction targets of 50-75% would have a more serious impact. This study analyses the impact of such ambitious long-term policy targets.

One possible group of strategies to reduce GHG emissions is based on the introduction of biomass as a substitute for fossil energy carriers and materials. Bioenergy can be applied for heating, as a feedstock for transportation fuels and for electricity production. Biomass can also be used for materials, e.g. the production of paper, for construction materials and as a feedstock for plastics and other synthetic organic products.

A large number of studies exists that focus on biomass for GHG emission mitigation. However the scope of these studies is limited: they do not consider costs and they do not account for alternative emission mitigation options. In order to solve these shortcomings, a new method has been developed. This method is based on an integrated energy and materials systems engineering model for Western Europe, called MARKAL MATTER 4.2.

The relevance of individual biomass strategies has been assessed. The potential is elaborated in Table S.2. The column with technological potentials is based on bottom-up estimates, the column with economic potentials is based on MATTER model calculations. The results show a considerable difference between the technological potentials and the economic potentials. Energy and materials substitution together are of similar importance as carbon storage in new forests and carbon storage in soils.

Table S.2 *The relevance of biomass GHG strategies: techno-economic potentials, 2030*

Strategy	Technological potential[3] [Mt CO_2 eq]	Economic potential[4] [Mt CO_2 eq]
Afforestation/soil carbon	180	150
Carbon storage in products	105	25
Energy substitution	400	100
Materials substitution	500	100
Increased production efficiency	100	Pm
Energy recovery from waste	100	25
Recycling/reuse	100	Pm

Regarding bioenergy, the development of bio-transportation fuels seems a promising strategy for GHG emission reduction. The production of ethanol and Ethyl Tertiary Butyl Ether (ETBE) from lignocellulose biomass, as well as a new type of biodiesel based on Hydro Thermal Upgrading (HTU) are promising technologies according to the model. However methanol and Di-Methyl Ether (DME) come close to these promising technologies with regard to cost-effectiveness. Fischer Tropsch biodiesel seems less attractive. Rapeseed Methyl Ester (RME) and ethanol from sugar crops seems no viable long-term strategy because of the high costs of the resources.

[3] Estimated on the basis of 10 Mha biomass crops, current reference system, not considering costs or interactions.
[4] Characterised by the contribution at a permit price of 200 EUR/t CO_2.

Energy recovery from processing waste and energy recovery from post-consumer waste seems also an attractive strategy. Gasification of black liquor and energy recovery from kitchen waste, from waste wood and from waste paper can contribute significantly to emission reduction.

Regarding biomaterials, the introduction of biomass feedstocks as a substitute for fossil fuel feedstocks for petrochemical products seems an attractive strategy. This introduction can be based on a combination of flash pyrolysis technologies and fermentation technologies. The introduction of more wood building materials and the introduction of paper packaging materials seems of secondary importance.

However, any such ambitious emission mitigation target poses a danger of international trade distortions. This is the first problem that must be solved before such comparatively costly emission mitigation strategies can be introduced. Moreover, because of the long life of industrial capital equipment, the introduction of such strategies will require a period of decades. However it seems appropriate to start R&D timely. In case the relevance of GHG emission mitigation increases in the future, the industries that are prepared will benefit significantly and biomass can pose an attractive business opportunity. Many technologies which have been identified in this study are not yet applied on a commercial scale. It remains to see which technologies will succeed eventually and who will reap the benefits.

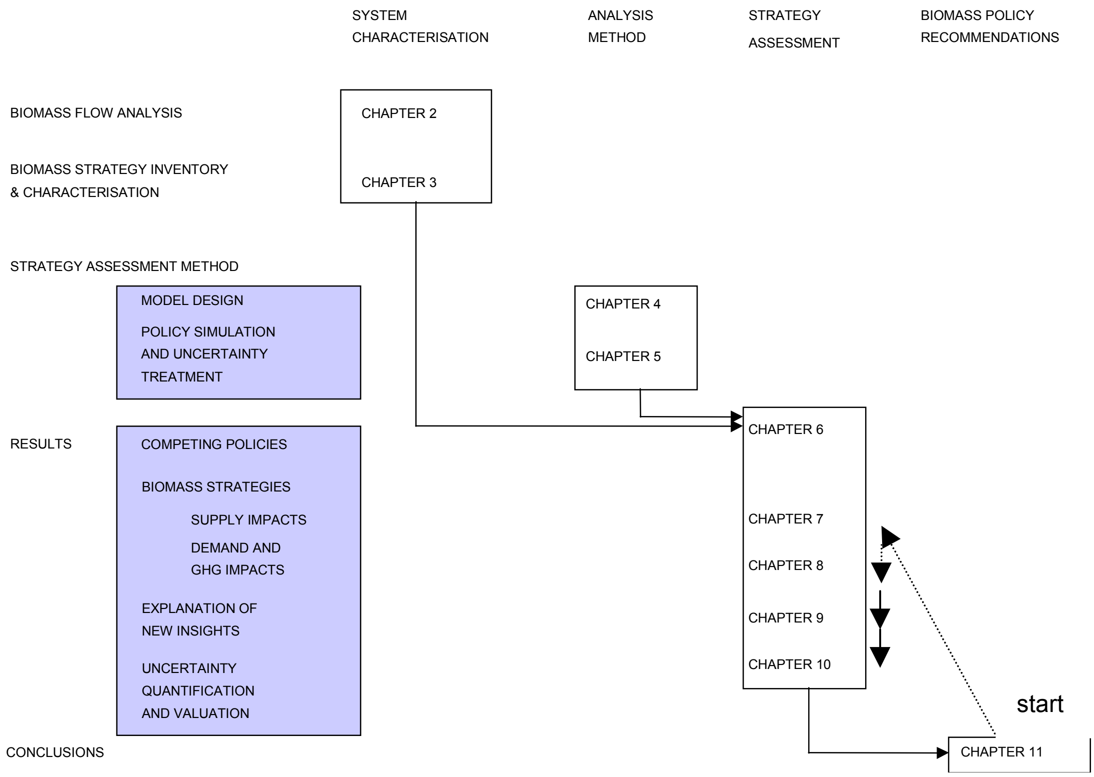


Figure S.2 *Recommended reading scheme for industry*

SUMMARY FOR FARMERS AND FOREST INDUSTRIES

This study focuses on the long-term impact of significant greenhouse gas (GHG) emission reduction on the structure of the Western European economy. Agriculture and forestry are closely linked to the natural carbon cycle, because atmospheric carbon is stored in forests and in agricultural crops. Contrary to the combustion of fossil fuels such as coal, oil and natural gas, agricultural and forestry products do not add to the global CO_2 emissions: the CO_2 emission in the product life is the same as the initial CO_2 storage in living biomass. This feature can be used for development of emission reduction strategies (called 'biomass strategies'). The agricultural and forestry sector can contribute significantly to emission reduction and can benefit significantly from such environmentally friendly activities.

On one hand, the carbon pool in agriculture and forestry and their products can be increased. Because of the carbon uptake from the atmosphere, CO_2 concentrations in the atmosphere will be reduced. This net increase of the carbon pool can be booked as a reduction of CO_2 emissions. This fact is the basis for 'carbon storage' strategies: carbon storage in afforestations (new forests on formerly agricultural land), carbon storage in soils and carbon storage in an increasing product volume in the economy.

On the other hand, agricultural products and forestry products can be used for substitution of fossil fuels. These products can be used directly for substitution of fossil fuels and they can be used for substitution of other materials. Because the production of other materials such as plastics and steel requires significant amounts of fossil energy, this results indirectly also in a significant emission reduction. Biomass can also be used in a cascade of applications: first as a material, next as an energy carrier.

The application of these strategies is limited by the availability of land and it is limited by the productivity of this land. The availability of agricultural land depends on the land requirements for food and fodder production, which will remain the dominant agricultural land use type.

Biomass strategies must compete with a number of other emission reduction strategies. For example in electricity production, biomass must compete with other renewable energy sources such as wind energy, solar energy, etc.. Not only competition, but also interactions of emission mitigation strategies must be considered for proper assessment. For example if the energy efficiency of steel production improves, the emission reduction which can be achieved through steel substitution decreases.

Competition exists for scarce biomass and land resources. Competition exists also between biomass strategies and other non-biomass related emission reduction strategies. Moreover all types of emission reduction options interact. Because of these reasons an integrated assessment of GHG emission mitigation strategies is required, beyond the agriculture and forestry sector. For this purpose a so-called energy and materials systems engineering model has been applied, called MARKAL MATTER 4.2. This model covers the life cycle of all energy carriers and materials 'from cradle to grave' and selects emission reduction strategies on the basis of cost-effectiveness. The model has been applied for the analysis of long term strategies for the period 2000-2050.

A detailed agricultural module has been added to the model, covering all types of land use, including food and fodder. A significant effort has been put into the characterization of existing and future productivity and costs of crops, short rotation forest plantations and afforestations, as well as the conversion of these resources to energy carriers and materials. These 'technology data' have been added to the existing database.

The results are shown in Table S.3. Biomass strategies are listed, and their contribution to emission mitigation is listed in two columns. The first column is based on back-of-the-envelope calculations, the second column is based on the model calculations. The model calculations show an emission reduction potential which is reduced compared to the first column, but which is still very substantial. The total emission reduction potential is 400 Mt, which equals 9% of the 1990 emissions. Carbon storage in afforestations and soils dominates, followed by energy substitution and materials substitution. The other strategies are of secondary importance from a GHG emission reduction point of view. The afforestations dominate in Southern European areas with low quality soils.

Table S.3 *The relevance of biomass GHG strategies: techno-economic potentials, 2030*

Strategy	Technological potential[5] [Mt CO_2 eq]	Economic potential[6] [Mt CO_2 eq]
Afforestation/soil carbon	180	150
Carbon storage in products	105	25
Energy substitution	400	100
Materials substitution	500	100
Energy recovery from waste	100	25

The results show a significant change in land use. Between 25 Mha and 30 Mha, 17-20% of the agricultural land, can be used for biomass strategies. However this land becomes only available when high incentives like 200 EUR/t CO_2 are given. More than three quarters of this land is used for afforestations, because there is no need for additional biomass use for energy or materials substitution. This shows that biomass availability does not pose a main problem, but the cost-effectiveness of energy and materials substitution does. Between 4 Mha and 10 Mha will be used for energy and materials crops. The area depends on the GHG policy ambitions and the policy instruments that are selected. This land is especially used for Eucalyptus plantations and other perennial forest plantations and crop types. Such land use is different from the current annual food and fodder crop rotations. It will require a major change of attitude in the agricultural sector. This is a significant barrier for the implementation of any of these land use change strategies.

The results indicate a switch to afforestation in Southern Europe, but only limited change of land use in Middle Europe. This would imply a serious change of farming practices in Southern Europe. This is typically the region where small scale, labour intensive farming still dominates. It remains to see if such drastic changes are acceptable to society. Anyway such policies cannot be implemented without accompanying social policy measures.

Regarding the application of biomass for energy and materials, transportation fuels and feedstocks for synthetic organic materials seem attractive. These new markets require co-operation with the petrochemical industry and refineries, parties that are not accustomed to agricultural practices. It is recommended to develop pilot projects of sufficient scale to establish such practices timely.

The value of land will increase significantly if GHG permit prices are introduced. This is beneficial for land owners, but it will also result in an increase of the production costs in Europe. Emission permit prices of 100 EUR/t and higher can seriously affect the competitive position of the European agriculture and forestry industry, if foreign producers are not affected by similar policies.

[5] Estimated on the basis of 10 Mha biomass crops, current reference system, not considering costs or interactions.
[6] Characterised by the contribution at a permit price of 200 EUR/t CO_2.

In conclusion, especially agriculture will be affected significantly by GHG policies. The land requirements for GHG policies can result in a decreasing competitive position of the European agricultural sector, if the wrong incentives are applied and accompanying policy measures are lacking. The impacts of forestry are predominantly positive: the increasing quantity of wood available from existing forests can be sold at attractive prices. The biomass contribution to GHG emission mitigation is significant, representing 9% emission mitigation compared to 1990 levels. This is significant contribution, but it is not the single solution to the GHG problem. The contribution could increase further if large scale plantations and afforestations are introduced in other world regions.

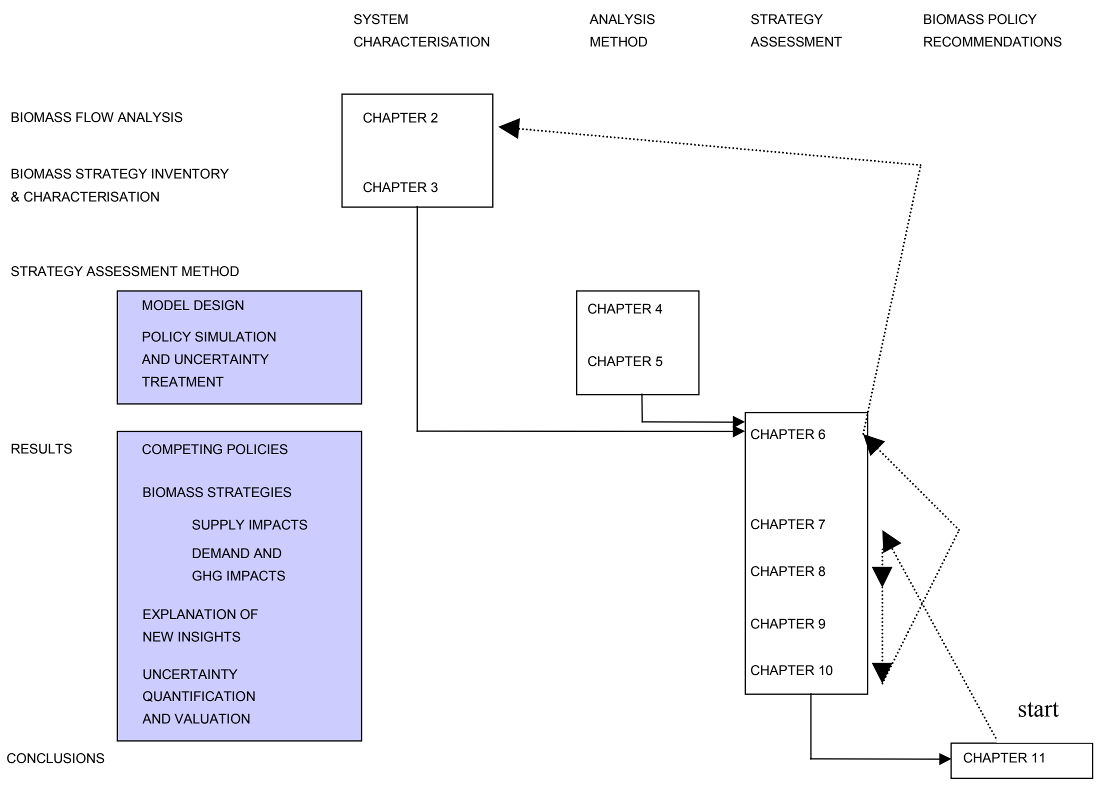


Figure S.3 *Recommended reading scheme for farmers and forest industries*

SUMMARY FOR SCIENTISTS

This study focuses on the long term impact of significant greenhouse gas (GHG) emission reduction on the structure of the Western European economy. Agriculture and forestry are closely linked to the natural carbon cycle, because atmospheric carbon is stored in forests and in agricultural crops. Contrary to the combustion of fossil fuels such as coal, oil and natural gas, agricultural and forestry products do not add to the global CO_2 emissions: the CO_2 emission in the product life is the same as the initial CO_2 storage in living biomass. This feature can be used for development of emission reduction strategies (called 'biomass strategies').

On one hand, the carbon pool in agriculture and forestry and their products can be increased. Because of the carbon uptake from the atmosphere, CO_2 concentrations in the atmosphere will be reduced. This net increase of the carbon pool can be booked as a reduction of CO_2 emissions. This fact is the basis for 'carbon storage' strategies: carbon storage in afforestations (new forests on formerly agricultural land), carbon storage in soils and carbon storage in an increasing product volume in the economy.

On the other hand, agricultural products and forestry products can be used for substitution of fossil fuels. These products can be used directly for substitution of fossil fuels and they can be used for substitution of other materials. Because the production of other materials such as plastics and steel requires significant amounts of fossil energy, this results indirectly also in a significant emission reduction. Biomass can also be used in a cascade of applications: first as a material, next as an energy carrier.

The application of these strategies is limited by the availability of land and it is limited by the productivity of this land. The availability of agricultural land depends on the land requirements for food and fodder production, which will remain the dominant agricultural land use type.

Biomass strategies must compete with a number of other emission reduction strategies. For example in electricity production, biomass must compete with other renewable energy sources such as wind energy, solar energy, etc.. Not only competition, but also interactions between emission mitigation strategies must be considered for proper assessment. For example if the energy efficiency of steel production improves, the emission reduction which can be achieved through steel substitution decreases.

Competition exists for scarce biomass and land resources. Competition exists also between biomass strategies and other non-biomass related emission reduction strategies. Moreover all types of emission reduction options interact. Because of these reasons an integrated assessment of GHG emission mitigation strategies is required, beyond the agriculture and forestry sector. For this purpose a so-called energy and materials systems engineering model has been applied, called MARKAL MATTER 4.2. This model covers the life cycle of all energy carriers and materials 'from cradle to grave' and selects emission reduction strategies on the basis of cost-effectiveness. The model has been applied for the analysis of long term strategies for the period 2000-2050.

A detailed agricultural module has been added to the model, covering all types of land use, including food and fodder. A significant effort has been put into the characterisation of existing and future productivity and costs of crops, short rotation forest plantations and afforestations, and the conversion of these resources to energy carriers and materials. These 'technology data' have been added to the existing database.

The results are shown in Table S.4. Biomass strategies are listed, and their contribution to emission mitigation is listed in two columns. The first column is based on back-of-the-envelope calculations, the second column is based on the model calculations. The model calculations show an emission reduction potential which is reduced compared to the first column, but which is still very substantial. The total emission reduction potential is 400 Mt, which equals 9% of the 1990 emissions. Carbon storage in afforestations and soils dominates, followed by energy and materials substitution. The other strategies are of secondary importance from a GHG emission reduction point of view. The afforestations dominate in Southern European areas with low quality soils.

Table S.4 *The relevance of biomass GHG strategies: techno-economic potentials, 2030*

Strategy	Technological potential[7] [Mt CO_2 eq]	Economic potential[8] [Mt CO_2 eq]
Afforestation/soil carbon	180	150
Carbon storage in products	105	25
Energy substitution	400	100
Materials substitution	500	100
Energy recovery from waste	100	25

The results differ significantly from earlier studies. The differences can be attributed to a number of distinct methodological features:

- cost accounting,
- cost discounting,
- endogenisation of technological change,
- endogenisation of co-production and market volumes,
- endogenisation of life span capital equipment,
- electricity load curve and heat demand load curve accounting,
- consideration of competing emission reduction options,
- consideration of afforestation,
- consideration of materials strategies.

The bulk of the surplus agricultural land is used for afforestation. However this land becomes only available in case high incentives of 200 EUR/t CO_2 are given. More than three quarters of this land is used for afforestations, because there is no need for additional biomass use for energy substitution of materials substitution. This shows that biomass availability does not pose a main problem, but the cost-effectiveness of energy and materials substitution does.

Regarding the application of biomass for energy and materials, transportation fuels and feedstocks for synthetic organic materials seem attractive. R&D conclusions on a more specific level are limited by data quality, technology upscaling results and uncertainties regarding future policies. It is thus recommended to develop competing techniologies and decide at a later stage which one is the most promising.

[7] Estimated on the basis of 10 Mha, current reference system, not considering costs or interactions.
[8] Characterised by the contribution at a permit price of 200 EUR/t CO_2

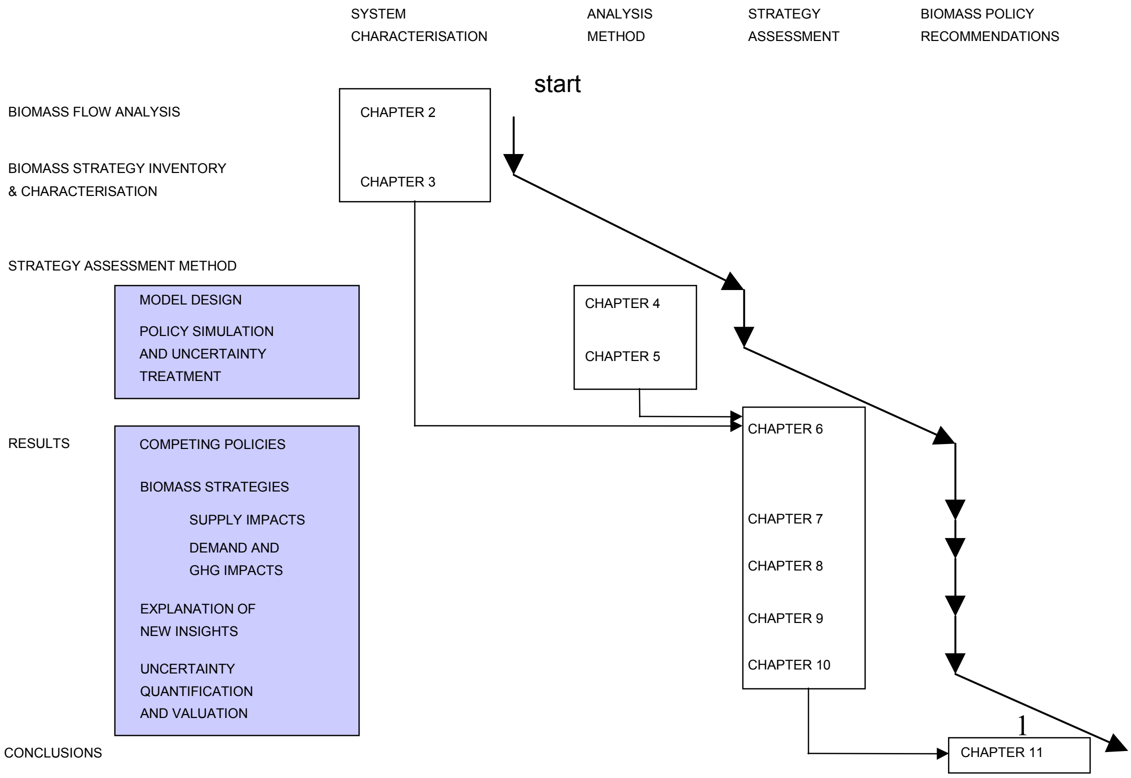


Figure S.4 *Recommended reading scheme for scientists*

1. INTRODUCTION

1.1 The climate change policy issue

This study is a contribution to the problem of greenhouse gas (GHG) emission reduction. The background and structure of the study will be discussed in this chapter. The global climate change problem will be explained first of all. GHG emissions are at the root of the climate change problem. A number of strategies have been proposed to reduce these emissions. Significant GHG emission reduction will be both difficult and costly. As a consequence, it is worthwhile searching for new emission reduction strategies. A major part of the GHG emissions, especially a significant part of the carbon dioxide (CO_2) emissions, can be reduced through changes in energy and materials production and consumption. *This study analyses to what extent biomass strategies can contribute to cost-effective GHG emission reduction on a West European scale over the next few decades, and which technologies must be developed to achieve such a reduction.* The study has been funded by the European Commission, DG Research, in the framework of the Environment and Climate programme and by the Netherlands Energy Research Foundation ECN. This report is the product of task 8 of the BRED project: the integrated model analysis.

The greenhouse effect is caused by atmospheric trace gases that permit incoming solar radiation to reach the Earth's surface unhindered, but restrict the outward flow of infrared radiation. These atmospheric trace gases are referred to as greenhouse gases. They absorb and reradiate this outgoing radiation, effectively storing some of the heat in the atmosphere, thus producing a net warming of the surface. Greenhouse gases have always been important for the earth's climate. Without this effect, the earth would be much colder. Mankind has added significant amounts of greenhouse gases to the atmosphere since the start of the industrial revolution. The concentration of these gases in the atmosphere has increased significantly over the past 100 years. For example the atmospheric concentration of CO_2 has increased by 30% since pre-industrial times (i.e. since about 1750) (see p. 16 the Intergovernmental Panel on Climate Change IPCC (Houghton et al, 1996). Because of the greenhouse effect, a rising greenhouse gas concentration in the atmosphere could result in a significant increase in global mean surface air temperature. The assumption is that this climate change will result in a number of detrimental effects for humans and for the environment. Higher sea water levels, desertification of large regions, and a decreased diversity of flora and fauna are examples of potential negative consequences. In other regions, positive effects may occur such as an increased agricultural production.

However, climate change effects have not been proven as yet, and the consequences of climate change are even more uncertain. Research has shown an increase in the average global temperature over the last 100 years. Global mean surface air temperature has increased by between 0.3 and 0.6°C since the late 19th century (according to IPCC: Houghton et al, 1996). However, there is still no conclusive evidence that this temperature increase is the result of the increased concentration of greenhouse gases. Especially the *extent* of the temperature increase that can be attributed to the increased concentration of greenhouse gases is under debate. Moreover the global mean surface temperature is only an indicator for climate change. Regional temperature changes can differ substantially from the global mean value. The regional impacts on precipitation and ecosystems are still not clear. This regional variability complicates the validation of climate models and the validation of models of climate change consequences on the basis of historical climate data. However, IPCC states that 'the balance of evidence suggests a discernible human influence on global climate' IPCC (Houghton et al., 1996).

The majority of the scientists and many policy-makers agree that in order to reduce the risk of significant climate change major emission reduction makes sense. In the spring of 1997 national governments of 165 countries agreed to strive for greenhouse gas emission reduction. These efforts are co-ordinated by the United Nations Framework Convention on Climate Change (UNFCCC). This convention has been signed by all industrialised countries. The ultimate objective is '...stabilisation of greenhouse gas emissions at a level that would prevent dangerous anthropogenic interference with the climate system. Such a level should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened and to enable economic development to proceed in a sustainable manner'. In December 1997, a treaty was drafted regarding the reduction of West European, North American and Japanese emissions in the period 2008-2012 by 6-8%, compared to the emissions in the reference year 1990 or 1995 (UNFCCC, 1997b). Such an emission reduction can have a significant impact on the economy. Because of this treaty and its economic consequences, GHG emission mitigation is currently an important issue on the political agenda.

Six categories of GHG emissions are considered under the UNFCCC protocol signed in Kyoto in December 1997:
- carbon dioxide (CO_2),
- methane (CH_4),
- nitrous oxide (N_2O),
- perfluorocarbons (PFCs),
- hydrofluorocarbons (HFCs),
- sulphurhexafluoride (SF_6).

The countries of the European Union (EU) agreed to an 8% reduction in their total emissions of GHGs in the period 2008-2012, compared to the emissions in the reference year (i.e. 1990 for CO_2, CH_4 and N_2O; 1995 for PFCs, HFCs and SF_6). Table 1.1 shows the emissions for the reference years.

Table 1.1 *West European emissions of greenhouse gases in the reference year 1990 /1995 (CO_2, CH_4, N_2O based on (UNFCCC, 1997a); PFC, HFC and SF_6 based on (Gielen, Koutstaal, Kram and Van Rooijen, 1998), additional data estimated in (UNFCCC, 1997c)*

	CO_2 1990 [Mt CO_2 eq]	CH_4 1990 [Mt CO_2 eq]	N_2O 1990 [Mt CO_2 eq]	PFC 1995 [Mt CO_2 eq]	HFC 1995 [Mt CO_2 eq]	SF_6 1995 [Mt CO_2 eq]	TOTAL [Mt CO_2 eq]	Land area [1000 km]
Austria	62	12	4	0.0	0.3	1.3	80	83.9
Belgium	106	13	10	0.1	0.6	0.5	130	30.5
Denmark	52	9	11	0.0	1.0	0.4	73	43.1
Finland	53	5	6	0.0	0.1	0.1	64	338.1
France	378	63	56	0.7	1.9	0.5	500	544.0
Germany	1003	119	70	1.7	3.2	6.0	1203	357.0
Greece	84	9	5	0.7	1.0	0.4	100	132.0
Ireland	31	17	9	0.0	0.5	0.3	58	70.3
Italy	410	49	51	0.1	3.1	0.3	514	301.3
Luxembourg	13	0.5	0.2	0.0	0.1	0.1	14	2.7
Netherlands	161	27	20	2.4	6.7	1.5	219	41.5
Norway	36	9	5	1.4	0.2	0.6	52	323.9
Portugal	45	17	4	0.0	0.9	0.4	67	92.4
Spain	208	46	29	4.5	6.5	0.2	294	506.0
Sweden	56	7	3	0.4	0.2	1.2	68	450.0
Switzerland	45	5	4	0.1	0.3	0.7	55	41.3
UK	580	93	63	0.6	15.4	0.7	753	244.1
Total	3323	500	350	12.7	42.0	15.2	4250	3602.1

The Kyoto Protocol can be considered as a first step towards GHG emission control. It is an indication that some governments are willing to reduce emissions, in spite of potentially serious economic consequences. However, further emission reductions are required in industrialised countries beyond the Kyoto Protocol time horizon. The Kyoto negotiation result may even be a mixed blessing because it can obscure the focus on significant emission reduction on the long term (Jacoby, Prinn and Schmalensee, 1998). It is still unclear as of yet if the Kyoto Protocol will be ratified. This uncertainty however, is not relevant for this analysis. This study focuses on the long term perspective for the first half of the 21st century. It will show how significant emission reductions can be achieved on the long term at acceptable costs.

1.2 The relation between the natural carbon cycle and GHG emissions

Biomass is produced by plants that fix CO_2 from the atmosphere. Renewable biomass is a CO_2 neutral resource. Nowadays, biomass is the basis of many economic activities. Biomass can be used for energy applications and for materials. Biomass represents currently approximately 13% of the global primary energy use, mainly fuel wood in developing countries. Biomass is also widely applied for building materials and materials such as paper. Apart from energy and materials, the production of food represents a very dominant part of the physical economy. For example in Western Europe, food production represents a mass flow of approximately 1000 Mt dry matter per year, compared to 165 Mt steel or 500 Mt oil. All these biomass based activities constitute a sustainable and largely CO_2 neutral part of the economy, a fact which is often neglected in the sustainability discussion.

Living biomass is an important carbon stock. The total global biomass carbon quantity is approximately 500-600 Gt C (equivalent to 1830-2200 Gt CO_2). The bulk of this carbon (81%) is stored in forests. Another 1200-1900 Gt C (equivalent to 4400-7000 Gt CO_2) is stored in soil carbon (Kohlmaier et al., 1998). Net emissions from changes in tropical land use account for 1.6 ± 1.0 Gt C per year (5.9 Gt CO_2). Uptake by Northern Hemisphere forest regrowth accounts for a net storage of 0.5 ± 0.5 Gt C per year (1.8 Gt CO_2).

New forests on formerly agricultural soil and on degraded land can constitute an important strategy for carbon storage. A global plantation program as proposed by Nilsson and Schopfhauser (Nilsson and Schopfhauser, 1995) can result in 1 Gt C storage per year (3.7 Gt CO_2 per year). However the carbon storage strategy for GHG emission mitigation must compete with bioenergy and biomaterial strategies. This competition will be further elaborated in this study.

These high global potential estimates for biomass related activities for GHG emission mitigation must be moderated for Western Europe. This region represents 2.4% of the global land area (note the different country land areas in Table 1.1, an indicator of the relevance of countries to European biomass strategies). Its population, approximately 350 million people, represents 7% of the global population. The land area limits the potential for land intensive biomass strategies, while the population poses additional limitations because of competing land use for food production, production of materials such as paper and competing land use for buildings and infrastructure. At the same time the Western European per capita GHG emissions are high: approximately 9% of the global GHG emissions arise in Western Europe (mid-1990's figure).

Despite their limited potential, biomass strategies deserve special attention because of important secondary benefits. Apart from GHG emission reduction, the introduction of biomass strategies can enhance the sustainability of our economy and increase the European economic competitiveness if the appropriate policy goals are set. Moreover, biomass production can sustain rural communities that are currently threatened by reduction of European subsidies, overproduction and market liberalisation.

Biomass constitutes the only renewable carbon source. Carbon is a vital element for our economy. The bulk of carbon is currently used as an energy carrier (in fossil fuels: gas, oil and coal). Important quantities of carbon are used for engineering applications: in plastics, as a building material, for paper, as chemical reduction agent in iron production, etc.. While the energy function can largely be satisfied without carbon, the engineering applications require carbon input. Biomass can play a very important role as a renewable carbon source in a sustainable economy.

1.3 Biomass GHG emission accounting in the framework of the Kyoto Protocol

The definitions in the Kyoto Protocol have consequences for the relevance of biomass strategies for GHG emission reduction. The definitions in the Kyoto Protocol regarding biomass are not clear. A detailed analysis of possible interpretations is currently on its way in the IPCC special report on forestry and land-use change, scheduled for May 2000 (Marland and Schlamadinger, forthcoming). Only stock changes in forests (possibly including forest soils) caused by the direct human activities afforestation, reforestation and deforestation, and taking place in the 'first commitment period' (2008-2012) are of interest. Credits are limited to projects initiated since 1990. For actions taken as part of the 'clean development mechanism' (CDM) for developing countries, banking of emission reductions is allowed from the year 2000 until 2008. CDM implies that Annex 1 countries (that signed the UN Framework Convention on Climate Change FCCC) can obtain from non-Annex 1 countries 'certified emission rights', which they can apply to achieve compliance with their reduction commitments. The current definitions suggest that certified emission reduction credits could be generated through prevention of deforestation in tropical countries. This is a potential loophole in the protocol because the definition of the baseline is not clear (Schmidt, 1998). However, this part of the biomass issues relating to the Kyoto Protocol are not considered in this study which focuses on Western Europe. More important for this study is that stock changes related to products and waste disposal sites seem to be excluded (Schlamadinger and Marland, 1998; Marland and Schlamadinger, 1998). Moreover the significant net carbon storage due to the increasing wood volume in the existing Western European forest stock cannot be accounted because these forests have been planted before 1990.

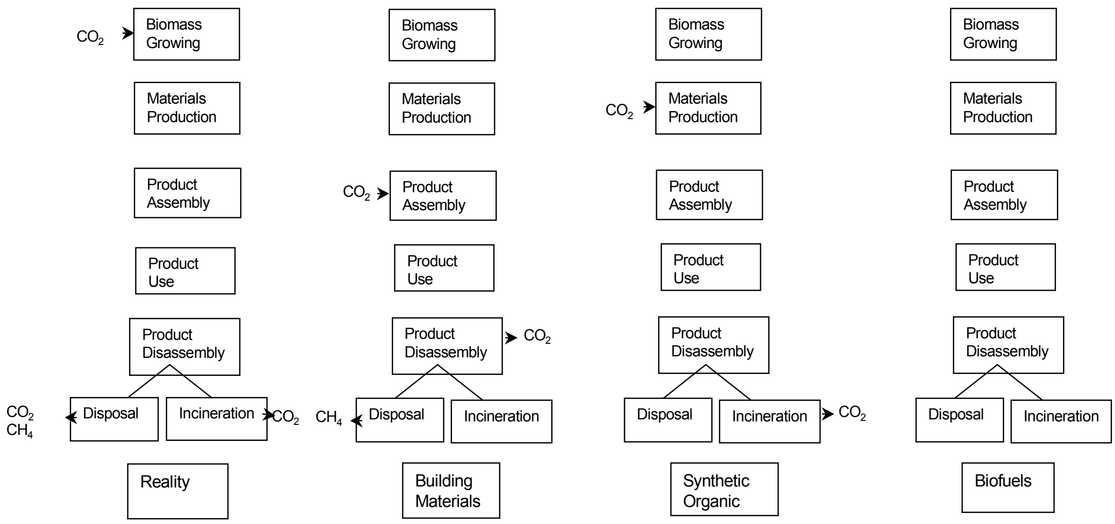


Figure 1.1 *Biomass GHG emission accounting according to the IPCC emission accounting guidelines, short rotation plantations on agricultural land*

According to these vague definitions, different biomass carbon flows must be treated differently with regard to carbon accounting. This is illustrated for products from short rotation agricultural plantations in Figure 1.1. The accounting differs substantially from the real GHG flows. Moreover, different product types are treated differently which adds to the confusion. The figure illustrates the complexity of carbon flow accounting, a potential source of errors and policy misconceptions.

In the BRED project, the general approach for accounting is to split carbon storage accounting for biomass growing and carbon storage accounting for biomass products (in line with the IPCC approach). Biomass growing can be split into short rotation crops, long rotation plantations, afforestations and existing forests. For short rotation crops, carbon storage is not accounted because the quantities are negligible. For long rotation plantations and afforestations, the carbon uptake in trees and soil is considered as carbon storage, which is released at the moment the trees are harvested (at the end of the plantation life). For wood from existing indigenous forests, no carbon storage or carbon release is modelled if no net deforestation occurs on a national scale (in line with the Kyoto Protocol). For imports of wood from other regions which results in deforestation, some of these emissions can be allocated to the timber industry[9].

In conclusion, the IPCC definitions are important for the carbon accounting and for biomass strategies. However, definitions in the Kyoto Protocol are still not clear. Moreover, they may change in the period beyond 2012. For this reason, some flexibility must be applied regarding the implications of the definitions in the Kyoto Protocol for the current modelling study. This is part of the sensitivity analysis (see Chapter 10).

1.4 Western European GHG emissions and their relation with biomass

Primary biomass resources can be split into two categories: forestry derived biomass and agricultural biomass. West European forests represent a net carbon sink. The situation is different outside Western Europe. Especially tropical rainforests are still used in a non-renewable manner, among other reasons for timber production[10]. Part of this timber is exported to Western Europe. This deforestation results in a net CO_2 emission. Because the materials consumption takes place in Europe, these emissions can be attributed to West European consumption[11].

The relevance of biomass for the greenhouse gas balance extends beyond CO_2 emissions. Significant amounts of CH_4 are produced in landfill sites and during manure storage. This methane results from the anaerobic digestion of biomass by micro-organisms. Ruminants use basically the same process for their digestion. This emission source will not be discussed in more detail as it can be allocated to food production. The bulk of the N_2O emissions arises in agriculture. Micro-organisms in the soil convert part of both natural nitrogen fertilisers and synthetic nitrogen fertilisers into N_2O. CH_4 and N_2O are on a weight unit basis more powerful greenhouse gases than CO_2. Based on a time horizon of 100 years, the global warming potential (GWP) for CH_4 is 21 and the GWP for N_2O is 310[12]. Table 1.2 shows the greenhouse gas balance of biomass production and biomass use in Western Europe. All emissions (within Western Europe and abroad) that relate to Western European materials consumption have been considered. The table shows that the use of biomass results in a net CO_2 emission reduction (due to carbon storage and due to substitution of fossil fuels). The emission reduction of 440 to 565 Mt per year must be compared to a Western European CO_2 emission of approximately 3300 Mt: the net emission reduction caused by the biomass chain represents 13 to 17% of the total emissions. One must add that the 340 Mt annual net storage in existing forests cannot be accounted in the national emission balances, as these forests planted before 1990 are excluded from the Kyoto Protocol (see Section 1.3).

[9] This practice will stop on the long term, either because sustainable forestry management is introduced or because the forests disappear. As a consequence, the relevance of this emission source will decrease on the long term. For this reason it has not been analysed in great detail. Sustainable management of the remaining tropical forests is highly recommended for many other reasons but GHG emission mitigation.

[10] Tropical deforestation accounts for 1.7 Gt C per year, equivalent to approximately 20% of the global CO_2 emissions.

[11] Note that such relations are not accounted for in the Kyoto Protocol.

[12] The GWPs differ for a 20 and 500 year time horizon. This affects the selection of optimal emission reduction strategies (see also Chapter 10).

However, the positive effect on the CO_2 emissions is balanced by the net emission of CH_4 and N_2O. CH_4 and N_2O emissions are nowadays largely related to food production and food use (e.g. N_2O emissions from pastures used for cattle grazing; CH_4 emissions from cattle raising and emissions caused by disposal of kitchen waste). These emissions are not directly related to biomass in the sense of this study. The figures for the food chain are included here in order to indicate that a life cycle approach can reveal that biomass is not always a GHG neutral resource. The figures in Table 1.2 indicate that both CH_4 and N_2O must be considered in a proper analysis of the potential of biomass strategies for greenhouse gas emission reduction. Moreover biomass strategies may affect emissions in food and fodder production, an interaction which must be considered in the strategy assessment.

Table 1.2 *The relevance of West European biomass production for greenhouse gas emissions (GWP 100 years), 1994 (European Environmental Agency, 1999; Nabuurs, Päivinen, Sikkema and Mohren, 1997)*

	CO_2 [Mt CO_2 /year]	CH_4 [Mt CO_2 eq/year]	N_2O [Mt CO_2 eq/year]
Increasing forest stock/land use change	-340	-	-
Fertiliser use	-	-	200
Imported wood products[13]	25-50	-	-
Increasing product stock	-75	-	-
Landfills	-25	140	-
Enteric fermentation	-	140	
Manure management	-	40	
Energy production/recovery[14]	-50 - -150	-	-
Total	*-440 - -565*	*320*	*200*

1.5 Analysis of biomass strategies: state-of-the-art

The amount of literature regarding biomass for GHG emission mitigation is impressive (see e.g. Waupotitsch, Schlamadinger and Madlener, 1999). It is not possible to discuss all studies in detail. Looking at the conclusions there seem to be some national differences. These differences depend on resource availability, demand structure of the economy and other factors in the system that is studied. In the European GHG emission mitigation strategies the following can be noted:

- Biomass for energy has received most attention.
- Within this category, biomass use for electricity production is favoured (see e.g. European Commission, 1997b).
- Within this category, gasification is favoured (see e.g. ETSU, 1997a).
- Biomass based transportation fuels are of secondary importance (see e.g. International Energy Agency, 1994).
- Biomaterials production has not yet been analysed on a national or supra-national level, and existing studies have been done on a product level LCA approach (see e.g. Börjesson and Gustavsson, forthcoming).
- Afforestation has not yet received a lot of attention. The estimates for storage potentials differ considerably (see e.g. Department of Energy, 1999).
- Soil carbon is often mentioned, but the estimates of emission mitigation potentials for Western Europe vary tremendously from 50 to 450 Mt per year (see e.g. Nabuurs et al., 1999, l'Academie d'Agriculture de France, 1999).

[13] The bulk of the emissions associated with wood products is related to deforestation abroad. Allocation of wood production, agriculture, road building, etc. is problematic. This figure represents a lower estimate.
[14] Compared to average European power production with 0.1 t CO_2/GJe, assuming 25% efficiency in conversion.

- Many preceding studies often have been done from a very limited perspective, focusing on one sector or one technology (see e.g. Faaij, 1997). This is an important source of differing conclusions.
- Studies are inconsistent regarding the marginal costs of biomass strategies, ranging from very cheap to very expensive (see e.g. Hall, 1994, Ybema et al., 1999).

France, with its electricity production largely based on CO_2 free nuclear power, focuses on biomass use for transportation fuels and afforestations. Sweden, with its ample wood resources, is also seriously considering bioethanol production. Denmark and the Netherlands on the other hand, both countries with large coal fired power plants, focus on biomass use for electricity production. Finland and Austria, both countries with ample biomass resources and a largely rural population, focus on biomass use for residential heating.

The different conclusions can to a large extent be attributed to the analysis method applied in relation to the special biomass system characteristics. Biomass strategies have special features with regard to the long time period of forestry rotations. Often strong emphasis is put on technologies which are not yet proven on a commercial scale. A more comprehensive approach is required if the results must be used for GHG policies that encompass the whole economy.

1.6 Project goal and research questions

Starting from the EU policy goal for greenhouse gas emission reduction, the objective of the BRED project is: Analyse the optimal use of indigenous biomass for energy and materials 'from cradle to grave' in the Western European (EU+EFTA) economy, in order to achieve cost-effective greenhouse gas emission reduction on the long term (period 2000-2050). The goal is to provide a consistent and scientifically well founded set of recommendations for RD&D and investment policies for policy makers and for industry.

A regional systems analysis approach is applied in this study, covering the countries of the European Union and the European Free Trade Association[15]. The analysis is based on calculations with an extended version of a Western European integrated energy and materials systems MARKAL model.

A number of strategies have been proposed to reduce greenhouse gas emissions. With regard to biomass the substitution of CO_2 intensive energy carriers and materials as well as carbon storage in a biomass stock (either forests or products) have been recommended (e.g. Dewar and Cannel, 1992; Hall, Woods and House, 1992; Marland and Marland, 1992; Patel, Korell, Kopf and Theiss, 1998). In this study, all strategies involving biomass and alternative land use practices are referred to as 'biomass strategies'. However, the applicability of these strategies in Western Europe is limited by the land availability and the biomass yields per hectare. This limits the potential of the biomass strategy for CO_2 emission reduction.

The following questions will be answered in this study:
1. What are current biomass flows in the Western European economy (Chapter 2)?
2. Which strategies exist to reduce GHG emissions with biomass (Chapter 3)?
3. What are the techno-economic characteristics of biomass supply and demand (Chapter 4)?
4. What is the potential of biomass strategies to reduce GHG emissions (Chapters 3 and 8)?
5. Which technologies must be developed for these strategies (Chapters 7 and 8)?
6. What is the impact of the changing reference system for GHG emission reduction (Chapters 6 and 9)?

[15] This study covers Austria, Belgium, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom.

7. Can an integrated energy and materials biomass strategy increase the penetration of bio-energy (Chapters 7 and 8)?
8. What policies should be initiated (Chapters 10 and 11)?
9. How should uncertainties be treated in decision-making (Chapters 5, 10 and 11)?

1.7 Structure of the analysis

Figure 1.2 summarises the project structure and the contributions of the project partners. The data collection has been split into three parts:

- competing food production and energy production,
- forestry and wood products,
- agricultural energy and materials crops and feedstocks for petrochemicals.

These data have been integrated into the existing MATTER MARKAL model for Western Europe (see Chapter 4).

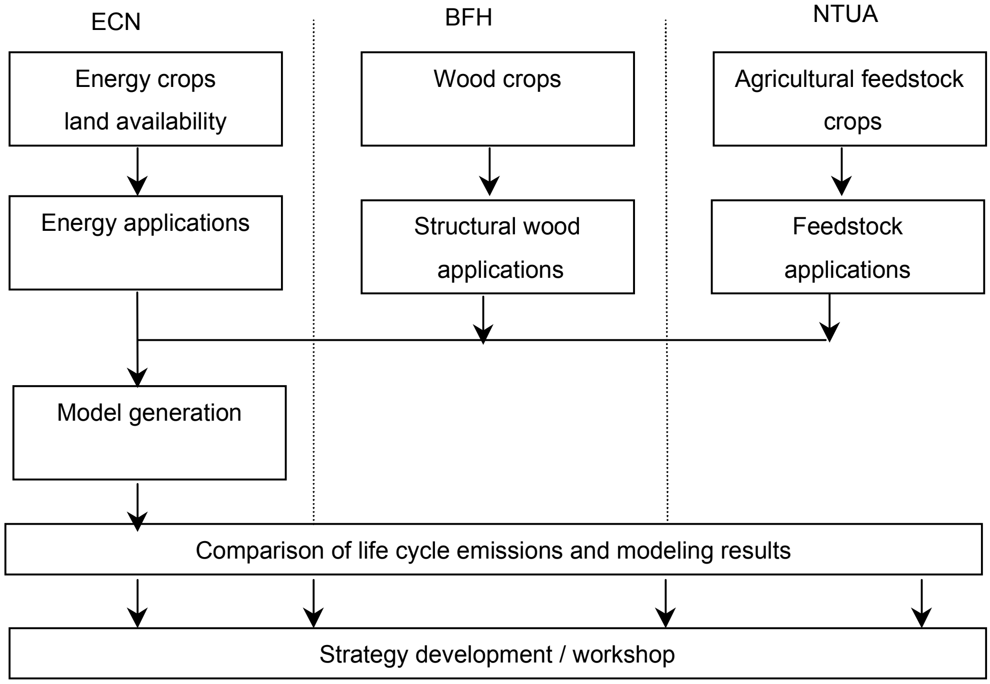


Figure 1.2 *General project structure*

Morgan and Henrion (1990) propose the following 'commandments' for good policy analysis:

1. Do your homework with literature, experts and users,
2. Let the problem drive the analysis,
3. Make the analysis as simple as possible, but not simpler,
4. Identify all significant assumptions,
5. Be explicit about decision criteria and policy strategies,
6. Be explicit about uncertainties,
7. Perform systematic sensitivity and uncertainty analysis,
8. Iteratively refine the problem statement and the analysis,
9. Document clearly and completely.

These guidelines have been followed in this project, both in the project structure design and in the reporting of the MARKAL modelling study. On a more abstract level, this project is one in a long series of biomass assessment studies of the Policy Studies unit of ECN, based on MARKAL modelling (e.g. Bos, 1991, Gielen and Van Doorn, 1995, Gielen, Lako, Dinkelbach and Van Ree, 1998). This sequence can be considered as an iterative approach. Based on the comments on one study, the modelling approach and databases for the next study are refined.

1.8 Structure of the reporting

This report discusses results for the MARKAL model analysis. A very significant part of the project efforts have been put at the collection of the proper model input data. These data have an important value by themselves. They can also be used for other environment-economy studies. Moreover, the reports with input data contain important background information such as data sources, data selection and data quality information. The analysis following in Chapter 2 (material flow analysis) and Chapter 3 (model structure for biomass) provides an abstract of the information in the background reports. Chapter 4 contains a description of the MARKAL MATTER model characteristics. Chapter 5 contains a discussion of the treatment of uncertainties in this study. Chapters 6-9 contain the discussion of the modelling results, split into a discussion of economic changes caused by GHG policies (Chapter 6, the framework in which biomass strategies must operate). The biomass supply side (Chapter 7) and the demand side (Chapter 8) are discussed separately. Chapter 9 contains an explanation of the most remarkable MARKAL results. Chapter 10 covers the uncertainties in the analysis and their consequences for the conclusions. Finally, Chapter 11 contains conclusions and policy recommendations. Figure 1.3 provides an overview of the structure of the reporting.

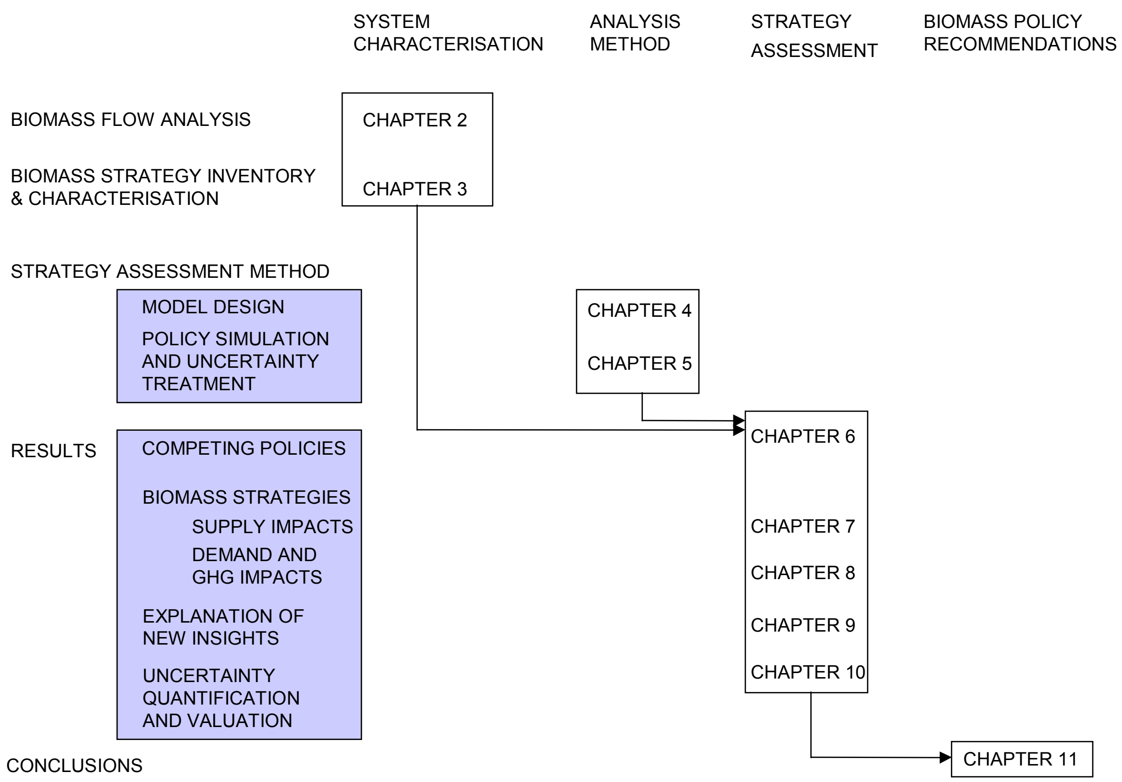


Figure 1.3 *Structure of the reporting*

More detailed information can be found in the following documents:

Model input data and model structure characterisation

Land availability

- T. Gerlagh: *Biomass for greenhouse gas emission reduction: Western European Land availability.* ECN-C--98-109. ECN, Petten, December 1998.
- T. Gerlagh, D.J. Gielen: *MATTER2.0. An agriculture and food module characterisation.* ECN-C--99-048, ECN, Petten, July 1999.

Agricultural crops

N. Diamantidis, E.G. Koukios: Biomass for Greenhouse Gas Emission Reduction. Agriculture as a Source of Biomass in Western Europe. NTUA, Athens, 1999.

Forestry, afforestations

M. Scharai-Rad, V. Sasse, J. Welling: Biomass for Greenhouse Gas Emission Reduction. Forestry and Forest Products Use in Western Europe. BFH, Hamburg, 1999.

Wood products and their applications

M. Scharai-Rad, J. Welling: Biomass for greenhouse gas emission reduction Task 4-6. BFH, Hamburg, 1999.

Feedstock applications

E.G. Koukios, N. Diamantidis: Biomass for greenhouse gas emission reduction Task 4-6. Techno-economic characterisation of biomaterials production. NTUA, Athens, 1999.

Energy applications

M.A.P.C. de Feber, D.J. Gielen: Biomass for greenhouse gas emission reduction. Task 7: Energy technology characterisation. ECN-C--99-078, ECN, Petten, December 1999.

Model structure characterisation

D.J. Gielen, T. Gerlagh, A.J.M. Bos: MATTER1.0. A MARKAL energy and materials system model characterisation. ECN-C--98-065. ECN, Petten, September 1998.

D.J. Gielen, T. Gerlagh, A.J.M. Bos: Biomass for Energy or Materials? A western European MARKAL MATTER1.0 model characterisation. ECN-C--98-066. ECN, Petten, November 1998.

Results

D.J. Gielen, T. Gerlagh, A.J.M. Bos: Biomass for greenhouse gas emission reduction (BRED). Paper presented at the Conaccount meeting, 21 November 1998, Amsterdam.

D.J. Gielen, A.J.M. Bos, T. Gerlagh: The MARKAL Systems Optimisation Model for Dynamic Life Cycle Analysis of Biomass Strategies for GHG Emission Reduction. In: D. Ceuterick (ed.): International conference on life cycle assessment in agriculture, agro-industry and forestry. Conference proceedings, 3-4 December 1998, Brussels. VITO, Mol.

D.J. Gielen, A.J.M. Bos, M.A.P.C. de Feber, T. Gerlagh: Reduction de l'émission de gaz à effet de serre en agriculture et foresterie. C.R. Acad. Agric. Fr., 1999, no. 6, Séance du 18 mai 1999.

N. Diamantidis, A.J.M. Bos, M.A.P.C. de Feber, D.J. Gielen, E.G. Koukios: Agricultural land availability for biomass production in Southern Europe as affected by the GHG emission reduction strategies. Forthcoming.

E.G. Koukios: Bio-products and the greenhouse effect: Results from ongoing research activity. IENICA newsletter number 6, February 1999.

D.J. Gielen, A.J.M. Bos, M.A.P.C. de Feber, T. Gerlagh: Biomass for energy or materials? The European BRED project. In: IEA Bioenergy Task 25 workshop proceedings, 27-30 September 1999, Gatlinburg, USA. Forthcoming.

D.J. Gielen, T. Gerlagh, M.A.P.C. de Feber, A.J.M. Bos: Bioethanol for GHG emission mitigation. A western European systems engineering perspective. Biofuels conference, Brussels, October 1999.
D.J. Gielen, A.J.M. Bos, M.A.P.C. de Feber, T. Gerlagh: Biomass for greenhouse gas emission reduction. Task 8: Optimal emission reduction strategies for Western Europe. (this report).
A.J.M. Bos (ed.): Biomass for greenhouse gas emission reduction. Task 9: workshop proceedings. ECN, Petten, forthcoming.

During the project, it was concluded that proper analysis of biomass strategies requires more insight into the total agricultural system. For this purpose, the model has been extended with a full agricultural module, beyond the scope of the original project plan (see Section 2.1). Moreover, a BRED internet site has been developed (http://www.ecn.nl/unit_bs/bred). All publications can be directly downloaded and printed from this site. The complete model input database is available via the internet site, as well as the model output files. In this way, maximum transparency and validation of the complex MATTER model are allowed.

1.9 Expert review of the study

This study was reviewed during an expert workshop in Brussels on 6 and 7 December 1999 (Bos, forthcoming). In total, 25 experts from the European Commission, from industry and from science participated in this meeting. The goal of the meeting was to discuss the model results and the development policy strategies on the basis of this study.

The experts concluded that the study reflects the complexity of the biomass problem very well. It is felt that the model contributes to an improved understanding of the complexity of the biomass issue. Within this study, fragmented biomass research and fragmented markets are treated in an integrated manner. This is an important value added of this study. This study gives insight in the interaction of competing land use options, competition between energy and materials use of biomass and competition of biomass strategies and other GHG emission reduction strategies.

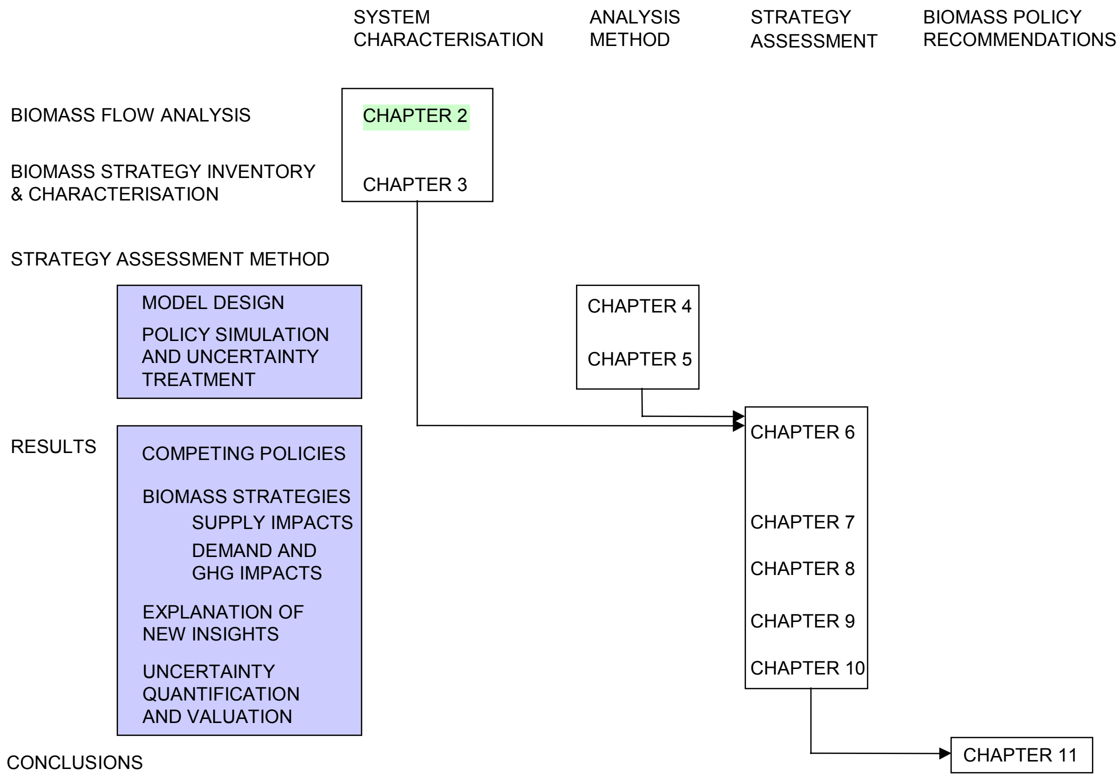
The EU has an ambitious GHG Kyoto target and this study can help to accomplish this goal. The fact that the research is funded by the Environment and Climate programme results in a positive connotation to this study for the general public and for many policy makers, which should be used in the dissemination. The 5th framework programme aims for key actions and sustainability, this study should be applied in this framework.

Regarding the results, the general opinion is that the application of the results in the next 5 years is not likely. The value added of the study is especially its thought provoking character, but a number of conclusions require further analysis before policies can be formulated. For example problems exist with regard to the other environmental impacts, which have not been considered (e.g. the high water consumption of miscanthus and Eucalyptus was mentioned). Moreover, the institutional framework deserves more attention (e.g. the German laws that forbid the conversion of afforested land back into cropland or pasture). The general opinion is that the results for afforestation overestimate the willingness of landowners and farmers to change the land use. According to one of the participants, the results for electric cars seem not in line with current activities on the development of fuel cell technology. Social issues (equity, unemployment) and non-GHG environmental issues of land use change have not yet been considered in detail. Issues such as trade balance and the impact of permit prices on the trade, habits, cash flow and investment risks have not been considered.

It was recommended to identify 'threshold values'for the introduction of bio-electricity (e.g. biomass costs, investment costs, efficiencies) and for afforestation (investment costs).

The results on the technology level are in a number of cases not robust (see Chapter 10). Considerable effort has been put into the identification of uncertainties and into the assessment of the consequences of these uncertainties. The results of the study should not be considered as blueprints for the future or a 'technology shopping list' for policy makers, but as a comprehensive view on the possible role of biomass in Western Europe on the long term.

2. CURRENT FOOD, BIOENERGY AND BIOMATERIAL FLOWS: A SYSTEMS ANALYSIS



Current statistics regarding production and consumption of biomass are scattered and often unreliable. One of the main reasons is that the analysis takes generally place from a non-biomass perspective (e.g. a sector activity analysis) or from an economic perspective (in monetary units). Biomass measurements in weight units are also complicated by the fact that the water content of different biomass types can differ significantly. Moreover, the chemical composition and the energy content of biomass type such as straw and meat will obviously differ significantly. From a carbon or CO_2 perspective, it makes sense to compare biomass mass flows in tonnes, because the bulk of the biomass has a carbon content in the range of 40-50% (per unit of dry matter weight). As a consequence, biomass flow data pose a good indicator of carbon flows within the economy. Considerable effort has therefore been put into the consistent mass flow analysis of all three market segments:

- food production,
- materials,
- energy.

The results of the mass flow analyses are discussed in the next three Sections 2.1-2.3. The analysis shows that the total flows are in the range of 1000-1200 Mt, more significant than all fossil energy carriers added together. Given the energy content (which is approximately 30% of the average energy content of fossil energy carriers) the biomass flows (especially in the food chain) represent an energy flow in the range of 25-30% of the fossil fuel energy flow. Compared to other materials, steel production and cement production are one order of magnitude smaller than biomass production (in mass terms). These comparisons show the relevance of biomass, even in the current situation. This insight is relevant because it indicates that the existing knowledge and the existing infrastructure regarding biomass can kick-start this technology trajectory, an important advantage of biomass strategies compared to other emission mitigation strategies.

2.1 Production and consumption of food and fodder

The bulk of the agricultural crops is used for animal products (see Figure 2.1). Total production of crops amounts to 765 Mt (dry matter, excluding residual straw), 630 Mt of which is used for animal breeding. Given these quantities, the adjustment of the product mix, especially with regard to animal products, is another important strategy to reduce GHG emissions. Such a strategy can simultaneously reduce CH_4 and N_2O emissions and make land available for biomass crops. However such strategies are beyond the techno-economic optimisation in this study (but for the demand scenario parameters, see Chapter 5).

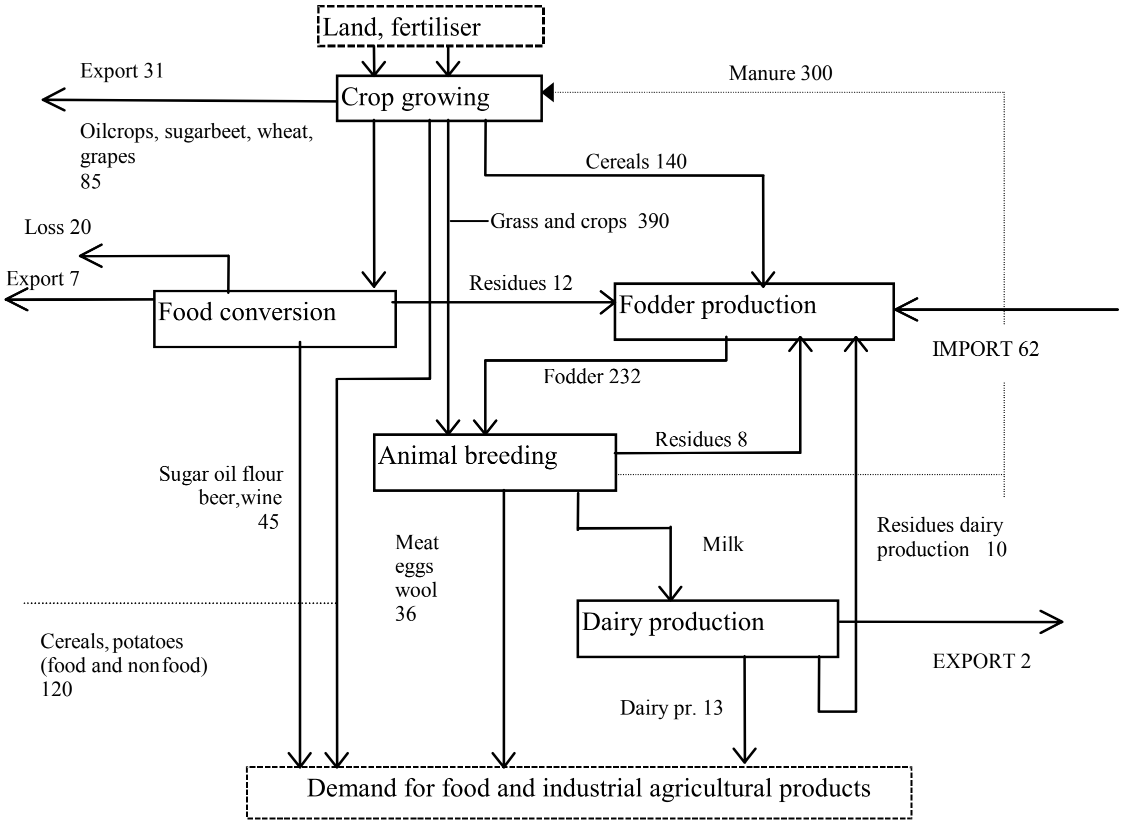


Figure 2.1 *Material flows in Western European agriculture (EU+EFTA), 1994. All stream quantities are given in Mt dry matter per year. Accuracy ± 20% (Gerlagh and Gielen, 1999)*

2.2 Production and consumption of bioenergy

Table 2.1 shows biomass use for energy (Radetzki, 1997). One must add that the amount of 1016 PJ includes peat, wood, wood waste, municipal waste, vegetal waste, industrial waste and black liquor. Assuming an average energy content of 15 GJ/t, Table 2.1 suggests a total consumption of 66 Mt biomass for energy purposes. This is a lower estimate since IEA states: 'Data under this heading are often based on small sample surveys or other incomplete information. The data give only a broad impression of developments, and are not strictly comparable between countries. In some cases complete categories of vegetal fuel are omitted due to lack of information'.

A bottom-up estimate confirms this statement. Estimates for black liquor consumption are in the range of 20-25 Mt dry matter (dm) per year (based on Confederation of European paper Industween countries. In some cases complete categories of vegetal fuel are omitted due to lack of information'.

A bottom-up estimate confirms this statement. Estimates for black liquor consumption are in the range of 20-25 Mt dry matter (dm) per year (based on Confederation of European paper Industries, 1994). Peat production in Western Europe amounted to 17 Mt in 1995 (however the water content relating to this figure is not clear (US Bureau of Mines, 1997). Some peat is used for heating, but a certain fraction is used for soil improvement (and is not included in IEA statistics). The paper content of MSW that is incinerated is approximately 5 Mt. The amount of incinerated kitchen waste is approximately 5 Mt dm. The total of these categories leaves no room for wood waste incineration by industry, straw boilers in agriculture and wood heating in the residential sector. However, these are important categories. As a consequence, a total biomass use for energy production of approximately 100 Mt seems more likely. One should add that the bioenergy use constitutes less than 2% of the total energy consumption in Western Europe[16]. Its relative insignificance is probably the main reason for the high uncertainties.

Table 2.1 *Biofuel consumption in OECD Europe according to IEA statistics, 1993 (Olivier et al., 1996)*

Country	Residential [PJ]	Industrial [PJ]	Total [PJ]	Total [Mt dm]
Solid biomass	209	706	915	60
Biogas + liquids	0	0	0	0
Municipal waste	4	0	4	0
Industrial waste	14	83	97	6
Total	227	789	1016	66

In 1996, France produced 0.06 Mt bioethanol on 28.000 ha (equivalent to 1.8 PJ) (Gaouyer, 1997). Bioethanol production for the transportation sector in other European countries was negligible. Moreover, approximately 20 PJ RME was produced in the same year in a number of Western European countries (Körbitz, 1997).

2.3 Production and consumption of biomaterials

It has been stated before that approximately 25% of the global CO_2 emissions are caused by tropical deforestation. The causes for deforestation are manifold and differ per region. However in parts of Asia and in Africa the production of timber is an important cause of deforestation. Moreover the production of certain cash crops such as palm oil is rapidly expanding causing large scale deforestation. The emissions related to this biomaterials production must be accounted for proper assessment of the carbon balance of biomass strategies.

A preliminary analysis of pulp and paper and building and construction material flows that serves as reference for the calculations is shown in Figure 2.2. Paper consumption amounted in 1992 to 65 Mt per year. Wood consumption for building and construction materials amounted to 82 Mt. Biochemicals and natural fibres are of secondary importance (together less than 10 Mt).

A more thorough analysis of wood flows and wood product flows has been done by BFH in the framework of the BRED project (Scharaid-Rad, Welling and Sasse, 1999). This analysis has shown that current flow statistics are inadequate, many statistical data are mere estimates. The analysis showed also that the data in Figure 2.2 are within 10% accuracy with regard to the wood supply and forestry products. Data for waste are generally of low quality (within 25% accuracy).

[16] According to the IEA statistics, this excludes food and biomass feedstocks for materials production.

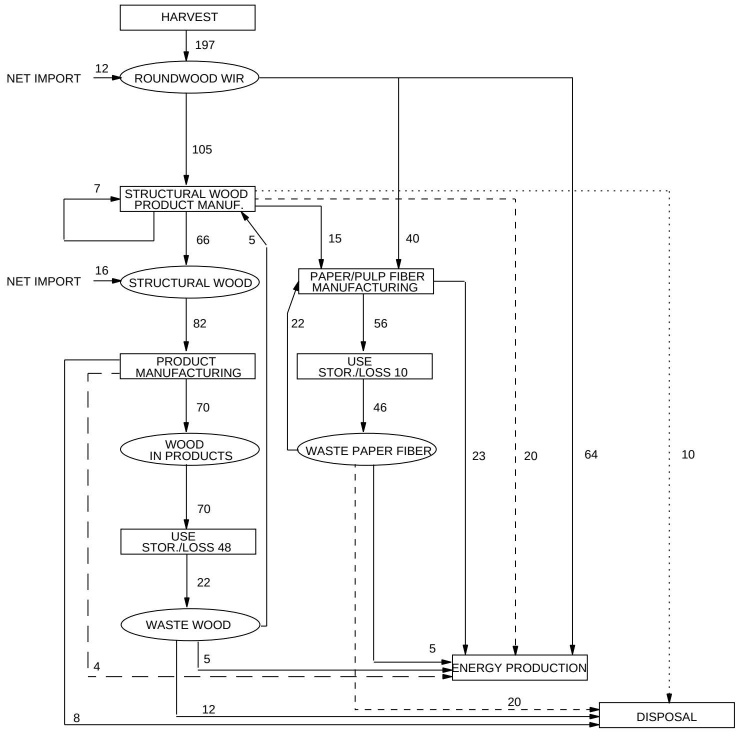


Figure 2.2 *Wood balance for Western Europe (figures indicate material flows in Mt per year; paper and pulp figures refer to the fibre content); 1992/1993; WIR= Wood In the Rough (all wood removed from forests and from trees outside the forests) (Gielen, 1999a)*

2.4 Post consumer waste flows

Data for waste flows in Western Europe are not consistent. In (APME, 1993) the amount of Municipal Solid Waste (MSW) is estimated to be 141 Mt in 1990. According to this source, 34 Mt waste was incinerated in 1992. 83% of the combustion capacity was equipped with energy recovery. The total MSW arising in Western Europe amounted to 225.3 Mt in 1993 according to (Schwager, 1995). According to this second source, 17% of this waste (38 Mt) was incinerated. The amount that is incinerated is similar according to both sources, but the amount of MSW differs. The difference is probably accounted for by a different definition of MSW. A recent analysis showed that different national definitions before 1994 are a major cause of inconsistent waste figures (Van Beek, 1997). A proper comparison for 1994, based on consistent definitions, showed MSW figures for 8 Western European countries between 460 and 585 kg per person per year, with an average of 537 kg per person per year. Assuming that this figure can also be applied to the other countries, results in an estimate of 190 Mt MSW in Western Europe for 1994. This figure is in between both earlier estimates. Municipal construction and demolition waste not originating from households is excluded from the survey in Van Beek (1997). Some of this waste may also be considered MSW in a broader definition. This narrower definition may explain the gap with the high estimate.

The energy content ranges from 9 to 13 GJ per tonne for individual countries. The MSW heating value is largely determined by the plastic content, the paper content and the amount of kitchen waste. In some countries, separate collection and recycling for these flows has reached high levels. A typical MSW waste composition for Western Europe is shown in Figure 2.3. The problem with the use of this type of figures for modelling purposes is however (again) the unclear definition of MSW.

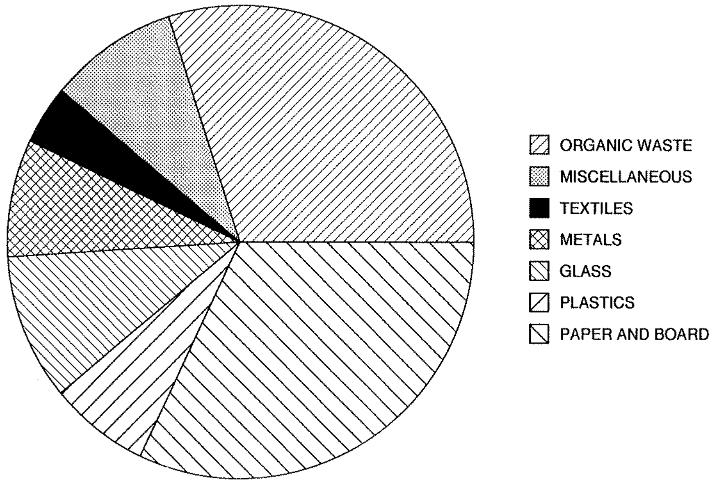


Figure 2.3 *Average European MSW composition, 1994 (Warmer Bulletin, 1994)*

Another approach for estimation of waste quantities is based on a balance for individual materials:

Waste arising = Materials consumption - losses - stock increases in the product use phase

A combination of both approaches has been used for Table 2.2. Note that the definition of recycling in Table 2.2 differs from the definition in some other statistics in order to generate comparable data for different materials. The definition that is applied here is: the amount of waste input into production processes divided by the waste arising. The waste arising is defined as the total of recycling, incineration and disposal (this excludes all kinds of 'losses'and excludes the increasing materials stock in the use phase).

For some natural organic materials, the amount of waste is considerably lower than the materials consumption due to net exports of semi-finished and finished products, increasing product stocks, losses in the use phase due to oxydation, etc..

The heating value of the total waste flows is indicated. The total energy content is approximately 2700 PJ, approximately 2 EJ is of natural origin. Total current Western European primary energy use is approximately 55,000 PJ per year. Comparison of both figures shows that waste materials can cover 5% of the primary energy consumption. However, recycling makes often more sense, as both feedstock energy and process energy use can be reduced. The selection of the best strategy from an environmental and cost point of view depends on the policy goals and the systems configuration.

Table 2.2 *Waste balance for important groups of materials, Western Europe (EU+EFTA), 1993/1994 (APME, 1995; CEPI, 1994; UN-ECE,1997; Van Duin, 1997)*

Material	Apparent consumption [Mt/year]	Waste arising [Mt/year]	Energy content [GJ/t]	Energy value [PJ/year]	Recycling[17] [%]	Incineration[18] [%]	Disposal [%]
Paper and board	67	60	15	900	50	10	40
Kitchen + garden waste	68	68	8	544	10	15	75
Glass	24	20	-	-	40	12	48
Metals	175	100	-	-	80	4	16
Plastics	25	16	35	560	5	16	79
Textiles	9	9	25	225	30	15	55
Wood products	82	34	16	544	15	26	59
Total				2773			

Apart from waste statistics, the amount of kitchen waste can also be estimated on the basis of consumption data, based on the mass balance principle (consumption = waste arising, if losses and changing stocks are neglected).

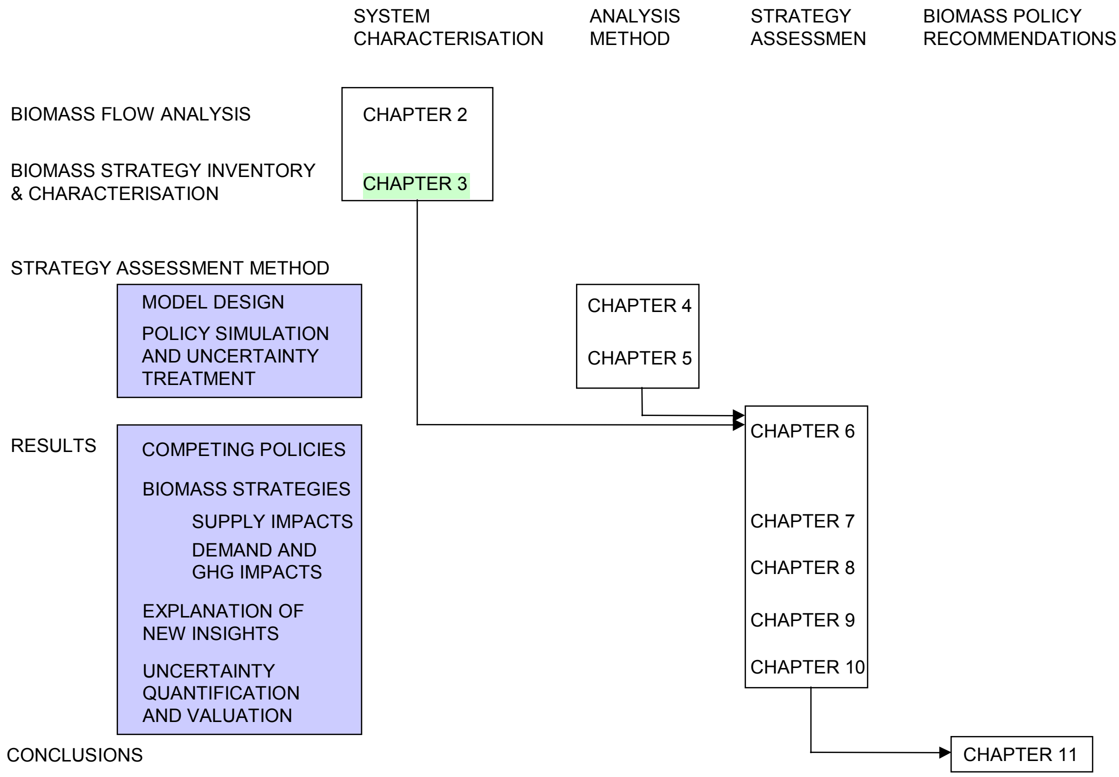
The total food supply to the consumer is 218 Mt according to the data in Figure 2.1. Basically there are three ways in which these flows can be released into the environment: CO_2, the sewage system and kitchen waste management systems. Assuming that 25% of this quantity is released as kitchen waste, this would equal 55 Mt, a figure that corresponds with the 68 Mt kitchen waste and garden waste in Table 2.2. Assuming an energy conversion efficiency of 25% for the remaining food intake (which is released as CO_2), the quantity of biomass in the sewage system is 125 Mt. However the bulk of this biomass waste cannot be used for energy recovery. Part of it is directly released (untreated sewage). An increasing fraction is treated, part of it ends up in the sewage treatment plant as sewage sludge. Some of this sludge is already used for energy recovery.

2.5 Summary: overview of flows

The most significant biomass flows are related to the food chain (approximately 900 Mt). Forestry products follow in a considerable distance (200 Mt). The current biomass system consists of a number of cascades: manure is used for fertilisation, waste paper is recycled, energy is recovered from process waste and from post-consumer waste. The total quantity of waste equals the total production: 1100 Mt. However the system losses (CO_2, directly applied manure, sewage systems) represents at least 600 Mt. A total quantity of 500 Mt waste available for recycling and energy recovery seems a maximum. This includes straw by-products from agricultural crops (100-200 Mt), manure (100-200 Mt), processing waste (100-200 Mt, both food processing and materials processing) and post-consumer waste (50-100 Mt).

[17] Includes anaerobic digestion (for food/garden waste) and recycling abroad (e.g. for textiles).
[18] Both with and without energy recovery.

3. BIOMASS EMISSION MITIGATION STRATEGIES



Energy and materials biomass strategies for greenhouse gas emission mitigation can be split into:

- carbon storage in new forests (i.e. afforestation),
- carbon storage in soils,
- carbon storage in products,
- substitution of fossil fuels for energy and feedstocks,
- substitution of CO_2 intensive materials by renewable biomaterials,
- increased efficiency of production,
- increased energy recovery from waste biomass,
- increased recycling/reuse of biomaterials.

Based on data from literature, the engineering characteristics of these strategies will be discussed and their potential for emission reduction will be quantified.

3.1 Afforestation

The carbon storage potential in new forests is closely related to the land area that is available. This area is limited in Europe in comparison to other regions. Nilsson and Schopfhauser (1995) estimate that 8.1 Mha is available in (Eastern and Western) Europe, compared to 245 Mha worldwide (3.3% of the worldwide area). Coupled to the comparatively high GHG emissions in Western Europe, the potential of an afforestation strategy for GHG emission mitigation is limited in this region.

The amount of carbon that can be stored annually depends on the growth rate of the trees. The total amount of carbon that can be stored depends on the carbon content of the mature forests.

Generally speaking the trees with the lowest growth rate result in the highest carbon storage because their growing period is much longer. Some data for the European situation are shown in Table 3.1. Apart from the tree species, the land quality and the climate conditions play an important role (Börjesson and Gustavsson, forthcoming)[19]. The annual storage can differ 50% in case of much better or much worse conditions.

Table 3.1 *Characteristics of different tree types for carbon storage (Sikkema and Nabuurs, 1995; Crabtree, 1997; Böswald, 1998)*

Type	Annual storage [t CO_2/ha/year]	Average fixation [t CO_2/ha]	Annual storage on 10 Mha land [Mt CO_2/year]
Oak/beech	5-6.9	154-535	50-69
Spruce	9.7-13	229-510	97-130
Poplar, 15 years	13.1	95	131
Willow, 1 year	15-20	50	50

Because of the trade-off between carbon storage and biomass production, any afforestation strategy must consider the purpose of the carbon storage closely: maximum biomass production (short rotation with negligible carbon storage in biomass, to substitute energy and/or materials), maximum medium term annual carbon storage for a limited period (to 'buy time') or maximum long term total carbon storage ('eternal carbon storage'). The second strategy is most relevant in case the GHG problem is considered a temporary problem that will be solved in the next 5 decades. The third strategy is most relevant in case the GHG problem is considered a major problem for the very long term (more than 100 years).

An area of 10 Mha can store up to 131 Mt CO_2 per year. The 10 Mha is an average estimate of the total amount of Western European surplus agricultural land which may become available for afforestation in the next decades (Gerlagh, 1998b). The 131 Mt CO_2 are equivalent to 3.1% of the Western European GHG emission in 1990. This quick estimate suggests that afforestation can be important, but it will not get a dominant place in Western European GHG emission reduction strategies.

Some regional differences must be accounted. The tree growth rate depends on local conditions such as climate, altitude, soil quality, environmental pollution, damage by animals, etcetera. The yields in Sweden alone can range from 10 t roundwood/ha in the South to 1 t roundwood/ha in the Northern part of the country. This complex issue has been considered in a simplified manner (see Section 4.6).

3.2 Carbon storage in soils

Examples in the United Kingdom have shown that a conversion of agricultural land to deciduous forest resulted in an increase of the soil organic matter (top 23 cm) by 50 gr/m2/yr over a period of 100 years (1.83 t CO_2/ha.yr). Conversion of agricultural land to planted grassland resulted in a carbon storage (top 15 cm) of 75 gr/m2/yr over a period of 15 years (2.75 t CO_2/ha/yr) (Watson, Zinyowera, Moss and Dokken, 1996a).

Large scale application of manure can increase soil C as much as can revision to natural vegetation. A UK example showed that the application of very high application rate of animal manure of 35 t/ha increased the carbon soil (measured in the top 23 cm) over a period of 150 years from 0.92% to 2.8% (Watson, Zinyowera, Moss and Dokken, 1996b). Assuming a soil density of 2 t/m3, this equals an annual storage of 2 t CO_2/ha/yr.

19 The figures in Table 3.1 do not take into account the release of soil carbon in case peatlands are drained for forest plantations (e.g. the case in Scotland and in Ireland). In case of a 2 m peat layer with 300 kg organic matter/m3, the quantity of soil carbon is 11,000 t CO_2/ha. It is obviously not sensible to start afforestation projects on such sites from a GHG perspective.

The carbon pool in western European[20] countries in vegetation is approximately 22,000 Mt CO_2, the pool in soils is approximately 60,000 Mt CO_2 (Watson, Zinyowera, Moss and Dokken, 1996c). These figures should be compared to the annual emission of 3,500 Mt CO_2 per year.

Carbon storage in agricultural soils that are converted to forests can amount to up to 500 t CO_2/ha (Norway spruce) after a period of 75 years (hence 6.67 t CO_2/ha/yr) (Sikkema and Nabuurs, 1994).However this value is virtually reduced to zero if the trees are felled after this period. For Norway spruce in central Europe, mixed deciduous forests in central Europe and poplar plantations in Western Europe the long term average sequestering potential is 429, 385 and 275 Mt CO_2/ha (Nabuurs, 1996).

Considering a surplus agricultural land area of 10 million ha, the potential for carbon storage in soils is 20-67 Mt CO_2 per year (2-6.7 t/ha. yr, or cumulative 10,000 Mt CO_2 after 100 years, average 4 t/ha. yr). A realistic value is probably 50 Mt CO_2 per year or cumulative 2500 Mt CO_2 (10 million ha, 5 t/ha. yr). This equals 1.4% of the annual CO_2 emissions.

This value is sufficient to warrant proper accounting in case of long rotation crops. In case of short rotation crops, the net carbon storage is negligible.

3.3 Carbon storage in products

Products made from natural organic materials result in CO_2 storage during their life span. An increase of the amount of natural organic materials in the economy poses a CO_2 storage strategy. Table 3.2 gives an estimate of the current volumes stored and the potential for increased storage.

Table 3.2 *Carbon stored in products, Western Europe, 1990s. Accuracy ± 25 %*

Product category	Current storage [Mt CO_2]	Potential storage [Mt CO_2]	Potential additional storage[21] [Mt CO_2/year]
Buildings[22]	5000[23]	10000	75
Infrastructure[24]	1000	1500	20
Furniture	500	750	10
Wood in storage[25]	500	500	-
Magazines/papers/books	50	50	-
Packaging[26]	15[27]	15	-
Other[28]	25	25	-
	7090	12840	105

The table suggests an additional storage potential of approximately 100 Mt CO_2 per year, the same order of magnitude as the storage potential for afforestation.

Apart from storage of carbon in products during their use, carbon can also be stored in waste products (disposal sites). Estimates for current disposal of synthetic organic waste suggest a net storage in the range of 20-30 Mt CO_2 per year (Gielen, 1999a). However the disposal of natural organic materials is an important source of methane emissions. Moreover, the current policies

[20] Figures for Eastern and Western Europe have been divided by 0.67 in order to generate an estimate for Western Europe (factor based on land areas).
[21] Potential minus current storage divided by the average life span.
[22] Includes all building types including floors, wall cladding, garden fences, storage facilities, etc.
[23] Estimate based on 350 million buildings, 10 t wood per building.
[24] Includes waterworks, sleepers, road facilities.
[25] Includes storage by industry, commerce and households.
[26] Includes pallets, crates, paper, etc.
[27] 350 million pallets of 25 kg.
[28] Includes transportation equipment.

aim for a reduction of waste disposal because of the ancillary negative environmental effects. As a consequence, this strategy has not been considered in the analysis.

Carbon storage in products will be considered, especially for the product group buildings this could be an interesting emission reduction strategy. A switch to product alternatives with a higher wood content per functional unit will result in a net increase of the carbon storage (e.g. a wood frame building instead of a concrete building).

The analysis requires care because the selection of building materials in the building sector can influence the insulation and the thermal mass. These two variables can influence the amount of energy that is required for heating and for cooling. A change of this so-called direct energy use can influence the CO_2 emissions and must be considered for proper analysis. Earlier analyses have shown that the impact can be substantial, because the direct energy use outweighs the indirect energy use (for materials production) by a factor 5-10 (Gielen, 1999d).

3.4 Energy substitution with clean biomass and biomass process waste

The substitution of fossil fuels with biomass fuels has received a lot of attention because of the GHG benefits of such a switch. The energy market is so large that the biomass supply poses constraints for maximised biomass introduction, not the market potentials. The CO_2 impact of bioenergy depends on the type of fossil fuel that is substituted. The CO_2 impact ranges from 56 kg CO_2/GJ natural gas to 73 kg CO_2/GJ oil and 94 kg CO_2/GJ coal. Assuming 10 Mha biomass crops, 20 t biomass per hectare, 15 GJ/t biomass and a substitution of oil on an energy par basis, the potential is 3 EJ and 220 Mt CO_2 emission reduction, 5% of the GHG emissions in the reference year.

A number of bio-energy markets can be discerned:
- electricity,
- heating,
- transportation fuels,
- gaseous fuels.

These markets are discussed below.

Electricity production
Electricity production has been split into co-combustion in large-scale plants separate dedicated biomass fired power plants, and cogeneration plants primarily used for heat production with electricity by-product.

A large number of dedicated concepts can be discerned. Most attention is currently paid to biomass gasification and subsequent use of the gas for electricity production. The advantages of this system are the higher energy efficiencies, lower cost and better gas cleanup possibilities than for conventional biomass fired steam cycles.

Gasification can be split into atmospheric and pressurised gasification. The latter one is generally more cost-effective for large-scale systems. Pressurised gasification can be applied for co-combustion in gas fired power plants (STAG, steam and gas power plants), co-combustion in integrated coal gasification combined cycle (IGCC) power plants. The advantage of such systems is the higher electric efficiencies of large-scale systems. However biomass availability poses often a problem. For this reason smaller scale (25-100 MW) stand-alone biomass power plant do also receive a lot of attention. One must say that all these systems are not yet proven on full scale, but a number of pilot plants exist around the world.

Solid biomass can also be co-combusted in conventional coal fired power plants. This option is already widely applied, e.g. in the Netherlands. For industrial use and for district heating small-scale cogeneration plants (producing electricity and heat) exist, for example in Scandinavia and in Austria.

Heating
In the heating market, a number of ovens and heating systems for industry, for agriculture and for residential heating have been considered.

The most widely applied wood based heating system is the open fire. However its heating properties are not good, and in some cases even negative because it creates a draft that results in cold air entering the buildings. Dedicated heating systems show a much better heat balance and approach efficiencies of 80-85%.

Industrial boilers are widely applied, especially in the woodworking industry. Heat production from agricultural residues such as straw has been applied in Denmark, but the low energy content, storage problems and uneven supply during the year pose problems with regard to large scale introduction of this technology.

Transportation fuels
Ethanol production on the basis of sugar is a well-established technology. The European production amounts to 5 Mt ethanol per year, mainly for alcoholic beverages. However sugar is a costly feedstock. The current R&D is aiming for lignocellulose feedstocks (wood and straw type feedstocks). The cellulose and hemicellulose fractions can serve as feedstocks. Cellulose conversion into ethanol is a proven technology, but the conversion of hemicellulose requires more research. Ethanol is a well-established gasoline additive (99% pure) or gasoline substitute (95% pure) in Brazil and in the United States.

Some ethanol for transportation is currently produced in France from sugarbeets. It serves as a feedstock for the production of ethyl tertiary butyl ether (ETBE). ETBE is a good octane booster. With the use of ETBE as an additive in gasoline vapour emissions are lowered. ETBE can serve as a substitute for MTBE (methyl tertiary butyl ether), which is currently used as an octane booster in lead-free gasoline. However, MTBE itself can off course also be produced from biomethanol.

Methanol and DiMethyl ether (DME) are produced on the basis of biomass gasification and subsequent synthesis. Methanol can be used as gasoline additive or gasoline substitute (used as such in the United States). The technology is not yet applied on a commercial scale. DME is a recent development and all DME engines and vehicles are still in an experimental phase. Before being used as a fuel, DME was used as an ignition booster in methanol engines. The technology is very similar to the methanol production, but DME has two important advantages: it is not toxic (such as methanol) and the energy content is much higher (hence less refuelling is required). Because of its good ignition properties, DME is very suitable for use in diesel engines (as a diesel substitute).

Fuels produced with the Fischer Tropsch (FT) process are of high quality (due to low aromaticity and absence of sulfur) and can be used as blending agents for transportation fuels derived from crude oil. Both FT-derived gasoline and FT-derived gasoil (diesel) can be produced, the relative amounts of which are dependent on the process conditions (catalyst, temperature, etc.). In the MATTER model, a process optimised for gasoline production is considered.

RME is a diesel substitute which has currently the largest market volume (20 PJ/year). However its price is high. The main problem is the comparatively high cost of rapeseed oil (caused by the low yield per hectare). Algae could be a source of oil feedstocks with a very high yield per hectare, but the production technology requires large costly ponds with a comparatively high energy use for aeration.

HTU oil production is based on pressurised cooking of biomass, yielding an oxygen free oil type product. This oil can either be used directly for electricity production or it can be further upgraded to biodiesel by removal of the remaining oxygen (through hydrogenation).

Flash pyrolysis of biomass can be applied for the production of pyrolysis liquids or bio-oil. The difference with HTU oil is the high oxygen content of the oil (at up to 40-50% wt on a wet basis). Pyrolysis oil can also be catalytically upgraded to biodiesel (through hydrotreating) which is proven in concept but not well developed. No technology is yet commercially available.

Production of gaseous fuels
Anaerobic digestion and production of biogas are processes which has been used widely for many years. Biogas consists mainly of methane CH_4 (50-70%) and has a LHV of 19-27 MJ/Nm^3. Anaerobic digestion of kitchen waste and manure are separately modelled, however during the last decade a technological breakthrough has occurred (in Western Europe) regarding animal manure co-digested with industrial organic waste and household waste.

Landfill gas (LFG) is a mixture of circa 50% methane and carbon dioxide, resulting from the anaerobic degradation of organic landfilled waste. The gas is collected and cleaned and then either burned to provide process heat or is used for electricity generation. Landfill gas recovery is modelled as to produce methane.

Hydropyrolysis is gasification of carbon containing feedstocks in a hydrogen atmosphere. It has been identified as a promising option for converting biomass and hydrogen to synthetic natural gas (SNG). Since the properties of SNG are very similar to natural gas, it is expected that the existing gas infrastructure can be used for SNG distribution. At present, hydro-pyrolysis of biomass is not yet applied on a commercial scale.

3.5 Materials substitution

Markets for biomaterials can be split into building and construction materials and biomass for substitution of fossil fuel feedstocks and petrochemicals. Both segments will be discussed separately.

Building and construction materials
Timber is the best known structural wood product. A number of other materials such as particle board, fibre board and engineered wood products pose forest products of secondary importance from a mass flow point of view. Wood products substitute concrete, steel or bricks in the building and construction sector.

Fossil fuel feedstocks and petrochemicals
Petrochemical products can be split into plastics, fibres, solvents, resins and a number of applications of lesser relevance. Plastics and fibres constitute the largest market segment (together approximately 30 Mt per year, see Chapter 2 and (Okkerse and Van Bekkum, 1996). Within this group, polyethylene, polypropylene, polyvinylchloride and polystyrene constitute three quarters of the market. Substitution is possible on the level of intermediate petrochemicals and on the level of end products. Intermediates like ethylene, propylene, butadiene and aromatic compounds like benzene, xylenes or phenol can be produced from biomass through a combination of pyrolysis and gasification technologies. Biomass consists of different substances: oils sugars, starch, cellulosis, hemicellulosis and lignin. Each constituent poses other opportunities. Alcohols like methanol, ethanol, i-propanol and butanol, acetic acid and acetone can be produced through biomass fermentation or through gasification and subsequent synthesis. Natural oils and

resins can be used for detergent, lubricant and paint production. Charcoal is another pyrolysis product from biomass. Coke and coal can be substituted by charcoal in blast furnace steel production. Apart from the intermediates, plastics and resins can be substituted by natural plastics and resins. For example natural rubber, which represents one third of the total rubber production, constitutes the high quality segment in the rubber market. Cotton and natural cellulose polymer fibres like rayon compete with synthetic organic fibres like nylon and polyester. The packaging market seems most suited for substitution of traditional polymers by biopolymers. Cellophane and new biopolymers like biopol can substitute conventional plastics. However their properties and their price pose still a major obstacle for substitution. Biopol (a copolymer of polyhydroxybutyrate PHB and polyhydroxyvalerate PHV), starch based plastics and polylactic acid have been considered in the model calculations.

A number of tropical hardwood substitutes is promoted in order to reduce logging as a source of tropical deforestation. The main advantages of tropical hardwoods that are used within Europe is superior durability and superior textures etc.. In cases where durability matters, a number of alternatives exists. This includes treated wood materials (e.g. engineered wood products, treated wood) or non-wood alternatives (such as plastics and steel). The CO_2 benefit of such substitution depends on the emissions for tropical hardwood production. The extent to which the emissions of tropical deforestation can be attributed to timber production are disputed and differ per region (higher in Asia than in most parts of South America).

The market potential for increased wood use in 2030 has been estimated in an earlier analysis (Gielen, 1995): 120 Mt sawn timber and board products in the building and construction market, 50 Mt biomass in the feedstock market. The CO_2 impact in the building sector is in the range of 50-125 Mt CO_2 (Gielen, 1999b), the impact of biomass in the feedstock market is 100 Mt CO_2 (taking the carbon content of the biomass feedstocks into account).

3.6 Increased efficiency of production

A large number of design strategies can be discerned that can reduce materials requirements (see e.g. Gielen, 1999c). A large number of these strategies can also be applied in the case of wood products, in the building and construction sector and with regard to paper. Two examples will be discussed:

- development of wood products with improved design features,
- increased product life.

Wood products with improved design features

The safety factors for the design of wood products are very high. The average strength is ten times higher than the design strength. The reasons for this over-engineering are occasional irregularities in the wood that must be considered in the design. However these irregularities are less relevant in engineered wood products such as laminated beams. As a consequence, the same constructions can be designed with less material.

Increased product life

Product life extension can be based on improved maintenance (e.g. in case of window frames), modular design (e.g. floor cladding which can be removed and reapplied easily), and it can be based on improved logistics (e.g. a trade system for second hand products) (Gielen, Kram and Brezet, 1999). The split if increased product life and increased recycling and reuse is not clear-cut. In this study, reuse of products and product parts is considered as increased product life, while use of materials for different products and product parts is considered recycling and reuse.

3.7 Increased energy recovery from post-consumer waste

A number of energy recovery technologies from post-consumer waste is currently applied or is being studied:

- landfill gas recovery,
- anaerobic digestion of kitchen waste,
- incineration in MSW grate incineration plants,
- gasification,
- pyrolysis,
- incineration in cement kilns.

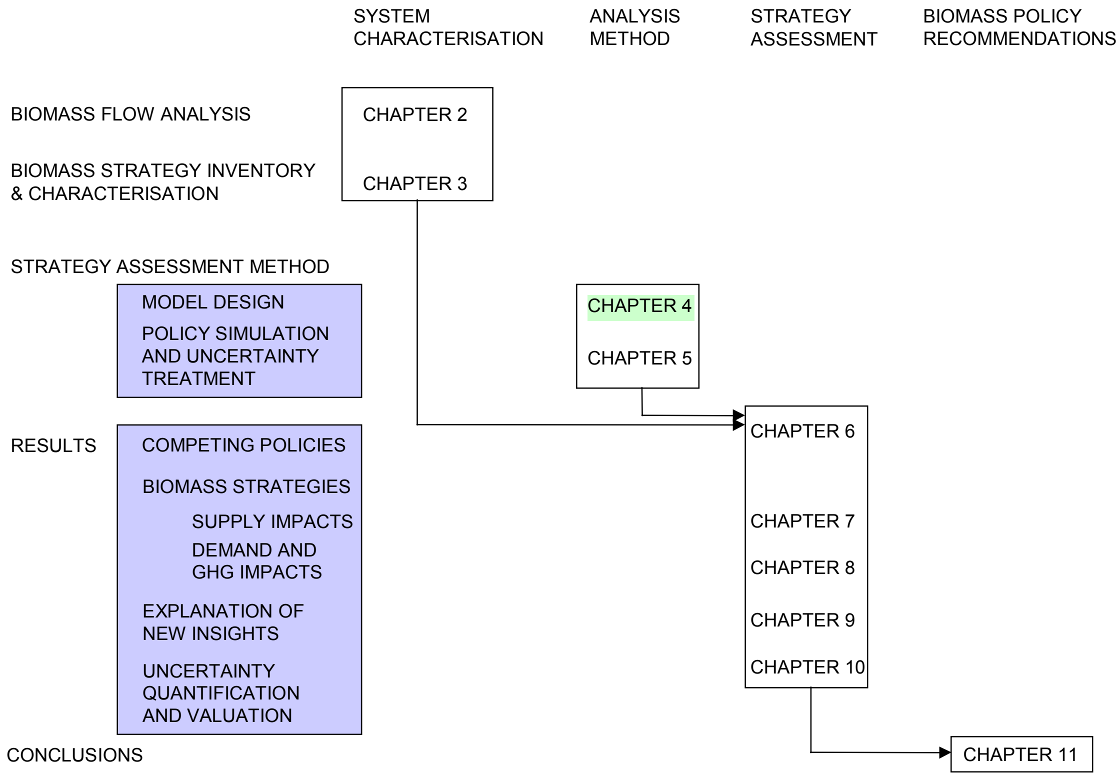
A number of technologies which is currently widely applied and promoted, such as co-combustion in coal fired power plants and co-firing in industrial boilers, has not been considered as long term solutions because of emission problems.

The future potential of these technologies depends on future waste volumes and waste policies. For example current plants to ban waste disposal will decrease the potential for landfill gas recovery dramatically. If the waste quantities of Section 2.4 are considered and an average electric efficiency of 30% for future technologies and a substitution coefficient of 100 kg CO_2/GJ electric (the European average) are assumed, then the potential is 60 Mt CO_2. On top of that methane emissions from landfills can be reduced by 200 Mt CO_2 equivalents (compared to 1990 levels) (Gielen, Koutstaal, Kram and Van Rooijen, 1998).

3.8 Increased recycling and reuse

Paper is the main material where recycling and reuse of post-consumer waste has been increasing rapidly. There is some potential for increased paper recycling. Regarding wood materials, a cascade of wood applications is also an interesting option (e.g. from floor joists to floor boards, to window frames to flake board to fibre board (Fraanje, 1997). However it is important to keep in mind that this type of optimisation makes only sense in case resource supply constraints exist, or in case cost savings can be achieved.

4. MODEL CHARACTERISATION



4.1 MARKAL

At present MARKAL[29] is one of the most widely used models for analysing the impacts of GHG emission reduction policies, although its results often have to be completed using top down models (like General Equilibrium models). A MARKAL model is a representation of (part of) the economy of a particular region. The economy is modelled as a system of interdependent technical processes. These processes are characterised by their physical and economic properties which determine the physical and monetary flows between these processes within that (part of the) economy of a region. It is a linear programming model that maximises an objective function (e.g. minimisation of emissions) under constraints (e.g. the attainment of certain production levels, the availability of certain technologies, etc.). The solution of a MARKAL model represents the equilibrium that would be achieved in an ideal market (according to the neo-classical welfare economics). In the following paragraphs the processes and the optimisation procedure are briefly described.

[29] The MARKAL linear programming model was developed 20 years ago within the international IEA/ETSAP framework (International Energy Agency/Energy Technology Systems Analysis Programme). More than 50 institutes in 27 countries use nowadays MARKAL [29]. MARKAL is an acronym for MARKet ALlocation. At present it is the most widely used model for analysing the impacts of GHG emission reduction policies.

Processes

Processes (also called technical options) are the building blocks of a MARKAL model. These are characterised by:

- their *physical inputs and outputs* of energy and materials,
- their *costs*,
- other characteristics (in this study their *GHG emissions and waste volumes*) over a number of time periods.

Implicitly these process descriptions yield a very detailed input-output structure linking several hundreds of processes that are analysed in a dynamic perspective, covering the total life cycle for both energy and materials. Of course not all substance flows in the entire economy are analysed. First, not all processes in the economy are included in the model. Secondly not all emissions are included in the description of the processes. This study for example is confined to GHG emissions and to processes with GHG relevance. Other environmental issues can in principle be analysed within the same framework.

Processes represent all activities that are necessary to provide certain products and services (in this study: the provision of energy and materials). Many products and services can be generated through a number of alternative (sets of) processes that feature different costs and different GHG emissions.

Process descriptions follow a standard format, consisting of two data sheets. One sheet describes the physical inputs and outputs (of energy and materials). The other characterises the economic data and the other process data. The input data structure depends to some extent on the process that is characterised. Data for different types of power plants, conversion processes, and end-use technologies are characterised in different ways. A schematic example of the input for conversion processes is shown in Table 4.1. The data input is divided into nine time periods (column heading 1-9). The length of the time period is set by the user of the model and is usually 5 or 10 years (10 years in this model version). One column is reserved for time-independent variables (TID). The physical data do not represent the total mass and energy balance where input equals output (because of flows that are not accounted for). The cost characteristics of the processes are divided into investment costs (which are proportional to the installed capacity), fixed annual costs (proportional to the installed capacity) and variable costs (proportional to production volume). The user of the model can impose restrictions on the deployment of certain processes (technical options). Such restrictions may include political preferences, intentions expressed in policy papers or long term physical constraints such as land availability.

Increasing process efficiency is modelled by decreasing inputs per unit of output (such as for energy carrier A and material A in Table 4.1). Decreasing costs or changing restrictions can be modelled in a similar way. This is illustrated for the investment costs in Table 4.1, which decrease in time. This is a way to account for so-called ‘learning curves’, accounting for decreasing costs as the installed capacity increases.

Table 4.1 *MARKAL model data structure for a conversion process*

Sheet 1: Physical flows	Period	Unit	TID	1	2	3	4	5	6	7	8	9
Inputs	Energy carrier A	[GJ/unit]		2.0	1.9	1.8	1.7	1.7	1.7	1.7	1.7	1.7
	Energy carrier B	[GJ/unit]		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	Material A	[t/unit]		5.0	4.5	4.2	4.0	4.0	4.0	4.0	4.0	4.0
Outputs	Energy carrier C	[GJ/unit]		0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Product A	[unit]		1	1	1	1	1	1	1	1	1
Sheet 2: Other data												
	Investments	[EUR/unit cap]		100	80	70	60	60	60	60	60	60
	Fixed annual costs	[EUR/unit cap./yr.]		5	5	5	5	5	5	5	5	5
	Variable costs	[EUR/unit]		2	2	2	2	2	2	2	2	2
	Delivery costs	[EUR/t A]		1	1	1	1	1	1	1	1	1
	Availability factor	[unit/unit cap]		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Life	[periods]	2									
	Start	[period]	1									
	N_2O emissions	[t/unit activity]		0.1	0.9	0.8	0.8	0.8	0.8	0.8	0.8	0.8
	Residual capacity	[unit cap]		2	0	0	0	0	0	0	0	0
	Maximum capacity	[unit cap]		5	10	50	50	50	50	50	50	50
	Minimum capacity	[unit cap]		0	0	0	0	0	0	0	0	0

Bounds

- The data sheets also allow for certain restrictions on the application of certain processes. These application restrictions are called 'bounds.' In this study the following bounds play a role: bounds on maximum penetration of certain technologies, reflecting e.g. social and strategic considerations (e.g. a maximum bound on nuclear and hydropower, a maximum import of natural gas from Russia).
- Bounds on the maximum investment rate in certain new technologies.
- Bounds reflecting the standing capacity from earlier periods (e.g. for the existing building stock).
- Bounds on the availability of natural resources (e.g. disposal capacity, land availability).

Time span

The time span to be modelled is divided into nine periods of equal length, generally covering a period of decades. The model is used to calculate the least-cost system configuration for the whole time period, meeting product and service demands and meeting emission reduction targets. This optimisation is based on a so-called 'perfect foresight' approach, where all time periods are simultaneously optimised. Future constraints are taken into account in current investment decisions.

In summary

The user of the model determines the processes from the database that will enter the calculations, he or she also determines the constraints for the individual processes, as well as constraints for the whole region. Constraints are determined by the demand for products and services, the maximum introduction rate of new processes, the availability of resources, environmental policy goals for energy use and for emissions, etc.. Processes are characterised by their physical inputs and outputs of energy and materials by their costs and by their environmental impacts. Environmental impacts are endogenised in the process costs and the costs of energy and material flows between processes. The time scale is chosen according to the questions analysed. Since most of the processes take a long time to reach their maximum penetration (often at the expense of others), such time horizons tend to cover several decades, in this study until 2030.

The calculation of least cost combinations (LCCs) of processes/technical options
MARKAL requires as input projections of energy service demands – for example room space to be heated or vehicle-miles to be travelled. In the model used (MARKAL MATTER), also the materials demand for these services are included.

Then, a reference case is defined in which no GHG policy is applied, called the Base Case. A series of runs is then made with successively increasing emission permit prices. Because of the underlying detailed input-output relations (imputed by means of the data sheets), interdependencies between the various processes or technical options are taken into account. The model thus automatically calculates the combined effects of these interdependent options. Moreover, the integrated dynamic systems approach ensures also that interactions between technical options in one period and interactions between periods are reflected.

In each case, the model will find the least expensive combination (least cost combination, LCC) of technologies that meet that requirement (up to the limits of feasibility). But with each further restriction the total energy (and materials) system cost will increase[30]. Thus, the total future costs of emission reduction are calculated according to how severe such restrictions may become. These can be plotted as continuous total abatement cost curves. In addition, the marginal cost of emission reduction in each time period[31] for each emission reduction is known (equivalent to the permit price level). This figure is of special interest in establishing abatement policy because it can be interpreted as the minimum amount of carbon tax, or the minimum price of GHG permits that would be needed to achieve this level of abatement.

Some uses of MARKAL/MARKAL MATTER are:
- to identify least-cost energy systems,
- to identify cost-effective responses to restrictions on emissions,
- to perform prospective analysis of long-term energy balances under different scenarios,
- to evaluate new technologies and priorities for R&D,
- to evaluate the effects of regulations or prices (taxes, tradable permits, subsidies), or both,
- to project inventories of greenhouse gas emissions,
- to estimate the value of regional co-operation.

4.2 MATTER

MARKAL has originally been used as an energy systems analysis tool. Conventional energy system models cover the conversion of primary energy into final energy and the subsequent final energy use in economic sectors. Of course, they include industrial use of energy e.g. to produce materials and will therefore include for example energy efficiency gains in the production of a material. However, conventional energy system studies do *not* analyse the effects of changes in materials life cycles such as materials substitution, increased materials efficiency and recycling.

In the MATTER4.2 MARKAL model (the model used in this study) however, all bulk material flows are included. They include all substances without relevant physical shape (not being consumer or investment goods) that are not defined as energy carriers and food products. The

[30] In the linear programming approach all processes are characterised as black boxes with a linear relation between inputs and outputs of energy and materials, costs and emissions. Economies of scale are not taken into account for any given process type.

[31] More precisely, the costs of the most expensive technology that must be applied in order to meet the predetermined level of emissions is calculated. So, actually the model calculations give us the cost of the marginal technology. All other technologies that are part of the least cost combination (LCC), cost less per unit of emission reduction. Those who can apply these more cost effective technologies will, when they are confronted with a tax or with a price of tradable permits, apply that technology, to avoid paying the tax or to free permits they can sell on the market. As a consequence more expensive technologies will not be deployed.

model covers more than 50 types of energy carriers and 150 materials, which means a substantial enlargement of more traditional MARKAL models. More than 100 products represent the applications of these materials. 30 categories of waste materials are modelled. These materials are characterised by their physical characteristics and by their quality. This means that a large number of technical options (processes) are added to the database of energy options. Identifying these options requires for each bulk material a rather detailed analysis of the flow of that particular substance through the economy 'from cradle to grave' (Gielen, 1999c).

The inclusion of materials technical options is important for a number of reasons:

- By adding materials flows, the model chooses from a more comprehensive set of technological improvement options when calculating the least cost combinations. As a result a typical MARKAL MATTER estimate of the least costs for attaining a certain GHG emission target tends to be lower than a typical MARKAL estimate. In fact, the differences in the obtained least cost combinations are quite substantial.
- Because the energy and materials systems are intricately interwoven, technical improvements influence each other strongly. Ignoring technical improvement options in materials life cycles may lead to an overestimation of the effects of energy options[32] and misguided policy choices.
- It is extremely difficult, if possible at all, to foresee the effects of these interdependencies if one does not apply a formalised model that is based on rather detailed information concerning the interrelationships between the various technical options.
- It requires a comprehensive analysis of energy and materials flows to identify the appropriate points of impact for policy measures (in particular regulatory approaches) and to identify unexpected responses to policy actions.

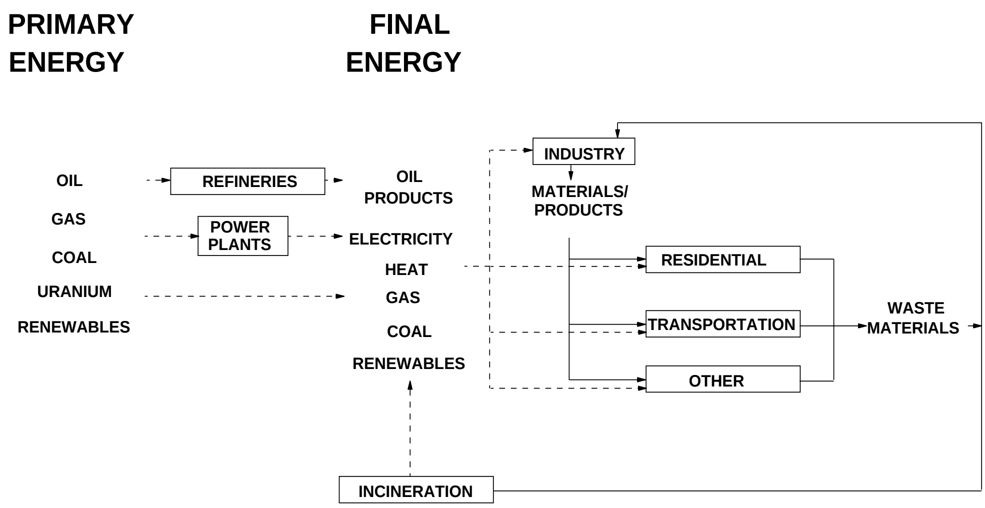


Figure 4.1 *Generic MATTER energy and materials system model structure, showing the close interactions of energy and material flows in the economy. Dotted lines indicate energy flows, drawn lines indicate material flows (Gielen, Gerlagh and Bos, 1998b)*

[32] For example, a technical change that reduces the emissions of electricity generation, will make the substitution from steel to aluminium (which primary production uses much electricity) more attractive. At the same token, it will reduce the environmental improvements that would result from using secondary aluminium instead of primary aluminium, (Secondary aluminium requires only 5% of the energy needed for primary material). Another example: If buildings are well insulated, an improvement of the efficiency of the heating system will have a less pronounced effect on overall emissions than in the case of poorly insulated buildings.

Figure 4.1 shows the energy and materials system model structure on an aggregated sector level and Figure 4.2 depicts the intersectoral flows of materials, that result from changes in a life cycle of a material. The actual model input data are on the level of individual processes in the product life cycle. Subsequently, these data are aggregated to produce results for economic sectors (see Figure 4.1) and for the economy as a whole.

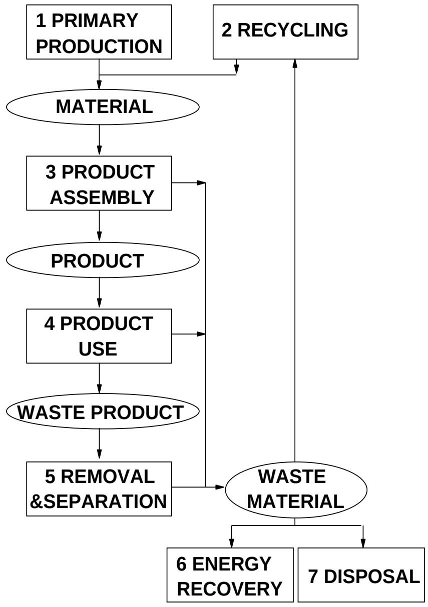


Figure 4.2 *Materials system model structure*

Figure 4.3 shows the definitions of the energy as well as the materials system. Conceptually it is difficult to separate energy from materials systems. After all, from an physics point of view, all environmentally relevant economic activities are just transformations of matter, using energy, and any distinction between the energy and materials system is arbitrary. In this study, all *energy used for materials production* (e.g. the production of iron, steel, aluminium, building materials, etc.) is considered to be *part of the materials system*. This is done because this study investigates the GHG effects of changes in materials life cycles. We want to know, for example, what changes in GHG emissions would result from changes in the inputs for of cement production. The effects of such a choice on GHG emissions are obviously strongly influenced by the energy requirements (quantity and quality) of the alternative inputs. Likewise, we want to know the effects on GHG emissions of building a car from aluminium or plastic, instead of from steel, or building a house from wood, instead of from concrete, steel and bricks. In both these cases the energy that goes into these *production* processes are part of the materials system. Ideally, also the energy required for space heating and driving the cars should be linked to the choice between alternative materials and therefore should be part of the materials system. Available energy statistics, however, do not permit this. Therefore, the energy that is needed for the *use* of the house (space heating) or the *use* of the car (fuels to drive it) is part of the energy system.

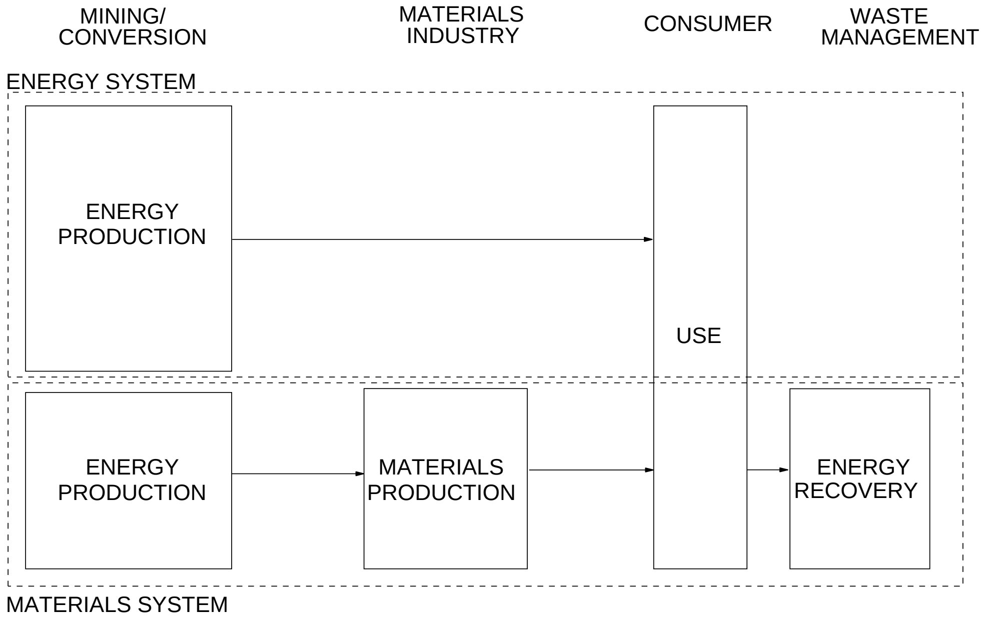


Figure 4.3 *Definition of the energy system and the materials system*

The MARKAL MATTER model version that was used for this analysis is version 4.2. Version 1.0 included the energy and materials system model. In version 2.0, a land use and food production module have been added. Version 3.0 includes a further extension with an elastic demand function. Common MARKAL is characterised by an exogenously defined fixed demand for energy and product services. However in the new model version that is applied in this study the demand depends on the product prices (see Section 4.3). MATTER versions 4.0-4.2 have been especially developed in the framework of the BRED study. They contain a further extension with new biomass data.

4.3 MED: Demand elasticities

A weak point of traditional 'common' MARKAL models is that price effects do not change demand (the demand is exogeneously defined). In recent years, the MARKAL model algorithm has been extended to make demand levels dependent on prices. Two approaches have been developed: MARKAL-MACRO (MM) (Hamilton, Goldstein, Lee, Manne, Marcuse, Morris and Wene, 1992) and MARKAL Elastic Demand (MED) (Loulou and Lavigne, 1996). While MM is a non-linear dynamic optimisation model that links the 'bottom-up' specification of a regional energy system to a 'top-down' macroeconomic growth model. MED is a partial equilibrium model where the exogenously defined useful demands have been replaced with demand functions (see below).

For this study, the MED algorithm has been selected instead of MM for a number of reasons:
- The MATTER model is too large to run with the non-linear MM algorithm.
- The difference between MM and MED results is generally small, while the calculation time differs significantly.
- MED allows a better representation of demand elasticities for individual demand categories, important for an in depth study of materials industries.
- In spite of the fact that the MARKAL MATTER 4.2 model covers 98% of GHG emissions and covers much more than the energy system, it leaves a substantial part (50% of GDP) uncovered, thus MACRO may not be a valid representation of the remaining parts of the economy.

'Top down' or 'bottom up'?

MARKAL models are 'bottom up' models, meaning that they start from detailed technical options 'at the work floor' so to speak. The optimisation procedure (calculating least cost combinations) is firmly based on the standard micro-economic tenet that welfare is maximised if the sum of consumers and producers surpluses is maximised (marginal costs equals marginal revenues). These models make maximum use of the available knowledge about technology (for example: at what oil prices energy from renewable sources becomes profitable? and how much time it is likely to take to install these renewable energy sources?). On the other hand these models are based on rather heroic assumptions, like perfect markets, perfect knowledge and foresight and assumptions regarding technological developments over a long period of time. Moreover most MARKAL based models lack the feedback of price changes on the economy and poorly describe trade.

Empirical economic models are 'top down' models. They contain much more economic detail, notably on money and trade flows. Being empirical, the sensitivity of e.g. investments in renewable energy sources to changes in oil prices, is derived from statistical data concerning the past, but such elasticities can change drastically due to for example technical change. Moreover profound technical changes may occur to slowly to clearly show up in statistical data. On the other hand these models implicitly take non price factors that influence technical change into account. The lack of technical detail allows for rather general conclusions only.

So far it has been proven to be rather difficult to merge both types of models. One such attempt is to link MARKAL to macro-economic models. This has resulted in MARKAL MACRO (MM). Another attempt is to introduce demand elasticities in MARKAL (MARKAL Elastic Demand, MED). The latter approach is followed in this study.

The MATTER model version used in this study is based on the MED algorithm. The decreasing demand due to increasing energy and product service prices is accounted for, but the rebound effect due to the redeployment of these funds is not considered. However from a modelling point of view, this approach has important advantages: the model is still based on linear equations, allowing rapid calculations. It is not possible to run the complex MATTER model with non-linear demand equations. Figure 4.4 shows the (simplified) equilibrium that is achieved in 'common' MARKAL (such as MATTER 2.0). Figure 4.5 shows the equilibrium that is achieved in the model version with elastic demands, such as the model MATTER 4.2.

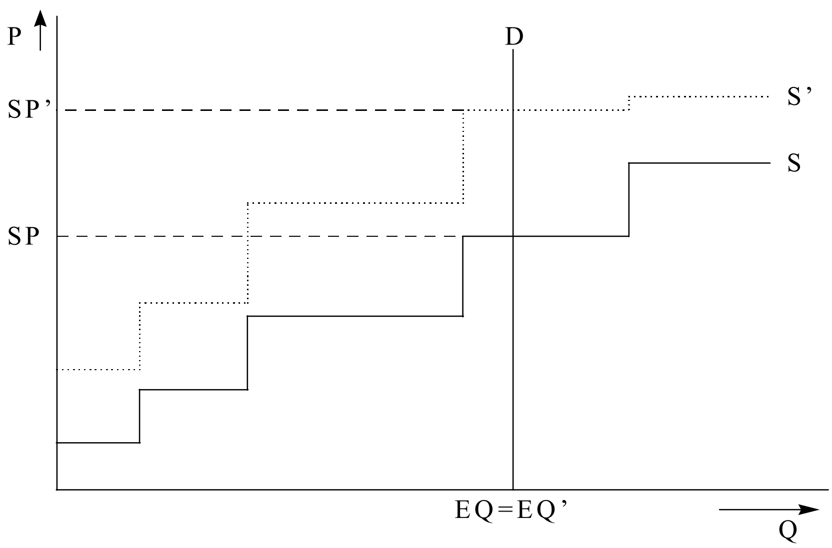


Figure 4.4 *Supply and demand equilibrium in MATTER 2.0 ('common' MARKAL)*

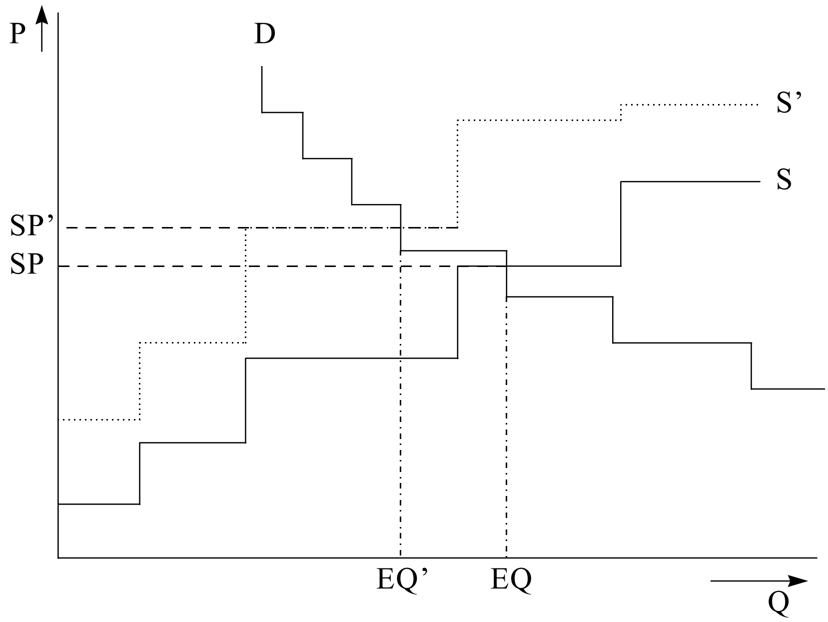


Figure 4.5 *Supply and demand equilibrium in MATTER 4.2 (MED)*

Figure 4.4 and Figure 4.5 each show a supply curve (S) and a demand curve (D) for the base case calculations (without GHG emission permit prices). Both curves are linearised in MARKAL in order to be able to use a linear programming algorithm, which has major advantages from a computing point of view. The horizontal axis Q represents the quantity, the vertical axis P represents the price. In common MARKAL (Figure 4.4), the demand is independent of the price, so the demand function is a vertical line. In MED (Figure 4.5) however, the demand decreases if the price increases, so the demand function is a curve. Equilibrium between supply and demand is reached in point EQ, which is the same for both figures in the base case. The price that is set in this market is the shadow price SP.

Supply curves are derived from the database of supply options in the model. Each supply option is characterised by costs, physical inputs and outputs and emissions. The potential contribution of each option is limited by the availability of the physical inputs and by the bounds on each supply option (e.g. a bound on wind energy because of the limited availability of suitable locations). MARKAL selects supply options on the basis of cost minimisation, thus simulating the supply curve.

If GHG permit prices are introduced, the supply curve moves in an upward direction because all emissions in the supply chain are penalised and transferred in the production chain through increasing energy and materials prices (S changes to S'). In the case of fixed demand (Figure 4.4), this has no consequences for the demand (EQ=EQ'). However, shadow prices are increased (from SP to SP'). In the case of elastic demand (Figure 4.5), demand decreases and a new equilibrium price and equilibrium quantity are achieved, below the prices and quantities in case of fixed demand.

Three variables are used to model the demand function: the elasticity, the maximum decrease of the demand, and the number of demand steps. The demand function is:

$$DM_{ip}/DM_{ib} = (P_{ip}/P_{ib})^{\wedge}(E_i)$$

where:
DM_{ip} = demand for i after introduction of GHG permit price
DM_{ib} = demand for i in the base case
P_{ip} = price i after introduction of the GHG permit price
P_{ib} = price i in the base case
E_i = price elasticity for i

The demand function is linearised into a step function. The number of steps can be chosen by the model user with a maximum of 20 steps (Loulou and Lavigne, 1996). The main modelling uncertainty regarding elasticities is the proper value of the elasticity coefficient. A literature study has revealed that the price elasticities from econometric literature diverge considerably (Franssen, 1999). The bulk of the long term demand elasticities ranges from -0.1 to -0.5. A significant part of the range can be explained by differing effects considered within this coefficient and different product price definitions. A default value of -0.5 has been applied for all 100 demand categories with a few exceptions, where better (generally lower) estimates have been derived on the basis of a bottom-up estimation procedure (Franssen, 1999).

The impact of elasticities is illustrated in Figure 4.6 for the 'globalisation' scenario (see Chapter 5 for a discussion of the scenario characteristics). The figure shows the impact of elasticities for increasing GHG permit prices. The impact is higher for higher permit prices. The maximum impact occurs at the permit price level of 200 EUR/t CO_2, equivalent to 300 Mt CO_2 in 2010 and 500 Mt CO_2 in 2030. These figures should be compared to the emission reduction without elasticities: 950 Mt in 2010 and 2000 Mt in 2030. These figure shows that the impact of demand reductions is 25-30% of the emission mitigation based on techno-economic optimisation.

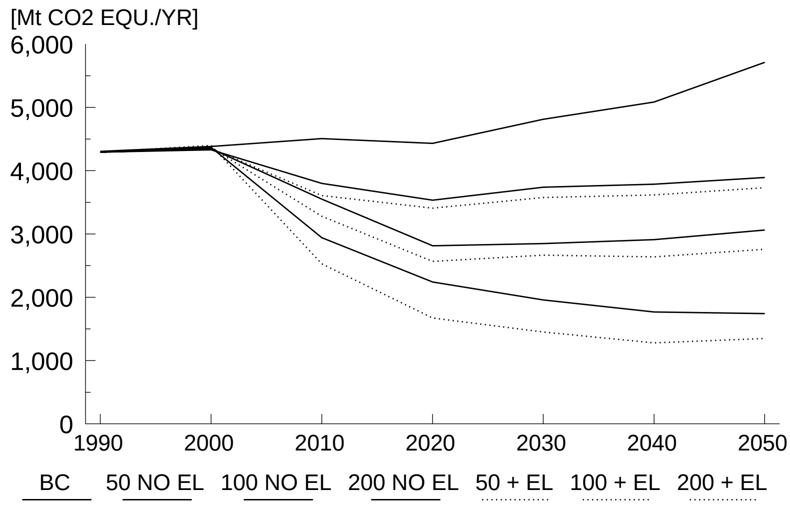


Figure 4.6 *Comparison of GHG emission reductions with and without elasticities, global scenario, for increasing permit prices(el = including elasticities)*

The impact of elasticities is generally a demand reduction in the range of 10-25%. Comparison of this figure and the resulting emission reduction indicates that limited demand reductions ease GHG emission reductions considerably, because demand reductions are concentrated in product categories with comparatively high emission intensities per EURO. Moreover within these demand categories, the fraction of demand with the highest emissions per unit of product can be avoided. As a consequence the impact is much more significant than one would expect on the basis of a general demand reduction on the basis of the ratio of GHG emissions and GDP.

4.4 Modelling biomass supply

4.4.1 Agricultural energy and materials crops

The selection of crops encompasses the important food and fodder crops and dedicated biomass crops (see Table 4.2). In the model, Europe has been split into North (Scandinavia), Middle and South. The South region has been further split into a high yield (HY) and low yield (LY) area, based on literature data regarding soil quality (Gerlagh and Gielen, 1999). Different crops have been selected for the Middle European region and for the Southern European region, because climatic conditions limit certain crops to certain regions. The crop selection and the crop characterisation is based on recent biomass feasibility studies and conference proceedings (e.g. Lysen, Daey Ouwens, Van Onna, Blok, Okken and Goudriaan, 1992). Apart from short rotation crops, afforestations and forest plantations have been considered.

Table 4.2 *List of biomass production processes in MARKAL MATTER 4.2*

Short rotation crops
Middle/North region
BP0 Biomass growing grass middle
BP1 Biomass growing grass middle extra fertiliser
BP2 Biomass growing wheat middle
BP3 Biomass growing wheat middle extra fertiliser
BP4 Biomass growing miscanthus middle
BP6 Biomass growing algae middle
BP8 Biomass growing marigold flower middle
BPA Biomass growing corn middle
BPB Biomass growing corn middle extra fertiliser
BPC Biomass growing rapeseed middle
BPD Biomass growing sugarbeet middle
BPE Biomass growing fodder middle
BPF Biomass growing sunflower middle
South high yield region
BQA Biomass growing sorghum south high yield
BQB Biomass growing wheat south high yield
BQC Biomass growing sugarbeet south high yield
BQD Biomass growing miscanthus south high yield
BQG Biomass growing grass south high yield
BQH Biomass growing grass south extra fertiliser high yield
BQO Biomass growing corn south high yield
South low yield region
BSA Biomass growing grass south low yield
BSB Biomass growing wheat south low yield
BSC Biomass growing olives south low yield
Afforestations
BR7 Coniferous roundwood afforestation north/middle
BR8 Coniferous roundwood afforestation south high yield
BR9 Coniferous roundwood afforestation south low yield
BRA Non-coniferous roundwood afforestation north
BRB Non-coniferous roundwood afforestation middle
BRC Non-coniferous roundwood afforestation south high yield
Forest plantations
BRD Willow short rotation plantation north
BRE Poplar short rotation plantation middle
BPH Biomass growing willow middle
BQE Biomass growing Eucalyptus south high yield
BRF Poplar short rotation plantation south

4.4.2 Forestry

Existing forests have been split into North, Middle and Southern Europe. Coniferous and non-coniferous forests have been added for simplicity reasons. A gradual increase of the annual increment has been assumed, which stabilises in the Middle of the next century as the forests approach maturity.

4.4.3 Residues from food production and food consumption

The food and fodder crops that have been listed in Table 4.2 result in significant quantities of by-products. Some of these by-products are currently used for animal fodder (see Figure 2.1). Others, mainly straw residues, are incinerated or left on the land for soil improvement. There is some potential for increased straw recovery. In the model it has been assumed that two thirds of all straw produced is required for other purposes. The quantity of straw available depends on the crop selection, which is endogenous in the model (in the range of 100-150 Mt dm).

4.4.4 Waste materials

Waste materials encompass:

- processing wood waste,
- lignin residues from chemical pulping and from ethylene production,
- post consumer wood waste,
- waste paper,
- kitchen waste.

All waste flows (except for kitchen waste) are generated endogenously within the model, depending on consumption trends for buildings, papers, packaging, etc.. Only for kitchen waste exogenous assumptions regarding future waste arising have been fed into the model, based on the analysis in Chapter 2.

4.5 Modelling biomass conversion

Figure 4.7 shows an important part of the biomass model structure that has been used for this study. The figure represents the use of wood and focuses on the supply side. The discussion following in this section focuses on the biomass use, split into bioenergy and biomaterials, and carbon storage in forests and soils. The use of paper and pulp is not discussed in this section because it is a traditional application. However it is included in the model calculations (Gielen, Gerlagh, Bos, 1998b).

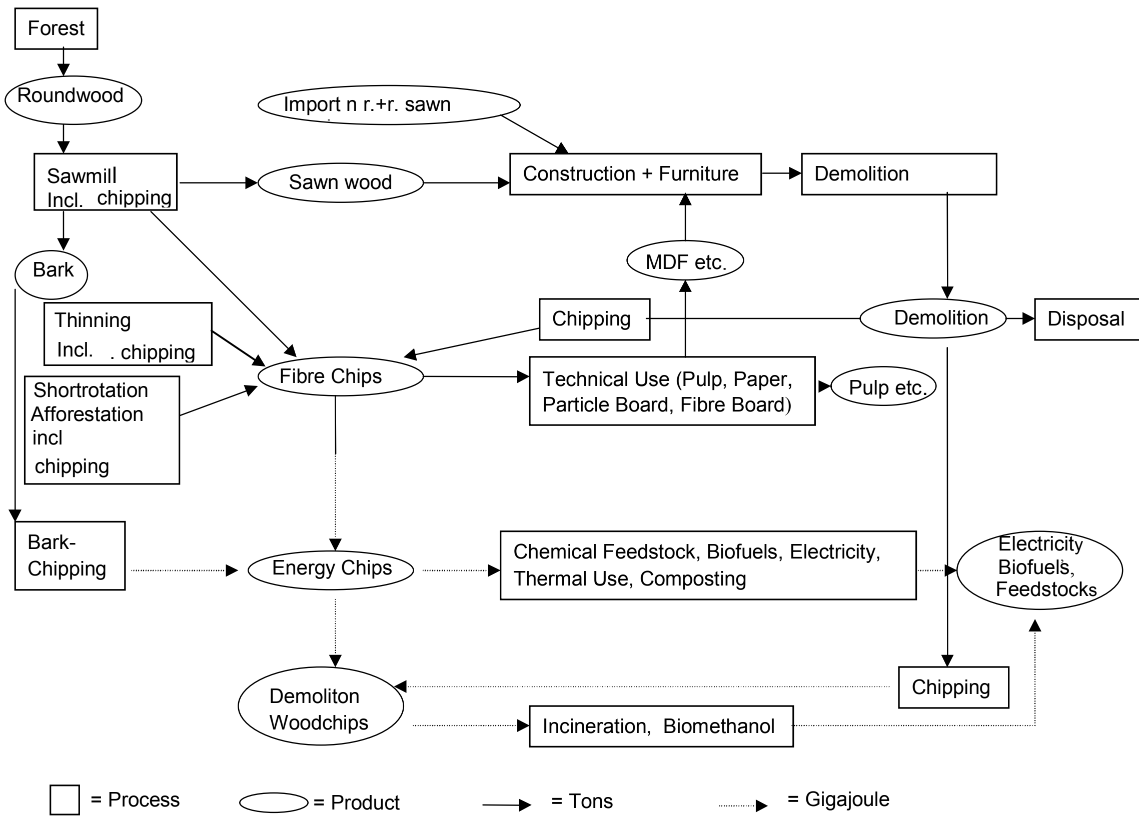


Figure 4.7 *Model structure for wood*

Figure 4.7 shows the different wood types which are modelled. The wood materials are modelled as a cascade with several quality levels, where every wood stream is also available for lower quality applications. For example roundwood can be used for timber for constructions but after chipping it could also be used for technical uses of energy use.

An important input of wood for materials is roundwood that is available in every region, the quantity depending on the resource base. However consumption may take place in other regions than where the forests grow. Transportation of roundwood from North to Middle and Middle to South Europe is modelled. The use of non renewable tropical hardwood is taken into account as an import.

The highest wood quality is sawn wood produced from round wood. Sawn wood is used for construction of dwellings and the making of furniture. Three types of single family dwelling and three types of multi family dwelling have been modelled for each climate region, which are distinguished by the quantity of building materials such as concrete and wood used. The use of sawn-wood in agricultural buildings, industrial buildings and offices is also modelled. A detailed description of the buildings can be found in (Scharai-Rad and Welling, forthcoming).

The second wood type is wood chips, e.g. from sawmill residues, (chipped) thinnings and short rotation forests. These can be used for paper, fibreboard and particle board. The boards are used in the construction of buildings and furniture.

Wood residues that are not suitable for technical use are modelled as clean energy chips. Besides use for conversion to electricity and heat these chips are also suitable as chemical feedstock for bio-plastics and for the production of biofuels. Because bark is not suitable for technical use the bark is only considered for energy applications. The last step in the cascade are the contaminated wood chips. These are handled as wood waste, only to be used in dedicated waste treatment plants. The current co-combustion practice for this type of waste (e.g. in coal fired power plants) is not considered because of pollution problems but for combustion in cement kilns.

Wood waste handling
In future contaminated and clean wood will be separated as strictly as possible. Therefore, in case the chips are contaminated it is assumed that the only option is waste incineration or a chemical conversion of waste into methanol. These chips are treated in the same way as demolition wood, which is also chipped and incinerated. Although clear, this system does not describe the current wood streams.

Nowadays part of the demolition wood is still re-cycled for use for board or paper production. For a proper representation of the current situation this option is modelled but only up to 2010. This is in line with the expected development within the EU waste handling policy. The same assumption is made for the disposal of wood waste. Because of the current practise it is modelled, but in future the disposal of wood materials will be forbidden.

Apart from wood, a number of agricultural products have been considered. For agriculture, the model can be split into dedicated crops and straw residues from the production of wheat, maize etc. (by-products from food production). The dedicated crops can be split into lignocellulose crops such as wood and straw and dedicated crops (this includes marigold flowers for solvent production, bacteria for biopol production, biolubricants etc.).

The wood chips are linked to the technical applications for wood from forestry (see Figure 4.7). Apart from the technical applications, the wood can also be applied for energy applications. Straw is only linked to the energy applications (including feedstocks for biochemicals such as acetic acid).

Co-combustion has been considered for coal fired power plants (both for steam cycles and for coal gasification IGCC) and for gas fired power plants. In case of IGCC and gas fired power plants, CO_2 removal has been considered as an add-on technology. This allows for biomass strategies with a net negative CO_2 emission: CO_2 is stored in biomass and subsequently removed in the combustion process (and permanently stored underground). However, this strategy can only be applied in case of sufficient CO_2 storage capacity (which is not available in all scenarios). The percentages of co-combustion that have been modelled are 10% in case of coal fired IGCC power plants and 25% in case of gas fired power plants.

Several dedicated biomass fired concepts have been considered. Two biomass gasification plants (BIG-CC) have been modelled (one based on wood, one based on straw), as well as a BIG-CC combined with a Solid Oxide Fuel Cell. Moreover, a smaller size stand-alone power plant has been considered. For industrial use, a small scale cogeneration plant (Total Energy unit) has also been modelled, based on the Stirling engine concept. Furthermore, two large scale cogeneration plants based on lignin (one boiler, one gasifier) are considered.

Three waste-to-energy plants have been modelled: waste incineration (grate firing) en two types of waste gasification: the Lurgi gasification and the Gibros PEC process. PEC technology is also adequate for CHP (including fuel cells) as well as syngas production.

Heating
In the heating market, a number of ovens and heating systems for industry, for agriculture and for residential heating have been considered. Moreover, the co-combustion of biomass in cement ovens has been considered.

Transportation fuels
Biofuels are liquid fuels produced from biomass feedstocks via a number of chemical processes. A number of biofuels can substitute both gasoline and diesel.

Gasoline substitutes/additives:
- Ethanol,
- Methanolm,
- ETBE/MTBE,
- Synthetic gasoline, based on Fischer-Tropsch synthesis.

Diesel substitutes:
- Rapeseed Methyl Ester (RME),
- Algae lipid methylester,
- DiMethylEster (DME),
- HydroThermal Upgrading (HTU) oil,
- Pyrolysis diesel.

Gaseous fuels
Three main routes have been considered for the production of biomass based gaseous fuels:
- anaerobic digestion (of kitchen waste and manure);
- landfill gas recovery,
- hydro-pyrolysis to produce synthetic natural gas (SNG).

Table 4.3 provides an overview of the processes within the model.

Table 4.3 *Biomass conversion technologies*

1+2 Production of liquid fuels/petrochemical feedstocks	
BO1/BO2/BO3/BO4/BO5	Sugar/starch from sugarbeet/sweet sorghum/wheat
BH3	Sugar/starch fermentation to ethanol
BH1/BH2	Cellulosis/hemicellulosis fermentation to ethanol
BH4	Ethanol 95% to 99%
BF1	Straw pyrolysis to methanol Batelle process
BF2	Wood chips pyrolysis to methanol Batelle process
BG1	RME from rapeseed
BI1	HTU oil production from wood
BI2	HTU oil production from lignin
BI3	Diesel from HTU oil
BJ1	Diesel from algae lipids
3 Production of solid fuels	
BB1	Straw briquetting
BC1	Wood chips from poplar/Eucalyptus
	Straw from crop residuals/miscanthus/sweet sorghum
IHA/IHC	Charcoal from wood for iron production
4 Production of electricity	
BD1	Lignine boiler/large industrial cogeneration
BD2	Lignine gasifier/large industrial cogeneration
BE1	Industrial CHP unit (Stirling engine)
BE2	Co-combustion in gas fired power plants 250 MW
BE3	Stand-alone biomass gasifier-STAG 100 MW
BE4	Biomass gasifier/SOFC
5 Production of building and construction materials	
IXA	Sawn wood production
IXB	Chipboard production
IXC	Durable wood through wood acetylation as tropical hardwood substitute
IXD	Durable wood PLATO process as tropical hardwood substitute

4.5.1 Materials

Materials can be split into:

- building materials,
- biochemicals,
- pulp and paper.

A number of building types are discerned for three regions (North, Middle, South). For each building type, a conventional brick/concrete alternative and a wood alternative have been modelled. The model structure for buildings is discussed in more detail in a separate report (Scharairad and Welling, 1999). Data for pulp and paper are based on earlier work (Hekkert, Joosten and Worrell, forthcoming). The model data for biochemicals have been updated on the basis of a BRED analysis (Diamantidis and Koukios, 1999). The production processes for biofeedstocks and biochemicals are listed in Table 4.4.

Table 4.4 *Production processes for biochemicals*

Ethylene/propylene/BTX production	
INH	Ethylene/BTX from wood flash pyrolysis
ING	Ethylene from ethanol dehydrogenation
INE	Ethylene/propylene/BTX from methanol pyrolysis (MTO process)
Other petrochemicals	
IOP	Acetic acid from biomass/synthesis gas route
IOQ	Butanol/acetone from fermentation
IOR	I-propanol from fermentation
IOS	Butadiene from wood flash pyrolysis
IOT	Phenol from lignine hydrotreatment
IOV	Surfactant (AES) from palm kernel oil
IOX	Marigold oil for solvents/resins in paint
IPC	PUR from lignine
IOY	PHB/PHV from sugar as PE substitute
IO4	Cellophane production
	Natural rubber for synthetic rubber in tires
BK1	Synthetic lubricants from rapeseed oil
IO3	Viscose for substitution of polyamide/PET
IOU	Carbon black from wood

4.6 Afforestation and carbon storage in soils

Afforestation

An example of afforestation modelling is shown in Figure 4.8. The figures refer to 1 hectare of agricultural land that is planted with trees. The life of the plantation is 50 years, after which the trees are cut. Carbon is stored in the trees during the growth period. Moreover, carbon is stored in the soil. The assumption is that all this carbon will be converted into CO_2 after the cutting of the trees (carbon storage in long life products is again accounted as storage). The assumption is that the growth rate of wood is 5 t/ha. yr (250 t over the whole life of 50 years). Because of the linear programming approach, the figures represent average growth rates over the life span of the plantations instead of the more realistic S-shaped growth curves. The carbon content of the wood is estimated to be 50% (1.8 t CO_2 storage/t wood). This is equivalent to 9 t CO_2 storage in aboveground biomass per ha. Moreover, it is assumed that the storage below ground is 5 t CO_2/ha/yr (see below). As a consequence, the net storage is 14 t CO_2/ha/yr, and 700 Mt CO_2 is released after 50 years (a simplification because all the carbon release is accounted for at once).

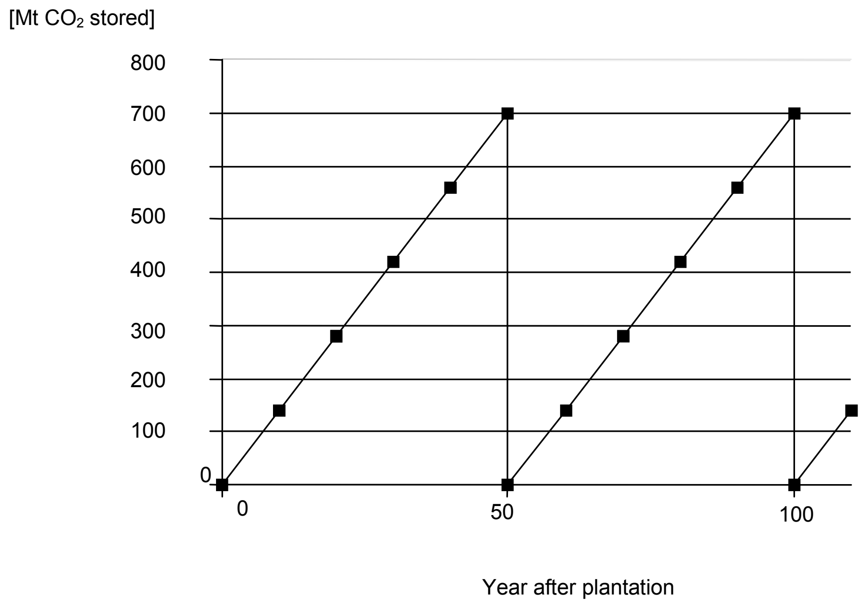


Figure 4.8 *Modelling of carbon storage in afforestations (above and below ground storage, 50 year rotation)*

Land use for afforestation has been split into North/Middle, South high yield and South low yield soils. A roundwood yield was assumed of 5 t/ha but for the South low yield region, where 2.5 t/ha was assumed. Carbon storage factors can be calculated on the basis of 50% carbon content of the wood: 9 t/ha in the high yield case and 4.5 t/ha in the low yield case (this excludes soil carbon, see below). The rotation length has also been varied in the South region (see Chapter 10).

Carbon storage in soils

Carbon storage is especially relevant for pastures and for forests (and forest plantations). However carbon storage in soils of existing forests can not be accounted in the framework of the Kyoto Protocol. For this reason, the potential of a carbon storage strategy for soils is limited to:

- grasslands
- afforestations/long rotation plantations.

Given the figures mentioned in Section 3.2, the storage factors in Table 4.5 have been applied.

Table 4.5 Model coefficients for carbon storage in soils

	Soil storage [t CO_2/ha/yr]	Life Span [years]
`BP0/BP1/BQG/BQH` (Grassland high yield)	2.75	15
`BSA` (Grassland low yield)	1	15
`BR7/BR8/BRA/BRB/BRC` (afforestation high yield)	5	50
`BR9` (afforestation low yield)	2.5	50

The modelling of carbon storage in soils is from a MARKAL modelling point of view similar to the modelling of carbon storage in the wood of new forests. The same modelling approach has been applied (in case of afforestations, the carbon storage factor has been increased from 9 t/ha/yr to 14 t/ha/yr in order to account for the 5 t storage in the soil). The assumption is that all this carbon is released after the life of the plantations.

The results show in the base case an annual exchange of 110-150 Mt CO_2 between soil and atmosphere from grasslands. From a CO_2 accounting point of view, the model is now biased in favour of carbon storage in soils (because the carbon storage is now fully accounted, while no consideration is given to the fact that either land use is fixed eternally or the CO_2 is released again). Given the time frame of the GHG problem (50-100 years), this is considered an acceptable simplification (land use changes beyond this time horizon are thought to be irrelevant).

4.7 Modelling GHG emissions

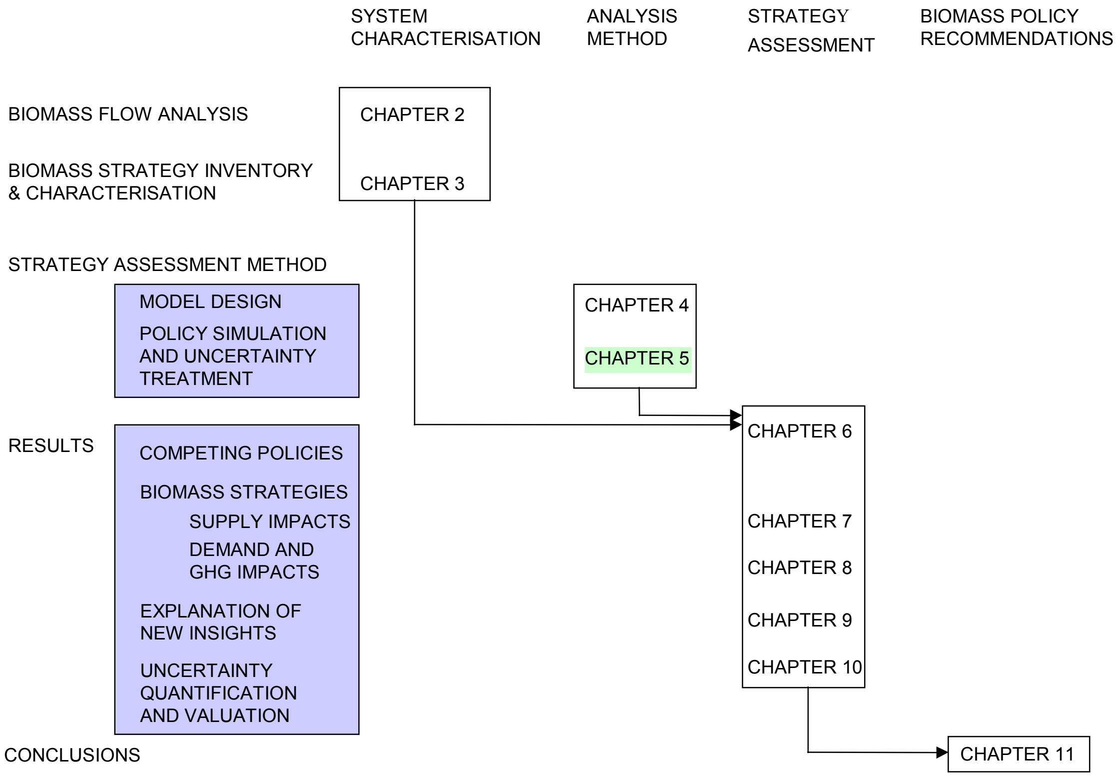
The emission accounting is basically based on the IPCC emission accounting guidelines (IPCC, 1997). GHG emissions can be split into CO_2 emissions that are related to fossil fuel combustion on one hand and on the other hand inorganic CO_2 emissions, CH_4, N_2O and PFC process emissions. The fossil fuel related CO_2 emissions are directly related to the carbon content of fossil fuels (a fixed relation). The process emissions depend on the process conditions and require detailed insight into the process conditions. This difference has significant consequences for the accounting approach.

CO_2 emissions of fossil fuels are modelled on the imports or the mining processes (i.e. the system inputs). Negative emissions (carbon losses) are modelled for the system outputs (exports, below ground CO_2 storage, afforestations). The actual emissions occur when the fuels are combusted, but such an accounting framework is complicated. For example, if methanol is used as fuel, it is not clear whether this methanol has been produced from natural gas or from biomass. Proper accounting would require the modelling of carbon storage for biomass growing and subsequent carbon release for methanol combustion. However the CO_2 emissions during methanol production from natural gas must also be considered for proper accounting. This requires a very complicated and laborious accounting framework, the carbon balance on the basis of the total system inputs and outputs is a much easier approach.

Inorganic CO_2 emissions, CH_4 emissions, N_2O emissions and PFC emissions are modelled as coefficients that are proportional to the activity of a specific process within the system.

For CO_2, a correction has been applied for the import of materials with significant emissions abroad that are related to Western European production (e.g. for imports of tropical hardwoods from regions where harvest exceeds growth, see also Table 1.2). This is balanced by a subtraction of emissions for materials produced in Western Europe for consumption abroad (see Gielen, 1999c, for a more detailed discussion).

5. DEALING WITH UNCERTAINTY



5.1 Introduction: treatment of uncertainty in preceding studies

Uncertainty is one of the key problems with regard to the use of model results for policy making. The uncertainty of the policy advice must be clear and must be clearly communicated as part of good advisory practice, because it influences the policy conclusions that can be drawn from a study. Moreover, the characterisation of uncertainty is a key element of sound scientific analysis. Biomass is typically a topic where uncertainty seems to be exceptionally large (see Section 1.5). For these reasons, two chapters in this report are devoted to uncertainty analysis (Chapter 5 and Chapter 10).

Uncertainty analysis is not a new topic in relation to MARKAL modelling. A number of approaches with regard to uncertainties emerge from earlier ECN-studies:

- The use of scenarios with regard to discount rate, fossil fuel prices, and policy regimes (e.g. the EMS study (Okken et al., 1993) and Syrene study (Ybema et al., 1995).
- The use of the cost/benefit indicator in MARKAL (e.g. in Syrene (Ybema et al., 1995).
- The use of sensitivity analysis for individual input data (e.g. in MATTER (Gielen, 1999c).
- Cost structure analysis for individual technologies and process chains (e.g. in a MARKAL biomass study for Novem (Gielen and Van Doorn, 1995).
- Hedging analysis for future CO_2 policies/uncertainty regarding emission reduction targets (Ybema and Kram, 1996).
- Expert review of model input parameters (e.g. Gielen, 1999b; IEA, 1997).
- Comparison of model input data with model input data from other regions.
- Comparison of modelling results and results from other studies.

The overview shows that the treatment of uncertainty is not consistent and rather ad-hoc. The following analysis provides an overview of the BRED uncertainty approach, which is based on (elements from) the mentioned earlier approaches.

5.2 Sources of uncertainty

Uncertainty on the systems modelling level can be divided into a number of categories according to the taxonomy developed by Wynne (Wynne, 1992):

- Indeterminacy: the system is complex or open, and thus defies prediction. If the system structure and the relation between system inputs and outputs are not known, it is not possible to identify relevant systems parameters, nor is it possible to define strategies to steer the physical systems configuration.
- Risk: the systems parameters are uncertain, but their probability distributions can be assessed. A Monte Carlo analysis is an example of a method that can be used to consider risk in decision making.
- Uncertainty proper: the systems behaviour is known, but its parameters cannot be described probabilistically. Model sensitivity analysis can help to identify the key parameters where this problem is relevant.
- Ignorance: what is not known is not known. Ignorance can be passive or active. Analysts can ignore issues because they deem them irrelevant, infeasible or improper. Active ignorance can be laid bare by extensive review and discussion, particularly by peers outside the narrow community. Passive ignorance refers to our limited capacity to know and understand. A structured approach to passive ignorance is inconceivable.

A number of different taxonomies exist (see e.g. Van der Sluijs, 1997, for a discussion), but their added value is generally limited. For this reason, they will not be discussed in more detail. Not all types of uncertainty are relevant for this systems analysis study. The energy and materials system is not indeterminable. Energy systems analysis is a well-established scientific activity. Analysis has shown that the materials system can be adequately described through a limited number of parameters. Analysis of historical trends indicates gradual changes that suggest that extrapolation is feasible. Regarding model input data, uncertainty proper is a more relevant issue than risk. Probability distributions for input data are only known for a limited number of model input data. Moreover, the sheer number of input data does not allow a comprehensive risk analysis. Uncertainty of model input data is a very relevant issue. Ignorance is the most difficult issue at stake. Some elements can be described in qualitative terms (e.g. which research approach would probably yield better results, but which is infeasible because of time and budget constraints).

The following discussion focuses on uncertainty properly.

5.3 Uncertainty handling strategy

The preceding two paragraphs have shown that a number of uncertainty categories can be discerned in systems engineering, and a number of uncertainty treatment methods can be discerned. In the analysis in this section, these elements will be linked to the modelling project stages. The results of the following modelling tasks must be validated and their relevance for the robustness of the conclusions must be assessed:

- input data,
- model structure,
- model results.

These tasks will be discussed separately.

5.3.1 Process input data uncertainty estimation strategy

Key uncertainty elements concerning input data are:
- Process data quality,
- New technology feasibility,
- Future policies, prices and demand structure.

These issues will be discussed separately.

Process data quality

Data taken from literature generally require extensive processing to make them suitable for model input. A major problem here is that the system boundaries in literature studies - both for energy and material inputs and outputs and for financial parameters - are often either different from the model system boundaries for processes or they are not clearly described. System boundaries refer to a certain time-related coverage, geographic coverage and technology coverage (Vigon, 1997). For example in a Western European model, the process data for blast furnaces in 1990 should represent the average blast furnace in 1990. However, data available for a specific plant may differ significantly from the Western European average, or they might relate to a different year. If data for different plants are available, then differences in energy use between individual plants can be attributed to different technology, a different plant age, the use of other resources, or a different product mix. A comparison of energy efficiencies on the basis of aggregated data for similar sectors in different countries is therefore often misleading and detailed analyses are required.

Technological progress and new environmental legislation, energy efficiency, labour productivity and investment costs for agricultural activities can imply a significant difference from the situation 10 years ago. Obviously the situation is even more problematic for a model that covers half a century. Generally speaking, many cost data can only be generated with an uncertainty in excess of 25%, while the physical characteristics can be obtained with an uncertainty below 10%.

Sensitivity analysis can be applied to identify key parameters. Given that the model contains thousands of parameters and each model run takes half an hour, such a sensitivity analysis is in practice limited to a selection of parameters.

The task of process data quality assessment can be facilitated by smart selection of key parameters. For example the combination of data uncertainty and process relevance for the whole system determines the sources with the highest level of uncertainty. *High uncertainties* for processes with low relevance from a systems GHG emission point of view are less relevant than *average uncertainties* for key processes with high relevance from the same point of view. Validation of model parameters should focus on such key processes. Moreover, the uncertainty of competing processes must also be taken into account. Too much attention is generally focused on the input data for existing processes for the year of commencement, while the uncertainty of data for new processes is not considered. However, this uncertainty is just as relevant for the comparison of new and existing processes in future decades.

Because various chains of processes transfer the cost of natural resource extraction to the final consumer, data quality requirements can depend on the data quality in another part of the system. It is difficult to trace such the impacts of such uncertainties through the system. Because MARKAL is an LP-optimisation model, monetary flows can be used for the analysis of such interactions. However this method is currently not widely applied because it is laborious and complex.

The accuracy of the data and how they affect the optimisation's conclusions is a complex issue. Future process data are not amenable to standard statistical analysis; i.e. they are not random samples taken from large populations that result in normal distributions around a well-documented average. No adequate method has yet been developed to incorporate data quality into the MARKAL type computer models that perform the calculations. The Monte Carlo approach that is in current use in risk analysis (and which is proposed for use in LCA (Vigon, 1997) offers no viable option because of the years of calculation time that are required.

New process feasibility
An important focus of the study is the analysis of the impact of technological progress. The data for new technologies are based on a mix of desktop studies, data for laboratory tests, data for pilot plants and data for first-of-a-kind plants. Technological feasibility increases along with the scale of the development and demonstration units. Many technological problems are outside the energy or GHG scope. However, these problems often prove to be major bottlenecks for introduction of new technology. They explain to a large extent the 'gap' between rather optimistic bottom-up models based on a technology assessment approach and the more conservative top-down models based on historical econometric analysis of autonomous energy efficiency trends, etc.. Such bottlenecks can be simulated in the bottom-up approach by a maximum restriction on the penetration or a maximum restriction on the penetration rate of very promising, but uncertain, new technology.

Future policies, prices and demand structure
Policies will change over a period of decades. Changing energy policies and changing environmental policies are dealt with by scenario analysis. However, labour policies, agricultural policies, educational polices and foreign affairs policies can also have a significant impact on the future. The relevance of these policies can only be assessed on the basis of expert estimates. The price of resources (e.g. future energy prices) are key parameters for the techno-economic analysis of GHG emission reduction. Prices over the past three decades have been three times as high as the current level. At the time, price forecasts suggested even higher prices. Current insights suggest low fossil fuel prices for the next few decades, but forecasts may change again when markets point in an upward direction. Finally, the future demand structure is a key source of uncertainty. While the demand for existing products can be forecast within a 50% range of uncertainty, the demand for new products is much more difficult to assess. Comparing the consumption levels and consumption structure of the 1940's with current consumption levels indicates the rate of structural change that can occur. No special attention has been devoted to the forecast of demand growth for new product categories in this study because little is known about the composition and production technologies, etc. This may be a cause of underestimating emissions.

BRED input data generation and validation has been based on the following procedure:
1. Selection of relevant materials and products through MFA (BRED task 1).
2. Inventorying of current processes and alternatives based on the situation abroad, on data for pilot plants and on engineering studies.
3. Data collection for these processes by experts, based on literature sources.
4. Estimating missing data on the basis of similar processes and on the basis of thermodynamic relations.
5. Data validation, based on expert interviews and expert workshops.

A lot of effort has been put into the documentation of the model. A large number of reports with input data and background information for these data have been compiled (Koukios and Diamantidis, 1998; Scharai-rad and Welling, 1999; Gerlagh, 1998a; Gielen, Gerlagh and Bos, 1998a; De Feber and Gielen, forthcoming; Scharai-rad and Welling, forthcoming; Diamantidis and Koukios, 1999). The database that is used for this study is available via Internet (*http://www.ecn.nl/unit_bs/markal/matter*). This is a first step in the process of proper discussion of the model input.

The quality of input data was measured according to the following criteria:
- the number of independent data sources,
- conflicting literature data have been interpreted as an indication of limited data quality,
- the age of literature data has been interpreted as an indicator of their quality,
- the perceived technological feasibility which increases in the order: estimates, engineering studies, pilot plants, full-scale production,
- collection of expert opinions regarding the input data quality through presentations at a large number of meetings.

Compared to earlier MARKAL studies at ECN (Gielen and Van Doorn, 1995; Gielen, Gerlagh and Bos, 1998a; Gielen, Lako, Dinkelbach and Van Ree, 1998) the general change of the input data is toward higher efficiencies and lower cost of energy recovery from biomass, while the production of biofuels and the production of biomaterials is characterised by increasing costs and decreasing efficiencies. However the data for the reference technologies have also changed. Especially in electricity production, data for gas fired power plants have been adjusted with regard to higher efficiencies and lower cost.

5.3.2 Uncertainty treatment for model structure design

The results are to a large extent determined by the model characteristics. The use of the MARKAL MED algorithm, for example, is a choice with significant impacts on the results (see the analysis in Section 4.3). Vos and Vellinga discern two approaches in connection with systems modelling(Tol and Vellinga, 1996).

The first approach tries to capture the underlying system as well as possible, resulting in very detailed models. The more detail, the less pronounced is the so-called ‘flip-flop’ effect which is generally seen in simple LP optimisation models (‘flip-flop’ is the sudden switch from one system configuration to another as a certain parameter exceeds a threshold value. This feature is often raised as a ‘proof of deficiency’ of the LP approach). Whether the model is sufficiently detailed depends on the type of question. Given the results which show gradual changes the model seems sufficiently detailed. However one could argue that this is not the case for results on a more detailed level, e.g. in the case of Southern Europe (see e.g. Chapter 7).

The second approach tries to capture the range of possible directions in which the underlying system may develop as well as possible without much endogenous model detail (‘scenario approach’). The choice to base this study on the former approach was made because the primary goal of this study is to provide more insight into system structure with regard to biomass and R&D and policy issues on a detailed level. However given the comprehensiveness of the system, scenarios have been added for analysis of economic and social driving forces beyond the scope of simple techno-economic optimisation (see Sections 5.4-5.6).

The current MATTER model structure has been developed on the basis of:
- analysis of currently relevant flows and processes,
- development of a generic model structure, based on physical characteristics of energy carriers (solid, liquid, gaseous) and end use categories,
- a literature study of possible future process routes,
- a literature study of GHG emission reduction strategies.

5.3.3 Uncertainty analysis for modelling results

There are no data to validate ex-ante calculations. The model is not suited for ex-post analysis where such data would be available. One of the main reasons for this is that uncertainties *at that time* (uncertainties on energy prices and technological change for instance) are *currently* facts that will result in a bias in the model building process for historical years. Validation of results from model calculations in the 1970's and 1980's suggests that these models did not represent the future adequately. The main reasons were completely wrong estimates of fossil fuel prices and wrong estimates of production growth. However one can argue that the modelling capacities have improved, so the current estimates are better than historical ones.

Some validation can be drawn from the comparison of the BRED results and results from other ex-ante model calculations. However, detailed models in this area of research are scarce, and the availability of well-documented results is even more limited. Moreover there is a danger of dependency between seemingly independent sources, as the body of knowledge in this field is limited. Such comparable results suggest validation while this is not the case. Especially in the area of biomass, with a large body of desktop studies of varying quality but little 'real world' data for validation, this is a major problem.

The model results are validated through a comparison of material flows and process activities that are calculated by the model for 1990 with flows and activities according to statistics (see the reports for task 1). In the base case (without GHG emission reduction) major deviations from the current systems configuration are only likely to occur over the next few decades if such changes can be explained by changing conditions (e.g. changing technology, changing resource prices, or a changing demand). If the model calculations show major changes that cannot be explained by such factors probably the model does not represent the actual situation accurately, and the model parameters and the model structure must be adjusted. Another important quality check is based on so-called shadow prices that are generated by the model. A gradual trend of the shadow prices of materials, products, and energy carriers over a period of time is an indicator of a good model structure. Fluctuating shadow prices indicate model instabilities, caused by restrictions on processes, supply or demand. The model structure has been adjusted in such cases.

Comparison with chain analysis studies (e.g. LCA studies, sector scenario studies) is another valuable quality check. Such studies provide a valuable yardstick for identification of remarkable results. Where differences do occur, detailed analyses of model inputs and outputs and sensitivity analyses can be applied in order to validate the results of the model calculations.

In conclusion the following methods have been applied for uncertainty characterisation regarding modelling results:

- scenario analysis (see Sections 5.4-5.6),
- sensitivity analysis (including benefit/cost analysis; see Section 5.7, 10.2 and 10.4),
- discussion of the expert review of the model structure, input data and results (see Section 10.1),
- discussion of results in comparison to other studies (Section 10.3),
- discussion of model expansions which have not been applied and their consequences (Section 10.5).

5.4 The scenario approach

In a fluid environment there are many possible futures. In a situation where the future depends on a large number of external factors, a reduction of complexity is required in order to allow further analysis. One way to approach this problem is the scenario approach. In a scenario approach, logic combinations of external factors are selected for further analysis. The probability of these combinations is no criterion for their selection. Strategy must now embrace 'what if?' questions that go outside the reach of our habitual mindset. Explorative scenarios are especially suited for long term analyses that provide insight into future trends on a high aggregation level (Weterings, Kuijper and Smeets, 1997).

A scenario is a view of the future that is logically derived from a set of assumptions concerning driving forces and trends in the society. Scenarios are distinctly structured views of the future that are self-consistent and plausible. The basis for a scenario is a scenario story. Scenario stories not only portray images of the future but also a pathway of events through time that could lead us from where we are now to that future world. Underlying this must be an understanding of the driving forces that are likely to shape our future. The set of scenarios should cover a broad scope of possible developments. Scenario analysis is important for policy making in order to analyse the sensitivity of the conclusions. The difference with conventional sensitivity analysis (see Chapter 10) is the logic combination of factors and the consistency of the assumptions. Developing scenarios of the future begins from becoming more aware of what is going on right now. There are always pockets of the future in the present. Some countries do things today that will take five or ten years to reach other countries. Some sectors of society are right now living in a way that is our future. Some people have ideas that will take twenty years to incubate and become generally accepted. Technologies exist that people have not yet heard of that will one day be commonplace.

Scenarios should:
- each present an imaginable coherent future,
- be structurally distinct,
- definitely not be confused as predictions,
- contain variables of interest and potential impact on directions,
- refer to pockets of 'future in the present',
- be challenging to customary assumptions and frameworks.

One must keep in mind that the goal of the analysis is not a precise *forecasting* of the future - the experience over the last three decades has shown that forecasts of modelling studies of this kind are generally inadequate. Instead, the model calculations represent an analysis of strategies in the framework of *feasible developments* for the future. The goal is 'modelling for insight, not for numbers' (Voss, 1997). *The goal of scenario analysis in this study is the selection of robust biomass strategies that are applicable in different possible future environments.*

5.5 Three scenario stories: Globalisation, Fortress Europe and Sustain

Looking at other energy scenario studies (e.g. Capros, Kokkolakis, Makris, Mantzos, Antoniou and Guilmot, 1995), important parameters for energy scenarios are economic growth rates, sectoral growth rates, discount rates and oil prices. These scenarios can be characterised as 'simulation scenarios' that focus on external economic factors. The following scenarios can be characterised as 'normative scenarios'. They focus on policy initiatives within the economy and lifestyle parameters within the economy. The paradigm is very different: a future which can be shaped by policy making, instead of an unpredictable world subject to poorly understood forces in society. It allows a very different discussion: in case the outcomes differ significantly, it might be worthwhile to strive for a certain scenario through policy making.

The Globalisation scenario
'The Japanese dream'

World trade increases dramatically. Due to the dynamic economic development and due to increasing global co-operation, technological development in many areas progresses rapidly. Europe is one of the main players on the world market. R&D policies stimulate technological progress, which is necessary to be able to compete on the world market. Products should be of high quality and sold against reasonable prices. Due to the worldwide competitiveness, the European import and export increase.

The economic growth is relatively high. However, due to strong technological progress, the dematerialization impacts are large (growth is concentrated in knowledge intensive sectors such as software and biotechnology). Therefore, the physical demand increases moderately. The fossil fuels prices increases moderately due to a combination of moderate physical demand growth, technological progress in fossil fuel extraction and due to competitiveness forces on the world market.

European and world wide supra-national institutions gain a more powerful position in relation to the national governments. The impact of national policies is limited. Market forces rule the economies. Government policies are limited to the removal of market imperfections and the generic market boundaries reflecting e.g. environmental policies.

People prefer luxury and comfort. The importance of material wealth makes it unlikely that lifestyles are adapted solely for environmental arguments. However the consumer preferences shift towards 'smart products' instead of status symbols: people prefer paying for new technologies and devices rather than changing their lifestyles. The structural change, driven by the combination of technology and changing preferences, is the main cause of decoupling of economic growth and the physical energy and materials demand.

The Fortress Europe scenario
'The American dream'

Europe protects its own market. Neither a strong competitiveness on the world market nor environmental values are strong stimuli for technological progress. Therefore, technological progress is less than in the globalisation scenario. Growth is concentrated in traditional industry sectors.

On the demand side, emphasis is on improvement and extension of existing energy and materials intensive products: for example luxurious passenger cars, more living space, and short vacations around the world.

The combination of moderate technological progress and a moderate economical growth result in a higher of the physical product demand than in the globalisation scenario. Fossil fuels prices increase significantly due to an increase of the physical growth around the world and the development of a new strong oligopoly on the energy supply side.

Power of the European parliament and European Commission increases. European policies replace national policies to a large extent. On the European scale, economical values dominate; environmental policies play a limited role. Other policies than greenhouse gas emission policies, e.g. agricultural policies, play an important role due to the European market which is closed to foreign producers.

The Sustainability scenario
'The green dream'

The European governments accept the shortcomings of the conventional definition of the Gross Domestic Product and decide to switch to a system of sustainable national accounts (Okkerse and Van Bekkum, 1996). This system is also introduced by the industry. Environmental impacts are fully endogenised into prices of goods and services based on marginal emission abatement costs at set policy goals and through a system of tradable emission permits. An ecological tax is introduced. First subsidies on energy are cut. Next, fiscal burdens on human labour are gradually reduced over a period of decades, while taxes are levied for non-renewable resources.

Governments are reorganised in order to support the changing policy priorities. The European and national economy, agriculture, transportation and agricultural, public housing, and cultural directorates are superseded by a European environmental planning council. Government intervention increase but is based on soft lifestyle policy instruments combined with strong R&D policies. This includes strong investments in the service economy, for example investments in improved public transportation systems and large investments in telecommunication.

The trend towards individualism is reoriented towards a positive contribution to society.
A strong emphasis on environmental values stimulates environmental progress by strong R&D and environmental policies. Yields increase due to improved growing and harvesting methodologies. Changes in the fodder composition and fodder use do increase the productivity of cattle breeding significantly while lowering the environmental impacts. Therefore, less land and less animals are required for the same amount of agricultural products. Consequently environmental impacts are reduced.

The number of working hours decrease. Leisure time is filled with sports, music, parties, cultural events and political discourses in order to support these changes. Environmentally destructive leisure activities such as short distance holidays are strongly discouraged.

5.6 Quantification of scenario parameters

Table 5.1 provides and overview of model input parameters that characterise the three scenarios. The first four parameters have been selected because of their importance for biomass and land availability. The remaining eight parameters have been selected because they determine the GHG emission trends and the emission mitigation potentials to a large extent. The physical demand growth is the result of GDP growth minus dematerialization. In practice demand growth rates are fed into the model on the basis of physical units (e.g. vehicle kilometres, tonnes packed beverages, useful floor surface etc.). A detailed discussion can be found in (Gielen, 1999c).

Table 5.1 *Scenario characteristics, 2030*

Parameter		Globalisation	Fortress Europe	Sustain
Meat/fish consumption	[Mt/yr]	45	45	38
Import soy	[Mt/yr]	75	30	0
Paper demand	[Mt/yr]	90	90	65
Meat export	[Mt/yr]	15	-?	0
GDP growth 1990-2030	[%/yr]	2.0	1.5	0.5
Dematerialisation	[%/yr]	1.5	0.5	0.5
Physical demand growth	[%]	0.5	1.0	0.0
Discount rate	[%/yr]	8.0	5.0	3.0
Fossil fuel price growth	[%]	+ 35	+ 75	+ 0
Nuclear	[EJ electricity]	2.5	0	0
Cheap PV	[EUR/kW peak]	1100	500	500
CO_2 storage	[Mt/year]	500	500	0

5.7 The MARKAL benefit/cost ratio

The MARKAL benefit/cost ratio allows a rapid analysis how close processes/new technologies are to introduction. This indicator is a measure for the cost-effectiveness of processes. It is defined as:

B/C = Annualised total financial benefits/Annualised total financial costs

The financial benefits are defined as the value of the process outputs. These outputs are valued on the basis of the model product shadow prices (which are equivalent to the product prices that would occur in an ideal market). The financial costs are calculated on the basis of the combination of financial process data, the physical process inputs and the process emission data:

Costs = Annuity of investment
+ fixed process costs
+ variable process costs
+ costs of physical inputs
+ emission permit prices

The annuity of the investment A can be calculated:

$A = r/(1-(1+r)^{-n}) \times I$

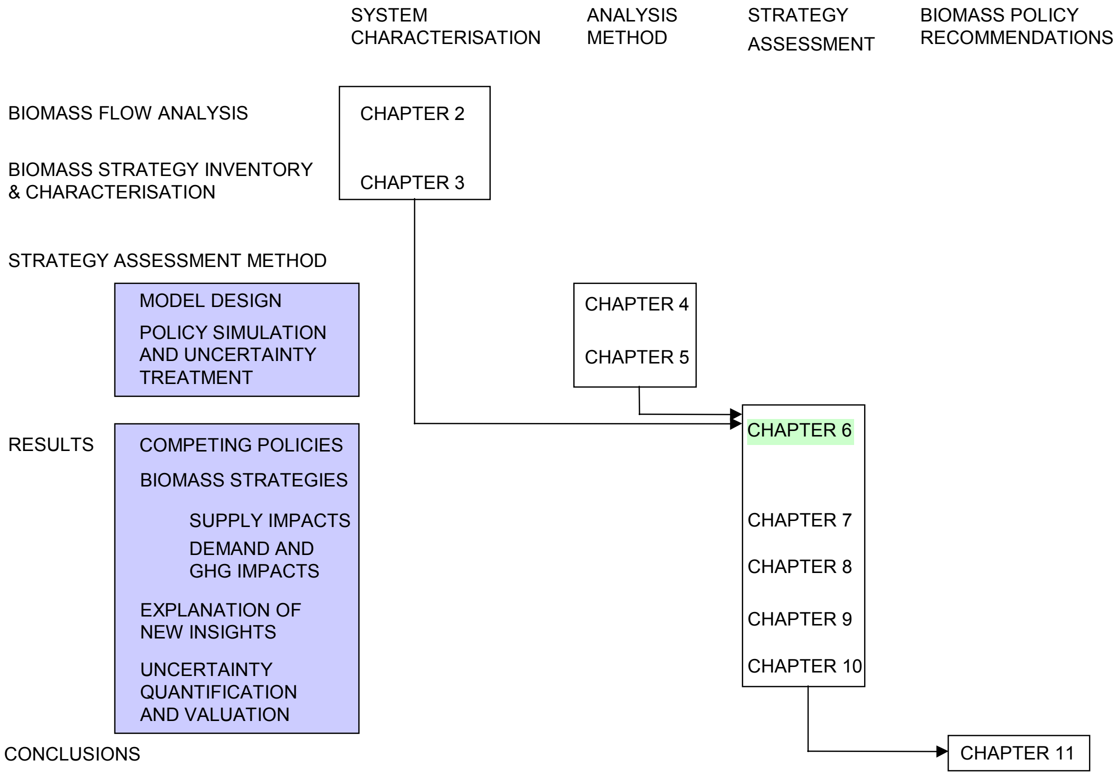
With r equal to the discount rate, n is equal to the process life span and I is equal to the investment sum.

Basically three types of B/C ratios occur: higher than 1, equal to one and below one. In case the ratio is higher than 1, it would be cost-effective to apply more of a certain process (because a profit can be made, hence reducing the system costs objective function). This situation can only occur if the process application is limited through bounds. It is worthwhile to check the validity of these bounds in case this situation occurs. A B/C ratio of 1.0 indicates that the process application is balanced: the supply meets the demand and the process represents the 'marginal producer' who does not make any profits. In case the B/C ratio is below 1, the process is not applied unless lower bounds are specified. The application of the process results in losses.

Especially in the latter situation, the benefit/cost ratio provides additional information compared to the analysis of the physical and monetary flow data. In case a process is not applied, these flows will be zero. However a benefit/cost ratio between 0.9 and 1.0 indicates that the benefits are less than 10% below the costs, so the gap to introduction is rather small. A benefit/cost ratio below 0.5 indicates a significant difference and a cost reduction of a factor two is required before introduction.

The benefit/cost ratio is a measure for the robustness of the modelling results. If competing technologies show a benefit/cost ratio above 0.9, the results regarding the technology selection are not robust (especially the uncertainty in cost input data is generally well above 10%).

6. THE FRAMEWORK: GENERAL RESULTS FOR THE WESTERN EUROPEAN ENERGY AND MATERIALS SYSTEM



In order to understand the results for biomass, it is important to consider the results for the economy as a whole. It has been stated before that emissions can be reduced in many ways, biomass strategies pose only one category. Due to the emission reductions, the reference energy and materials system will change, thus changing the potential for emission reduction on the basis of biomass.

The first issue to be discussed is the trend of GHG emissions in the base case and the underlying emission driving forces. The base case is the situation without GHG policies. Next, the impact of GHG permit prices and the impact on the systems configuration will be elaborated.

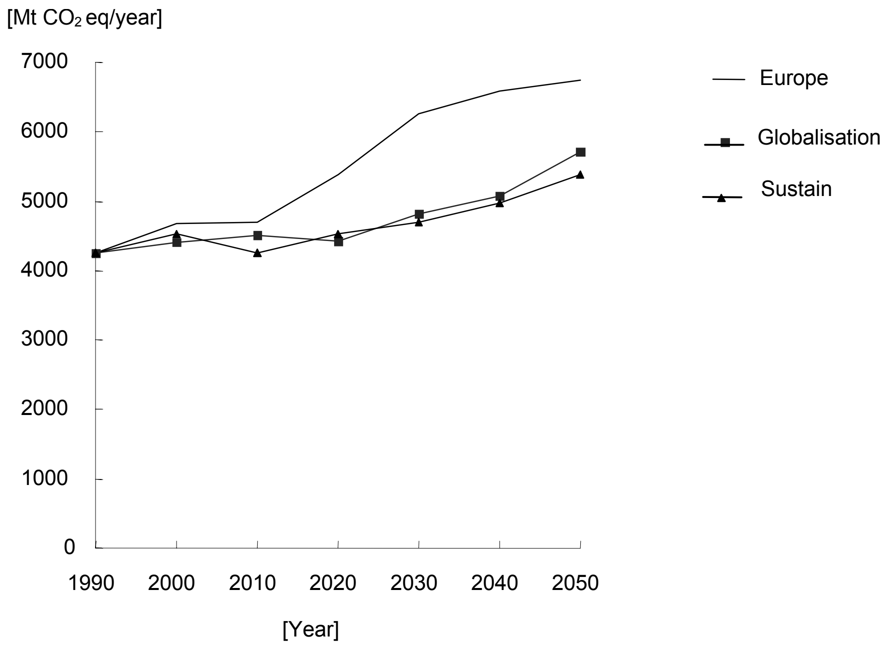


Figure 6.1 *GHG emissions in the base case, period 1990-2050, 3 scenarios*

The GHG emissions in the base case are shown in Figure 6.1. The figure shows the total for 4 categories of emissions according to the Kyoto Protocol, aggregated for the 100 year GWP time horizon according to the Kyoto Protocol conventions (CO_2, CH_4, N_2O and PFC). The CO_2 emissions include foreign emissions related to Western European consumption, but exclude emissions within Western Europe for foreign consumption (for example emissions related to wood imports are included, while emissions for net steel exports are excluded (Gielen, 1999c). However this correction (net GHG 'imports' – 'exports') is of secondary importance (additional emission 100 Mt in 1990). The growth of emissions until 2010 is moderate in all three scenarios. In fact, the sustain scenario shows even a slight decline. This moderate growth is the results of a number of interacting developments: closure of the Eastern German inefficient industry (part of the Western European economy), substitution of coal by natural gas and a significant autonomous reduction of non-CO_2 GHG emissions, driven by e.g. waste policies and agricultural policies (e.g. nitrogen fertiliser standards). However the picture changes dramatically after 2010. The reason is the continuing economic growth that is not balanced anymore by autonomous trends. Especially the Fortress Europe scenario shows a very significant growth of emissions. The growth is more moderate in the Globalisation and Sustain scenarios. In 2030, the reference year in the following chapters, the emission ranges from 4800 Mt in the Globalisation and Sustain scenarios to 6200 Mt in the Fortress Europe scenario. The growth of total emissions between 1990 and 2030 ranges thus from a mere 12% to 46%. Note that the Globalisation scenario and the Sustain scenario result in comparable emission levels, while the socio-economic development is radically different: the relation between economic growth and GHG emissions is complex, several routes can result in a more sustainable development.

The primary energy demand in the base case for all three scenarios is shown in Figure 6.2. The picture is very different from the development for GHG emissions. The Sustain scenario shows a decline of energy consumption between 2000 and 2020, spurred by negligible economic growth and increasing energy efficiencies. Primary energy demand in 2030 is only 52 EJ (-16% compared to the reference year 1990). The Globalisation scenario shows a moderate growth to 69 EJ in 2030 (+11%). The Fortress Europe scenario shows the most significant increase, up to 80 EJ in 2030 (+30%).

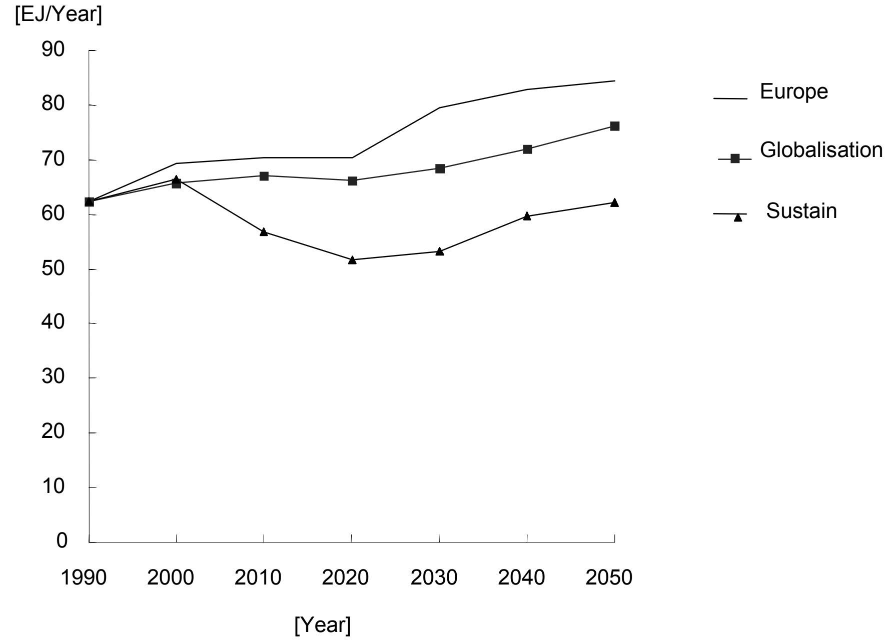


Figure 6.2 *Primary energy demand in the base case, 3 scenarios, period 1990-2050*

Comparison of the trends in GHG emissions and the trends in primary energy use indicates carbonisation trends in the Sustain scenario and Fortress Europe scenario, while the average carbon intensity of energy use remains constant in the Globalisation scenario. These trends can be explained through a change towards more coal and a ban on nuclear in the Fortress Europe scenario, and a ban on nuclear in the Sustain scenario. These trends overrule the introduction of significant quantities of natural gas in all three scenarios. The absolute quantity of renewables remains at the same level in all three scenarios.

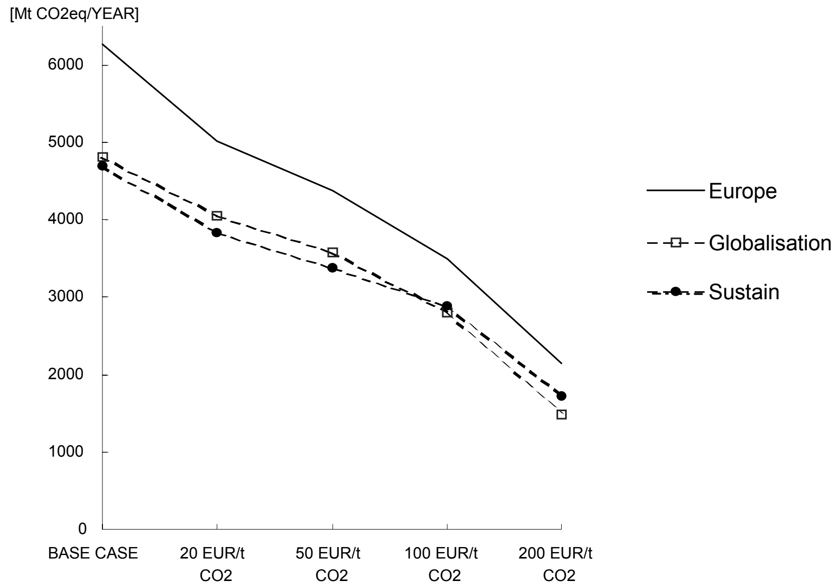


Figure 6.3 *GHG emission reduction as a result of increasing GHG permit prices in 3 scenarios, 2030*

The impact of GHG emission permit prices on the total emissions is shown in Figure 6.3. A long term perspective (2030) is shown, because any significant emission reduction will require a transition period of decades due to the long life of the existing capital equipment stock etc.. The figure shows that in all three scenarios, the emissions can be reduced to levels close to 2000 Mt CO_2 equivalents or below, an emission reduction of more than 50% compared to 1990 emission levels (4250 Mt within Western Europe, see Table 1.1). However such a reduction level is only achieved at a high permit price of 200 EUR/t CO_2, far above the levels which are currently considered. It is interesting to note that the emission levels in the three scenarios converge at the permit price level of 200 EUR/t. This suggests that a 'safe landing' is possible independent of the scenario characteristics. However the *total* costs will differ significantly (see Figure 6.7 below).

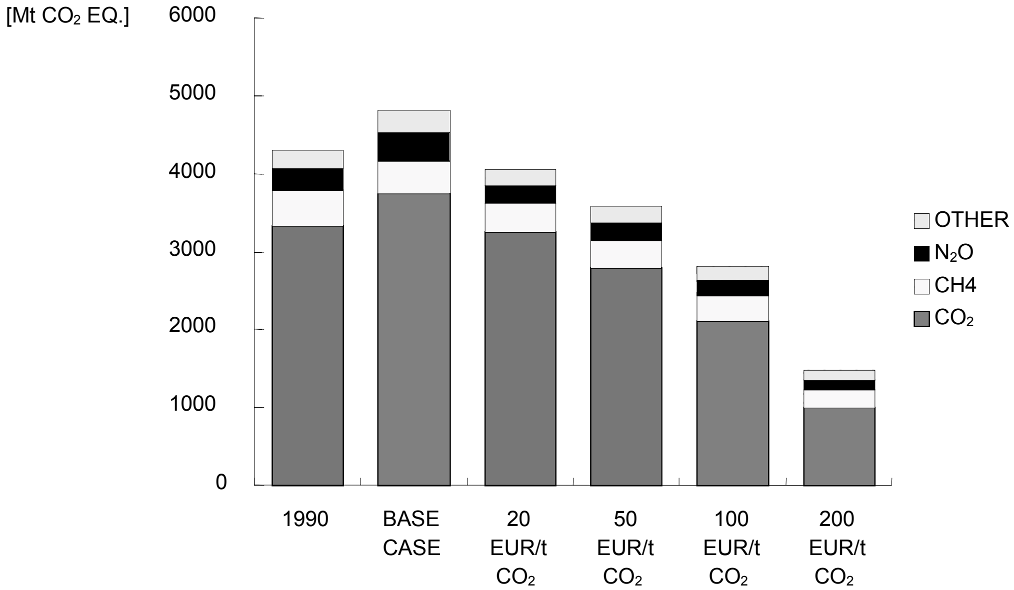


Figure 6.4 *Structure of GHG emissions as a function of increasing emission permit prices, Globalisation scenario, 2030*

Figure 6.4 shows the structure of the emissions. The structure of the emission reduction can also be derived from this graph. The figure shows that reduction of non-CO_2 GHG emissions dominates at low emission permit prices. However the bulk of the emissions are CO_2 emissions. As a consequence, CO_2 emission reduction is the dominant strategy at more ambitious emission reduction targets. These emissions are closely related to the consumption of fossil fuels. The primary energy consumption in all three scenarios is shown in Figure 6.5, split into different kinds of energy carriers. The figure shows an increase in all three scenarios in the base case, compared to the 1990 level. However the growth in primary energy use differs considerably between the three scenarios. The highest energy use occurs in the Europe scenario. Moreover, the coal consumption is the highest in the Europe scenario. Both effects are a main reason for the high GHG emissions in this scenario (CO_2 emissions are a result of the energy consumption and the CO_2 intensity of the energy carriers that are applied). The total energy consumption decreases in all three scenarios if GHG policies are introduced. Part of this reduction can be attributed to the demand reduction on the end use level (see Figure 4.6), another part can be attributed to the increased conversion efficiency (including increased efficiency in materials use). The impact is substantial: in the Fortress Europe scenario, the demand reduction in the 200 EUR/t case is 35%, compared to the base case scenario. In the Sustain scenario, the reduction is 28%. In conclusion for a technology and resource availability perspective the economy can be shaped in such a way that drastic GHG emission mitigation can be achieved.

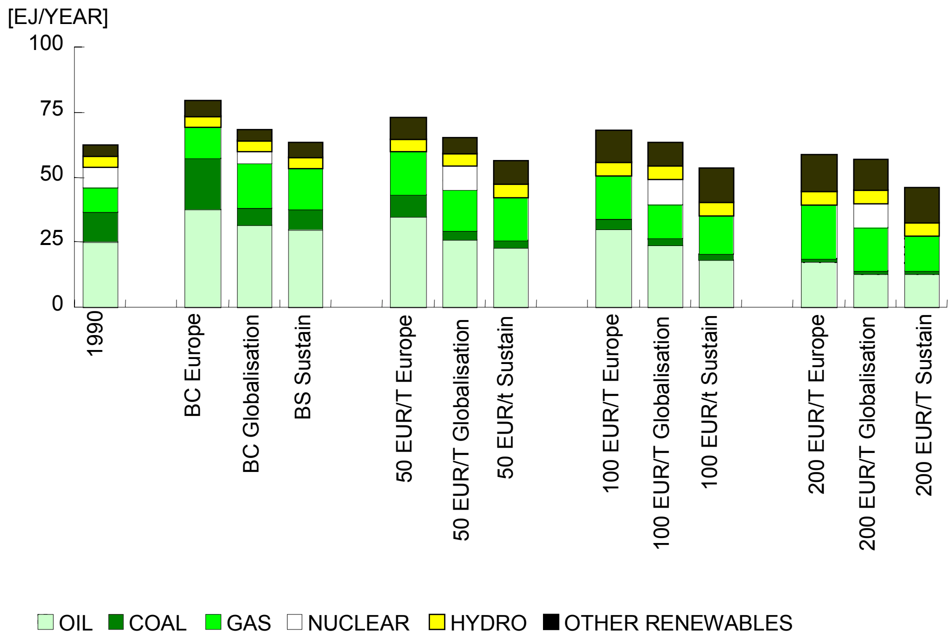


Figure 6.5 *Primary energy use with increasing GHG permit prices, 3 scenarios*[33]

It is also interesting to note the switch in the primary energy carrier mix. The use of coal and oil decreases, the use of natural gas stabilises or increases, and the use of nuclear increases if this option is allowed, and the use of renewables increases. However, the figures for the 200 EUR/t case indicate that renewables can only constitute part of the solution. Demand side management (efficiency gains, changing consumption patterns) and other options such as CO_2 removal and underground storage are also necessary in order to achieve a significant emission reduction for Western Europe as a whole. The contribution of different strategies to emission reduction is illustrated in Figure 6.6, based on earlier analyses (Gielen and Pieters, 1999). Note the importance of efficiency improvements (including all measures on the energy and materials demand side) which constitute half of the total GHG emission reduction. While slight differences with the BRED analysis exist (especially because of the more extensive BRED biomass module), the dominance of efficiency improvements is still valid.

[33] The substitution principle has been applied in the calculation of primary energy equivalents for nuclear, hydro and renewable electricity (multiplication of the electricity output with a factor 2.5). For solar boilers and heatpumps, a reference system conversion efficiency of 85% has been assumed.

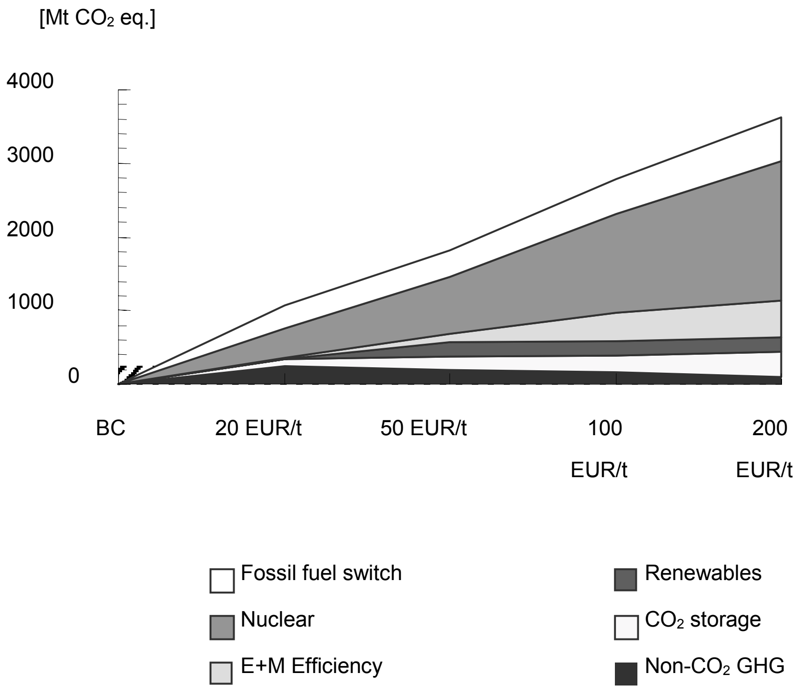


Figure 6.6 *Contribution of different types of GHG emission reduction strategies, 2030 (Gielen and Pieters, forthcoming)*

The total costs of emission reduction are shown in Figure 6.7. The figure shows that the costs differ substantially among the scenarios, if a certain emission level must be achieved, compared to the Kyoto target level. The Kyoto target level represents an 8% emission reduction (a reduction from 4250 Mt to 3910 Mt, this a reduction of 2290 Mt from the base case 2030 level of 6200 Mt in the Fortress Europe scenario, see Figure 6.3)[34]. Costs for this target are small in the Globalisation and Sustain scenario, but amount to 170 billion Euro in the Fortress Europe scenario. Given that more ambitious emission reduction targets can be expected, an additional emission reduction of 2000 Mt (representing a 50% emission reduction from 1990 levels) costs between 150 billion and 400 billion Europe, depending on the scenario. These figures can be compared to a GDP of 10000-15000 billion Euro in 2030: the costs of 50% emission reduction represent 1.5-2.8% of the GDP[35].

[34] Note that the Kyoto Protocol refers to the period 2008-2012, while this analysis focuses on 2030.

[35] Note that consumer/producer surplus and GDP are not the same (the consumer/producer surplus is higher than GDP), so this comparison overestimates the relative loss of welfare. However more serious welfare losses may occur in case the trade balances change (this is not considered in the analysis). Moreover, multiplier effects have been neglected (eg a loss of service industries that depend on specific national heavy industry sectors that are affected).

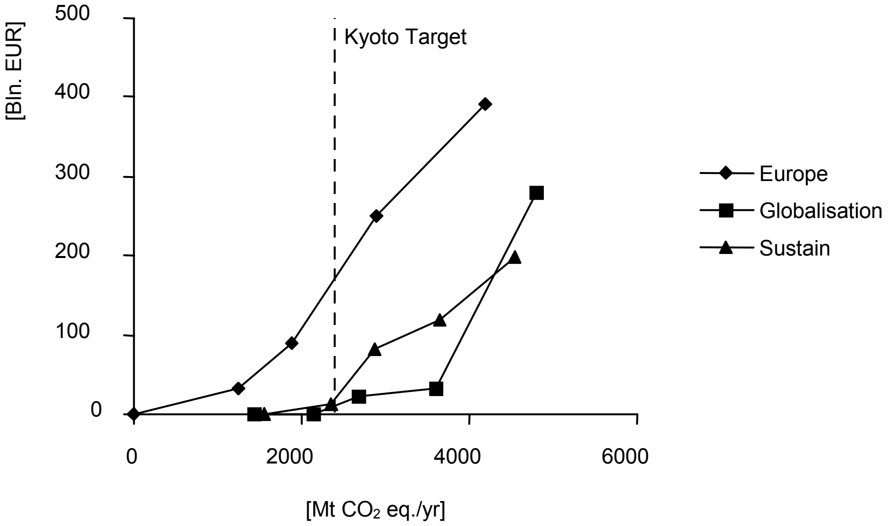
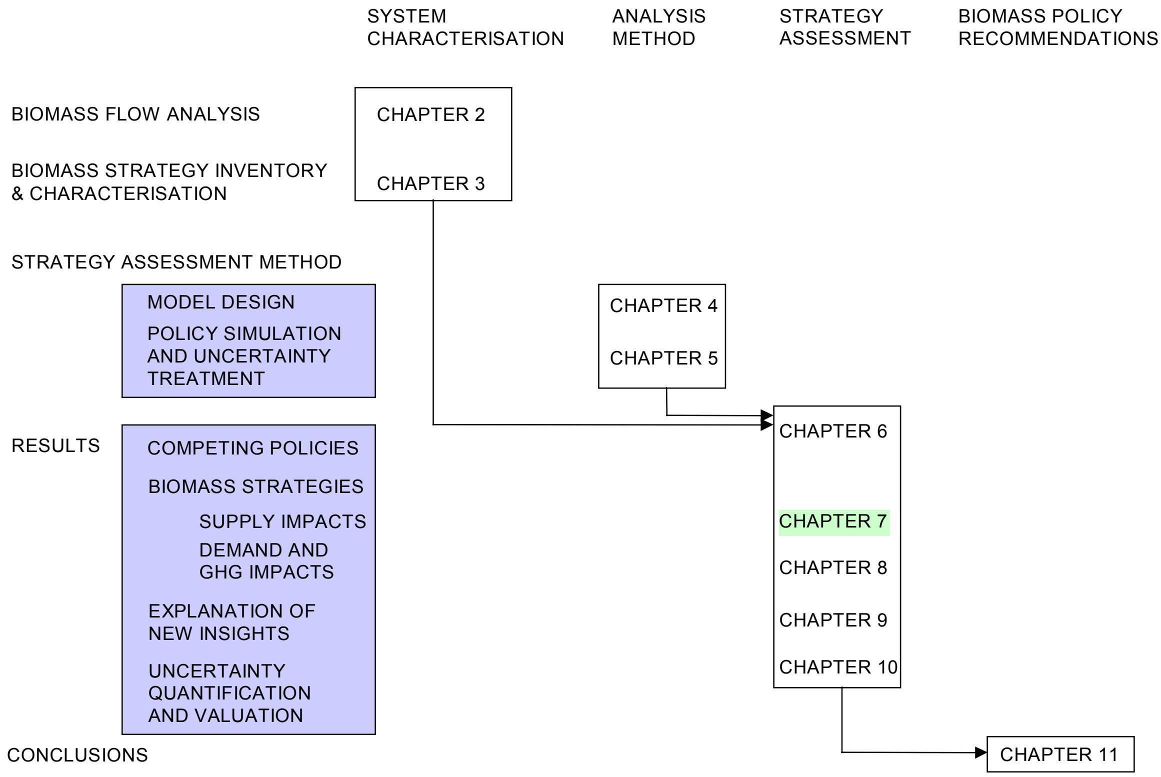


Figure 6.7 *Loss of consumer/producer surplus as a function of the emission reduction compared to the base case emissions in the Fortress Europe scenario, 2030*

7. RESULTS FOR BIOMASS SUPPLY



The results for the supply side will first focus on the total supply structure from all four sources: forestry, agricultural crops, agricultural residues and waste. Next, the analysis will focus on developments in agricultural land use, as the earlier analyses have shown that dedicated agricultural biomass crops are potentially the largest biomass source. Total biomass supply for three scenarios and increasing GHG permit prices is shown in Figure 7.1. This supply covers the primary biomass for energy and materials (from agriculture and from crops) and the energy recovery from waste. In all three scenarios, the supply increases significantly for increasing permit prices. While in the base case (0 EUR/t permit price) the supply is markedly lower in the Sustain scenario than in the other two scenarios, the three scenarios converge at a permit prices of 100 EUR/t. Above 100 EUR/t, the biomass use is higher in the Fortress Europe and Globalisation scenarios than in the Sustain scenario. Total biomass supply increases up to 630 Mt dry matter, an increase of 60-120% compared to the base case.

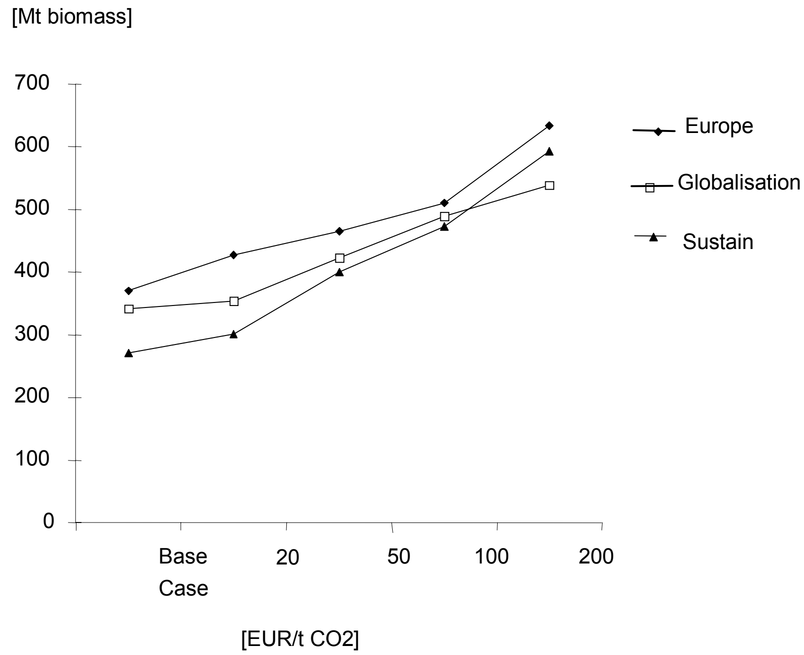


Figure 7.1 *Total biomass supply for three scenarios, 2030, for increasing GHG permit prices*

Figure 7.2 provides a detailed overview of the supply structure in the Globalisation scenario in 2030. Biomass from existing forests has been split into roundwood, bark and forestry residues. Roundwood from existing forests, waste (kitchen waste and post-consumer wood and paper waste) and Eucalyptus plantations in Southern Europe dominate in the case of low GHG permit prices. The main new category at higher permit prices is residual straw from agriculture. Part of the growth is accounted for by additional wood plantations (Eucalyptus) and increased wood recovery from existing forests. Note that paper recycling and energy recovery from manure has been neglected in Figure 7.2[36].

[36] Increased paper recycling would show up as a reduced biomass supply. It is implicitly interpreted as an increased efficiency in materials use

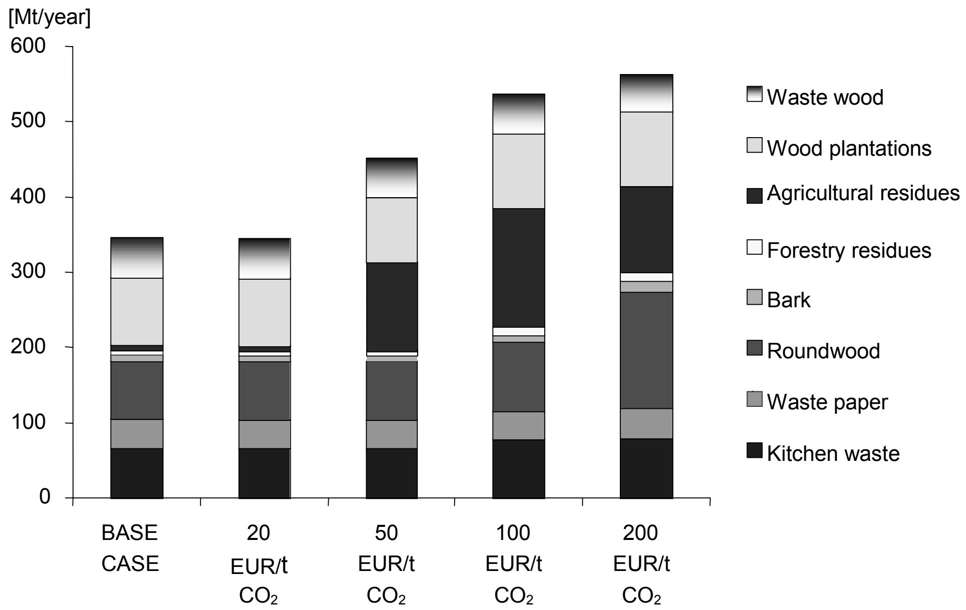


Figure 7.2 *Biomass supply structure for increasing GHG permit prices, Globalisation scenario, 2030*

7.1.1 Agriculture and afforestations on formerly agricultural land

The total amount of agricultural land is limited. The total agricultural land area is 147 Mha. This land can be used for production of food and fodder crops, for production of dedicated biomass energy and materials crops (either annual crops or short rotation forestry) and it can be used for afforestation (long rotation forestry, primarily intended for carbon storage). Figure 7.3 shows the agricultural land use for Western Europe in 2030. The results show only a limited growth in dedicated biomass crops for energy and materials. Little change occurs between 1990 and the base case for the Globalisation scenario in 2030. The main change is the introduction of 5 Mha afforestation, a lower bound in the model that represents current policy plans. 3 Mha Eucalyptus plantations are introduced in the South European region (categorised as energy and materials crops). In the case of a 50 EUR/t permit price, Eucalyptus plantations are present in the Globalisation and the Fortress Europe scenario. Afforestation increases markedly in the Globalisation scenario at 100 EUR/t. In the 200 EUR/t permit price case, the area for afforestation increases significantly in all three scenarios. Moreover, the area for biomass crops increases significantly in the Sustain scenario. Between 25 and 30 Mha are used for either biomass crops or afforestation, with comparatively little differences between the three scenarios. Afforestation dominates biomass crops. This is a surprising result that contradicts the results from many other studies. It can be explained through a combination of cost accounting, discounting, consideration of the changing reference situation and proper accounting of land quality issues. In Chapter 9, the first two elements are explained in more detail

The impact of food requirements can be explained through a closer look at the areas that will become available. It is interesting to note that the area for pastures declines markedly at the 200 EUR/t permit price. This can be attributed to the combined effect of reduced meat consumption because of increased meat prices and a switch to prepared fodder with higher conversion efficiency.

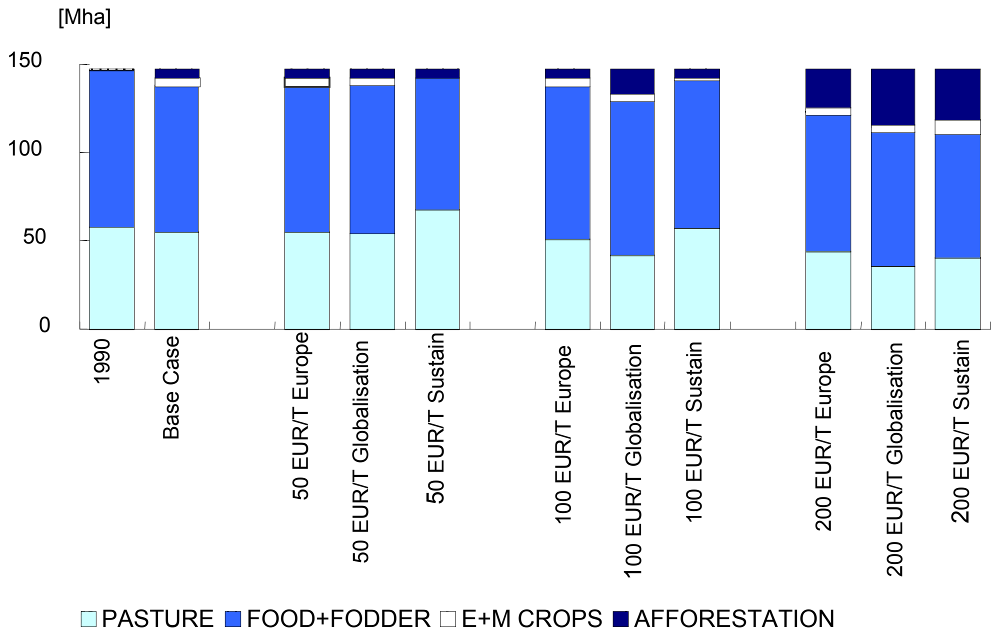


Figure 7.3 *Total agricultural land use 2030, three scenarios*

Figure 7.4 shows that almost all changes occur in the Southern European region. In the model, land use in Southern Europe has been split into a high yield section and a low yield section, 30 Mha each (see Chapter 4). This split represents differences in soil quality, different water availability and others factors which affect the productivity. Figure 7.4 shows very significant changes in Southern Europe. The results show that afforestation is concentrated in the low yield land area, land that is not suited for biomass crops (low and high yield areas are not illustrated separately). In the low yield land area, only afforestation has been modelled as a competitor for olive trees, pasture and wheat growing (thus no dedicated biomass crops, see Chapter 4)[37]. The 25 Mha afforestation in this area represent more than 80% of the total land area in this low yield region, a very high fraction. Such major change is not very likely. The consequences of a lower maximum afforestation area in this region are analysed in a sensitivity analysis in Chapter 10. The analysis shows that the model is very sensitive to such a bound, but that such limitations have limited impact on the GHG emission mitigation potential (part of the afforestation takes place in other regions).

[37] This regional differentiation affects the optimisation. The choice is for example 'afforestation on low yield soils and wheat production on high yield soils' vs. 'bioenergy production on high yield soils and wheat production on low yield soils' (of course much more configurations are feasible, given the 20-30 crop/region combinations in the model).

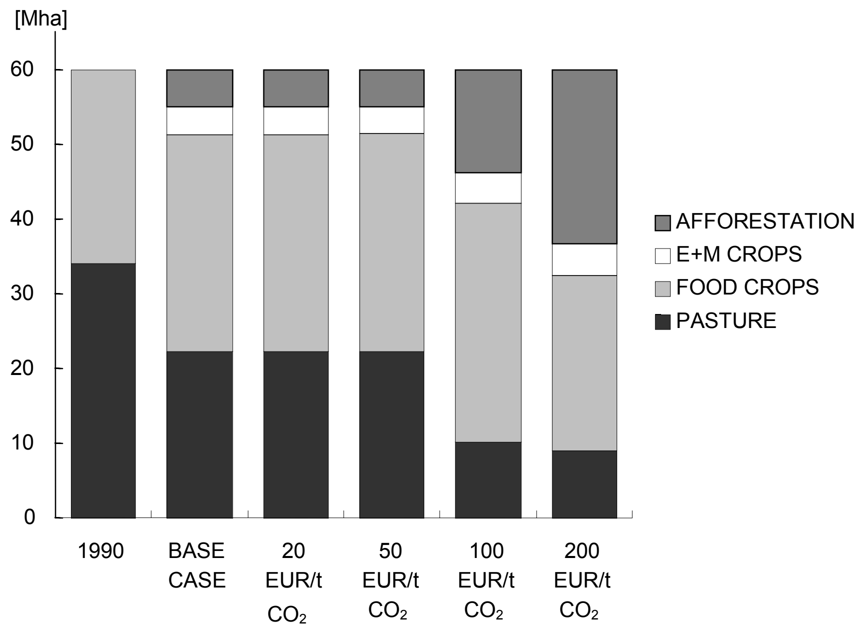


Figure 7.4 *Agricultural land use in Southern Europe, Globalisation scenario, 2030*

The increased demand for agricultural land has a significant impact on land rent prices, as land availability is limited. This is illustrated in Figure 7.5, which shows the land use costs (so-called shadow prices, a measure for the land rent) in the three model regions. Initially prices decrease because demand reductions for agricultural productions and increased productivity reduce the demand for land. At permit prices above 50 EUR/t, the shadow prices increase. The increase can be directly related to the competing land use for afforestation, which sets the minimum land price for all other applications at higher permit price levels. In case of 7 tonnes annual carbon storage per hectare (in the South European low yield (LY) region, see Chapter 4) and a permit price of 100 EUR/t, the land value is 700 EUR/ha (with some small corrections for investment costs and revenues for harvested wood etc.). The land price in the Middle region and the South high yield (HY) region is a derivative of this value because both regions are linked through the wheat, vegetable oil and meat markets.

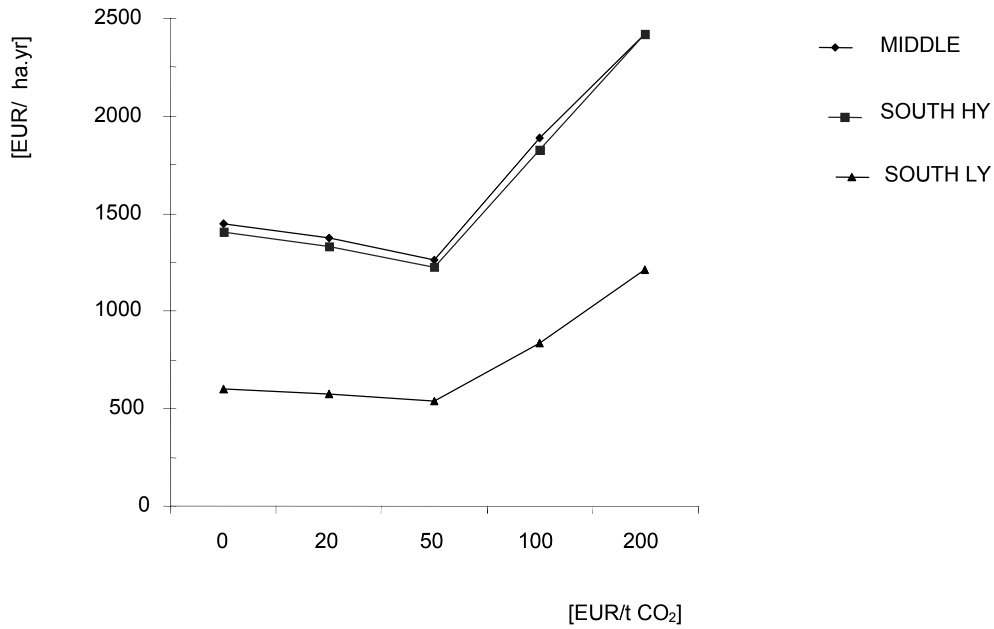


Figure 7.5 *Changing land use costs, Globalisation scenario, 2030 (HY = high yield; LY = low yield)*

The changing land rent, the changing prices of other physical process inputs and the changing value of products changes the cost-effectiveness of crops. Table 7.1 shows the benefit/cost ratios for important agricultural crops in the three regions Middle/North, South high yield and South low yield (see Section 5.7 for an explanation of benefit/cost ratios). The figures show that additional fertiliser use (in order to increase agricultural yields) decreases at higher permit price levels. The reduction of N_2O emissions is the main incentive for reduced fertiliser use. Apparently the increased yields through fertiliser use, which could increase biomass yields, do not match the increased N_2O emissions. In other words, GHG permit prices result in a reduction of fertiliser use. However total production (food crops + energy and materials crops) increases, mainly through an increased efficiency of animal raising. Note the low benefit/cost ratio for energy crops such as miscanthus and sweet sorghum (but for the high 200 EUR/t permit price case). The main reason are the high additional costs in comparison to the additional emission reductions, if the competing land use options are considered (Figure 7.5). The marginal costs of intensive land use compared to afforestation make such a switch less attractive (see Chapter 9).

Table 7.1 *Benefit/cost ratios of selected agricultural crops, Globalisation scenario, 2030*

1 Production of crops	Base case	20 EUR/t	50 EUR/t	100 EUR/t	200 EUR/t
Middle/North region					
BP0 Biomass growing grass middle	0.94	0.95	0.97	1.00	1.00
BP1 Biomass growing grass middle extra fertiliser	1.00	1.00	1.00	1.00	1.00
BP2 Biomass growing wheat middle	1.00	1.00	1.00	1.00	1.00
BP3 Biomass growing wheat middle extra fertiliser	1.00	1.00	1.00	0.99	0.93
BP4 Biomass growing miscanthus middle	0.25	0.25	0.26	0.49	0.69
BP6 Biomass growing algae middle	0.01	0.01	0.13	0.21	0.31
BP8 Biomass growing marigold flower middle	1.00	1.00	1.00	1.00	n.a.
BPA Biomass growing corn middle	0.92	0.92	0.93	0.96	1.00
BPB Biomass growing corn middle extra fertiliser	0.98	0.99	0.99	0.99	0.96
BPC Biomass growing rapeseed middle	0.32	0.33	0.34	0.39	0.30
BPD Biomass growing sugarbeet middle	1.00	1.00	1.00	1.00	1.00
BPE Biomass growing fodder middle	1.00	1.00	1.00	1.00	1.00
BPF Biomass growing sunflower middle	0.33	0.34	0.36	0.46	0.38
South high yield region					
BQA Biomass growing sorghum south high yield	0.16	0.11	0.20	0.53	0.99
BQB Biomass growing wheat south high yield	1.00	1.00	1.00	1.00	1.00
BQC Biomass growing sugarbeet south high yield	0.93	0.93	0.93	0.93	0.90
BQD Biomass growing miscanthus south high yield	0.27	0.27	0.28	0.54	0.75
BQG Biomass growing grass south high yield	0.94	0.95	0.97	1.00	1.00
BQH Biomass growing grass south extra fertiliser high yield	1.00	1.00	1.00	1.00	1.00
BQO Biomass growing corn south high yield	1.00	1.00	1.00	1.00	0.96
South low yield region					
BSA Biomass growing grass south low yield	1.00	1.00	1.00	1.00	1.00
BSB Biomass growing wheat south low yield	0.57	0.57	0.56	0.58	0.70
BSC Biomass growing olives south low yield	0.55	0.57	0.60	0.58	0.27

Table 7.2 shows the benefit/cost ratios for forestry plantations and afforestation projects. One must add that the B/C for afforestations is an estimate, based on spreadsheet calculations. The MARKAL benefit/cost ratio does not account for costs and revenues at the end of the plantation life span, and therefore it produces wrong estimates for this type of projects. In this case because of CO_2 emissions and wood yields after 50 years, financial burdens and benefits which are not accounted for in the annual benefit/cost ratio. Note that this is only a reporting error; the model optimisation algorithm does take end of life financial burdens and benefits into account.

The benefit/cost ratio of afforestation is strongly affected by the permit prices. Only at the highest permit price level of 200 EUR/t, afforestation becomes cost-effective in the low yield regions of Southern Europe.

The benefit/cost ratios for plantations show that Eucalyptus plantations are already cost-effective in the base case. The benefit/cost ratio even exceeds 1 at permit prices higher than 50 EUR/t. This indicates that the Eucalyptus plantations have reached the maximum bound in the model calculations. If this bound would be removed, it would result in an increased Eucalyptus plantation area. However physical constraints forestall such drastic expansion (like e.g. water availability). The other wood plantations are not cost-effective, except poplar in Southern Europe at a 200 EUR/t permit price. The selection of poplar is however not clear-cut, since willow in Middle Europe (with model code BPH) is also very close to selection with a benefit/cost ratio of 1.

Table 7.2 *Benefit/cost ratios of afforestations and forest plantations, Globalisation scenario, 2030*

1 Afforestation and short rotation forest plantations	Base case	20 EUR/t	50 EUR/t	100 EUR/t	200 EUR/t
Afforestations					
BR7 Coniferous roundwood afforestation north/middle	<0.1	0.19	0.51	0.70	0.98
BR8 Coniferous roundwood afforestation south high yield	<0.1	0.20	0.53	0.73	0.98
BR9 Coniferous roundwood afforestation south low yield	<0.1	0.21	0.55	1.00	1.00
BRA Non-coniferous roundwood afforestation north	<0.1	0.19	0.51	0.70	0.98
BRB Non-coniferous roundwood afforestation middle	<0.1	0.19	0.51	0.70	0.98
BRC Non-coniferous roundwood afforestation south high yield	<0.1	0.20	0.53	0.73	0.98
Plantations					
BRD Willow short rotation plantation north	0.58	0.56	0.54	0.69	0.67
BRE Poplar short rotation plantation middle	0.51	0.51	0.52	0.70	0.68
BPH Biomass growing willow middle	0.62	0.62	0.63	0.85	0.83
BQE Biomass growing eucalyptus south high yield	1.00	1.00	1.00	1.35	1.31
BRF Poplar short rotation plantation south	0.65	0.65	0.65	0.88	0.85

Table 7.3 shows the changing shadow prices of agricultural products for increasing GHG permit prices. Note the significant price increases for meat and for most wood products such as sawn wood and pulp. Such price changes pose a threat of carbon leakage, as it may become more cost-effective to import such products from other regions. All price increases of more than 100 EUR/t product (compared to the base case) have been indicated through a shading. Intercontinental transportation costs for bulk commodities are well below 100 EUR/t product, and a price increase of more than 100 EUR/t is an indicator that imports from other continents may become competitive. Given the sheltered and heavily regulated European agricultural market, this is not a new threat. However, the results suggest that the problem may become more pronounced because of GHG policies. Most affected products are beef, chemical pulp, graphic paper, sawn timber and board materials. Wheat and mechanical pulp are close to a 100 EUR/t price increase at permit price levels of 200 EUR/t CO_2. The deteriorating competitive position is one of the main obstacles for an ambitious European GHG policy, in case other regions do not develop similar policies. Note also that waste becomes a valuable resource: waste prices change from negative (waste management costs money) to positive (waste management generates money).

Table 7.3 *Changing biomass shadow prices, Globalisation scenario, 2030*

Product [EURO/t product]	Base case	20 EUR/t	50 EUR/t	100 EUR/t	200 EUR/t
Wheat	187	186	185	229	280
Corn	217	214	210	255	263
Straw	25	25	25	50	110
Beef meat	8385	8475	8610	9380	10050
Chicken meat	2378	2375	2370	2469	2467
Roundwood	59	58	58	83	110
Mechanical pulp	147	165	188	210	234
Chemical pulp	550	540	527	603	801
Graphic paper	548	570	604	681	897
Sawn timber	149	157	166	182	297
Particle board	194	207	227	298	443
Medium Density Fibreboard MDF	276	292	316	392	543
Energy wood chips	55	60	63	30	139
Waste paper, separately collected	-19	-11	0	5	81
Kitchen waste	-13	-8	0	3	54
Demolition wood	-47	-39	-26	-21	64

7.1.2 Wood from forests and forest plantations

Figure 7.6 provides an overview of the primary wood fibre supply in the Globalisation scenario in 2030 for increasing GHG permit prices. Even in the base case the results show a significant shift towards fibre supply from plantations on formerly agricultural land. The primary wood fibre supply increases from 190 Mt in the base case to 280 Mt in the 200 EUR/t case. At this high permit price level the wood production from existing forests is back at the 1990 level. Comparison of the supply figures in Figure 7.6 and Figure 7.1 shows that 60% of the biomass supply comes from forestry and forest plantations. Note the regional consequences of the switch from existing forests to high production plantations: wood production in Scandinavia decreases in favour of Eucalyptus plantations in Southern Europe. As a consequence a regional specialisation will occur, with sawn wood production in Scandinavia and increasing board and pulp production in the South. Especially Scandinavia will profit from rigid GHG policy targets.

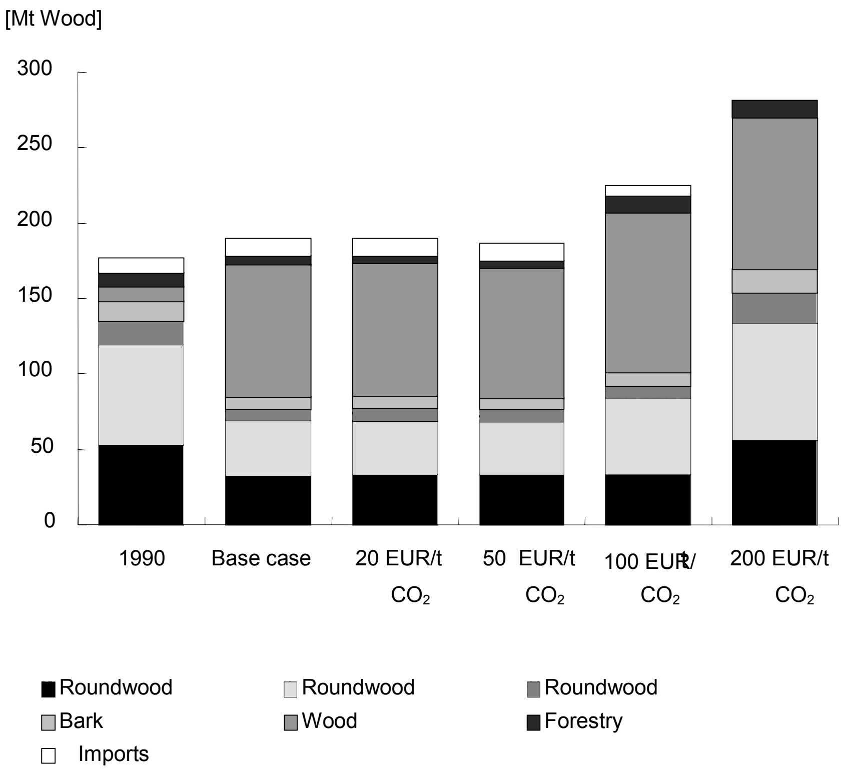
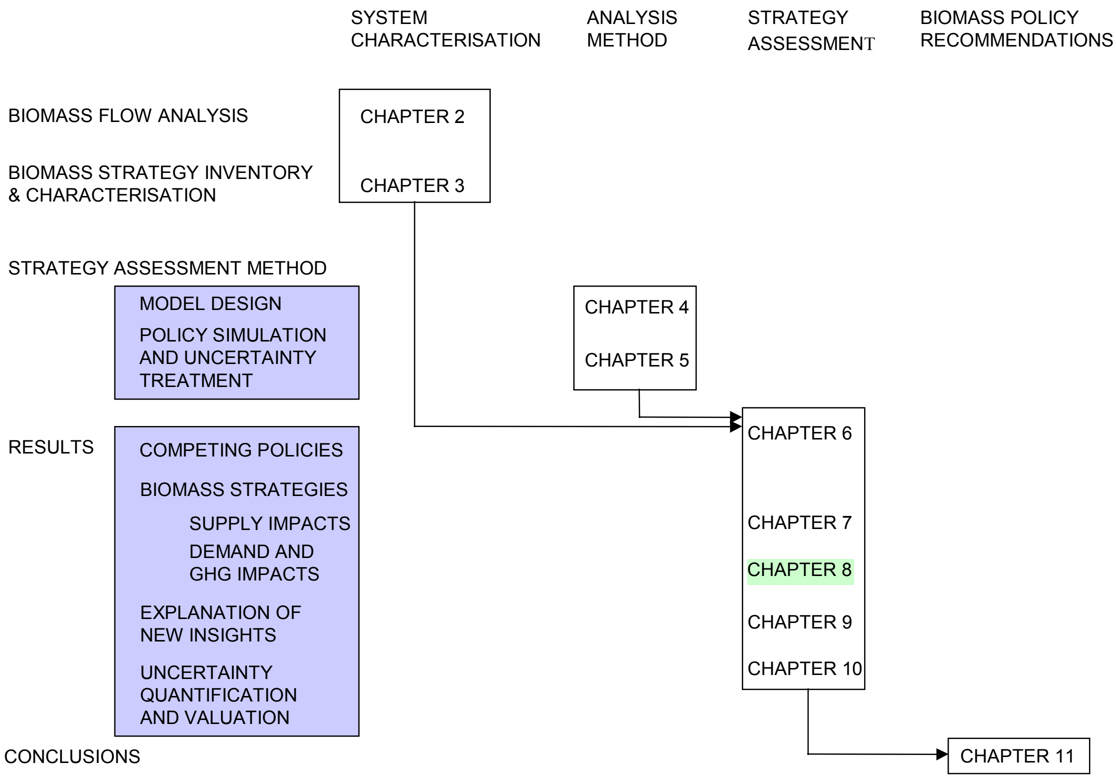


Figure 7.6 *Wood fibre supply for increasing GHG permit prices, Globalisation scenario, 2030*

8. RESULTS FOR BIOMASS DEMAND



8.1 Aggregate biomass use: the impact of GHG policies

Figure 8.1 shows the aggregated biomass use in the base case for the Globalisation scenario (this excludes food and fodder). The figure shows an initial decline, followed by a gradual recovery. The decline is related to bioenergy use (in the heating market, see Section 8.2). Biomaterials use increases steadily. While materials use dominates up to 2000, energy and materials use reach a comparable level in 2010. From 2010 onward, energy use dominates.

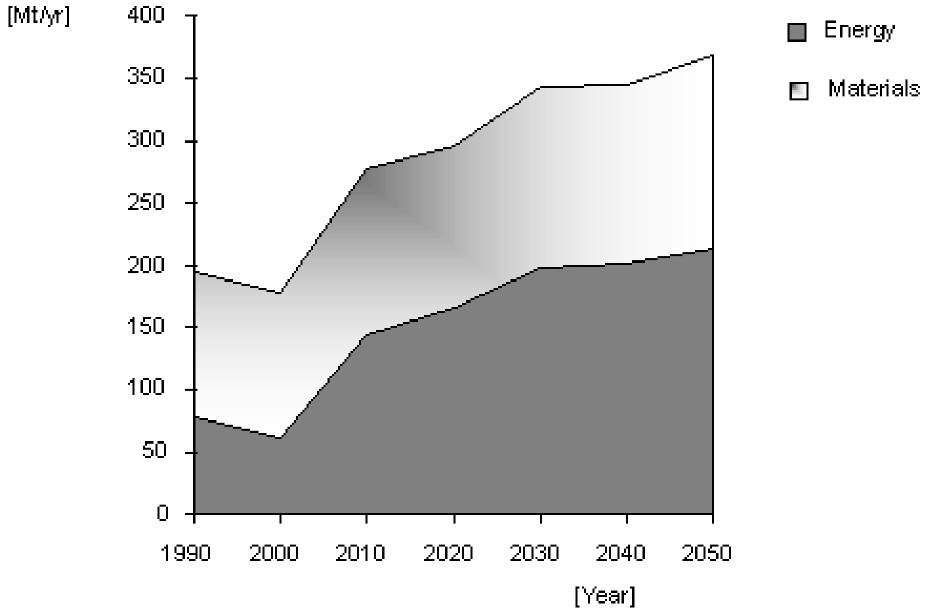


Figure 8.1 *Biomass use, base case, Globalisation scenario, 1990-2050*

Biomass use depends on the scenario characteristics and on the GHG permit price. This is shown in Figure 8.2. The differences between the scenarios are limited. This suggests that the GHG permit price has more impact than the different scenario characteristics, and that the results are robust with regard to the scenario differences. Whether this similarity of the results for the different scenarios is driven by the supply side structure or by the demand side structure, is determinative for the robustness and the uncertainty regarding this result. The analysis in Chapter 7 has shown that the supply could be increased significantly though an increased area of biomass crops, but that such a strategy is not cost-effective. This result suggests that this effect is driven by the demand side. This demand dominance feature implies three things. First, increased biomass use is not a dominant GHG emission mitigation strategy in either energy or materials markets in all three scenarios. Second, the market price structure is not very different in all three scenarios. Third, the market potentials are not significantly affected by the scenario parameters. These hypotheses will be analysed in more detail in the next sections.

In Figure 8.2 it can be seen that the growth of biomass use mainly takes place in the energy market. The material market also growth up to a permit price level of 100 EUR/t. In the 200 EUR/t case however, the materials market actually declines, while the energy market shows a very strong growth. At 200 EUR/t three quarters of the total amount of biomass is used for energy purposes. This result shows the importance of a clear policy target: the system configuration (and thus the optimal biomass use) changes significantly, depending on the policy ambitions: a gradual approach can result in a sub-optimal lock in effects for the economic structure.

The biomass use for energy and materials is analysed in more detail in Sections 8.2 and 8.3. Finally Section 8.4 discusses the GHG relevance of the biomass strategies.

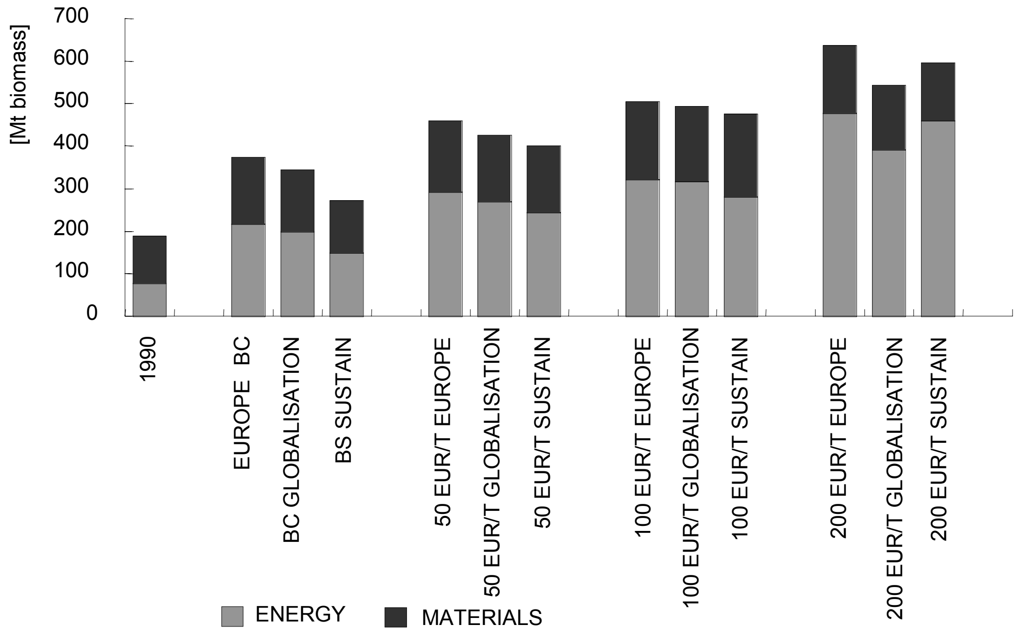


Figure 8.2 *Biomass use with increasing emission permit prices, different scenarios, 2030*

8.2 Bioenergy

Figure 8.3 shows the biomass use for energy applications in the Globalisation scenario in 2030, for increasing emission permit prices. The figure shows significant changes between the 1990 situation and the 2030 base case. The total biomass for energy use increases from 80 Mt to 200 Mt. While the biomass use for heat production disappears, the energy recovery from waste biomass (mainly for electricity production) increases significantly from 20 Mt in 1990 to 150 Mt in the base case in 2030. This energy recovery remains at a constant level up to the 200 EUR/t permit price. The decline in the heating market in the model calculations must be nuanced; for example the use of fireplaces or the use of biomass in remote mountain regions is not well captured in the model. In reality, this part of the heating market could probably be greater. Some biomass use for heating purposes re-emerges at 50 EUR/t onward (small industrial kilns). The energy recovery from lignin via gasification and subsequent cogeneration increases at 50 EUR/t, but declines again at 200 EUR/t. These changes are related to the ethanol production from wood (from 50 EUR/t upward), which results in lignin by-products that are used for energy recovery. In the 200 EUR/t case however, part of this lignin is used for HTU oil production. From 50 EUR/t upward, biomass energy use increases significantly, up to 390 Mt biomass in the 200 EUR/t case. The main increase can be attributed to the production of transportation fuels, especially ethanol, methanol and HTU biodiesel.

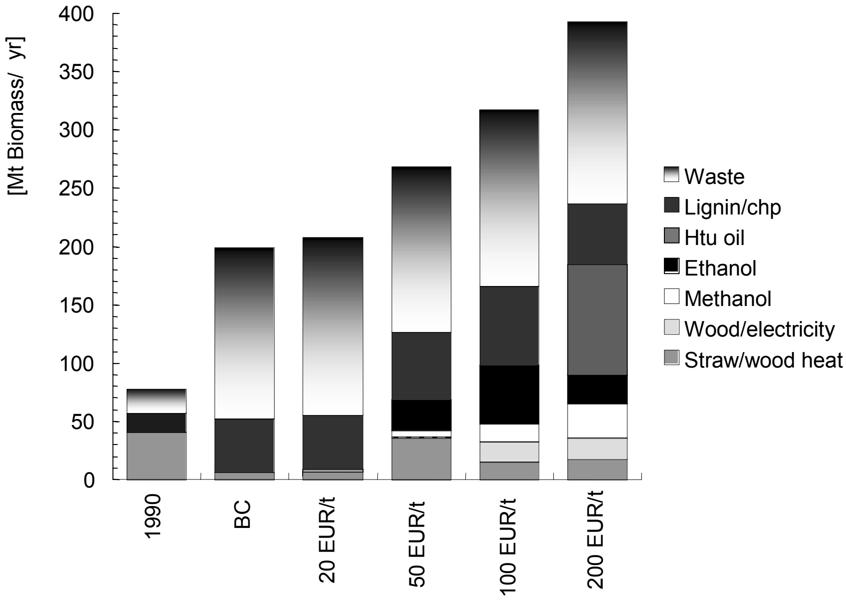


Figure 8.3 *Biomass use for energy, expressed in primary biomass equivalents, Globalisation scenario, 2030*

Figure 8.4 shows that comparatively small differences occur between the three scenarios. In case of a 100 EUR/t permit price, the total biomass use changes from 280 to 320 Mt between scenarios. This is equivalent to 4.5-5.5 EJ primary energy (6-9% of the primary energy use in 2030). The main difference is accounted for by ethanol or HTU oil production for the transportation market (see Section 8.2.2). Another difference is the biomass use for co-combustion in gas fired power plants. This strategy is only selected in the Globalisation and Europe scenario, but still represents limited quantities compared to the total electricity production of approx. 400 PJ biomass (see Section 8.2.1).

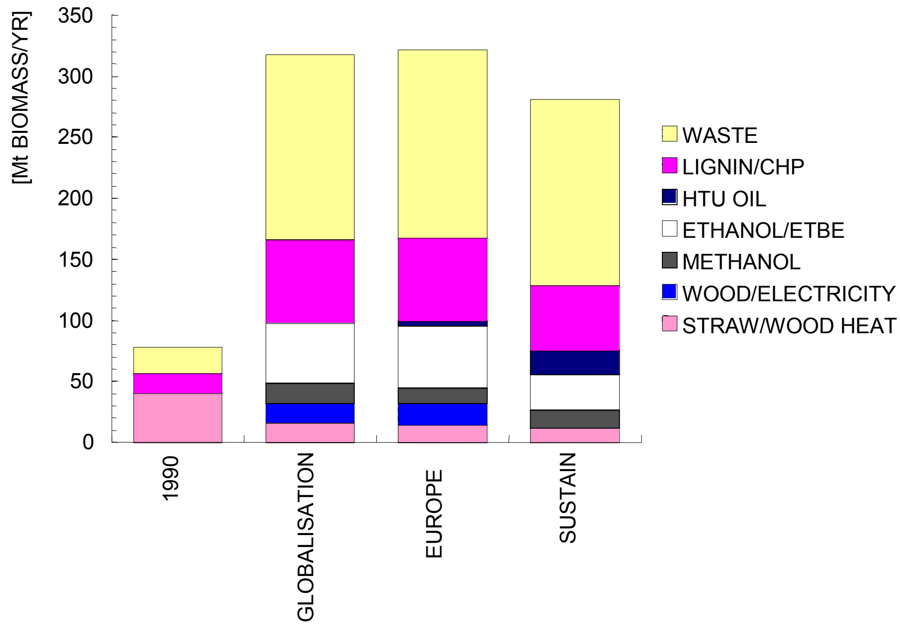


Figure 8.4 *Biomass use for energy, expressed in primary biomass equivalents, permit price 100 EUR/t, for three scenarios, 2030*

This similarity can also be explained on the basis of price trends. Table 8.1 provides an overview of shadow prices of important energy carriers and materials in the three scenarios at a 100 EUR/t permit price case. Biomass could in principle be used as a resource for all these products, either as a feedstock (e.g. HTU oil instead of naphtha for cracking) or as a substitute (sawn wood as a substitute for concrete and steel beams). The figures show that the price differences between the scenarios are limited, despite very different fossil fuel price trends and different discount rates. The results indicate the dominance of the (high) GHG permit prices within the price structure.

Table 8.1 *Shadow prices of important energy carriers and materials, 3 scenarios, 2030, 100 EUR/t permit price*

Product	Unit	Current	Globalisation	Fortress Europe	Sustain
Electricity	[EUR/GJ]	15	17.5	23.1	19.3
Gasoline	[EUR/GJ]	4	14.0	15.7	13.8
Diesel	[EUR/GJ]	4	14.0	13.0	12.7
Natural gas	[EUR/GJ]	3	10.2	11.4	9.7
Fuel oil	[EUR/GJ]	3	10.5	11.9	11.1
Hot rolled steel coil	[EUR/t]	300	386	431	394
Ethylene	[EUR/t]	300	590	587	535
Cement	[EUR/t]	20	112	97	90
Bricks	[EUR/t]	30	75	75	55
Waste paper	[EUR/t]	0	5	41	29

8.2.1 Biomass use for electricity production

Electricity production has always been considered an important market opportunity for bioenergy. For this reason, electricity production in all three scenarios is elaborated in Figures 8.5-8.7. The figures show limited differences in the total quantity of electricity produced in the 2030 base case, but show a very different electricity production structure. The use of natural gas dominates in the Globalisation and the Sustain scenarios, while the use of coal dominates in the Fortress Europe scenario (an effect which can be attributed to price trends). Nuclear is only allowed in the Globalisation scenario (see Section 5.6).

The results show an initial decline of the total electricity production in all three scenarios for increasing GHG permit prices, which can be attributed to the increased efficiency of electricity use. At a 200 EUR/t permit price level, electricity consumption increases again because of the introduction of electric vehicles (a moderate ‘electrification’ of the energy system). This effect is especially pronounced in the Globalisation and the Fortress Europe scenarios (see Section 8.2.2). With increasing GHG permit prices, the supply structure converges for all three scenarios: natural gas dominates and the use of renewables, especially wind, increases significantly. In two scenarios (Globalisation and Fortress Europe), gas fired power plants are equipped with CO_2 removal and underground storage. Nuclear power increases to its upper bound in the Globalisation scenario.

As a consequence of these changes in production structure, the CO_2 intensity of electricity production decreases very significantly and additional biomass use thus has only limited additional CO_2 benefits (see Chapter 9). As a consequence, costly biomass based power production does not occur and the contribution of biomass based electricity production is limited to co-combustion in gas fired power plants.

CO_2 removal and underground storage for coal and gas fired power plants is not allowed in the Sustain scenario (see Section 5.5). As a consequence, the CO_2 intensity of electricity production remains comparatively high in this scenario. The gas-fired power plant is still widely applied in this scenario at 200 EUR/t permit price. This is typically a situation where increased biomass use for electricity production could result in a substantial reduction of GHG emissions if this biomass is applied as a substitute for natural gas. The fact that this does not happen can be explained on the basis of the characteristics of the competing afforestation option. This issue is elaborated in Chapter 9.

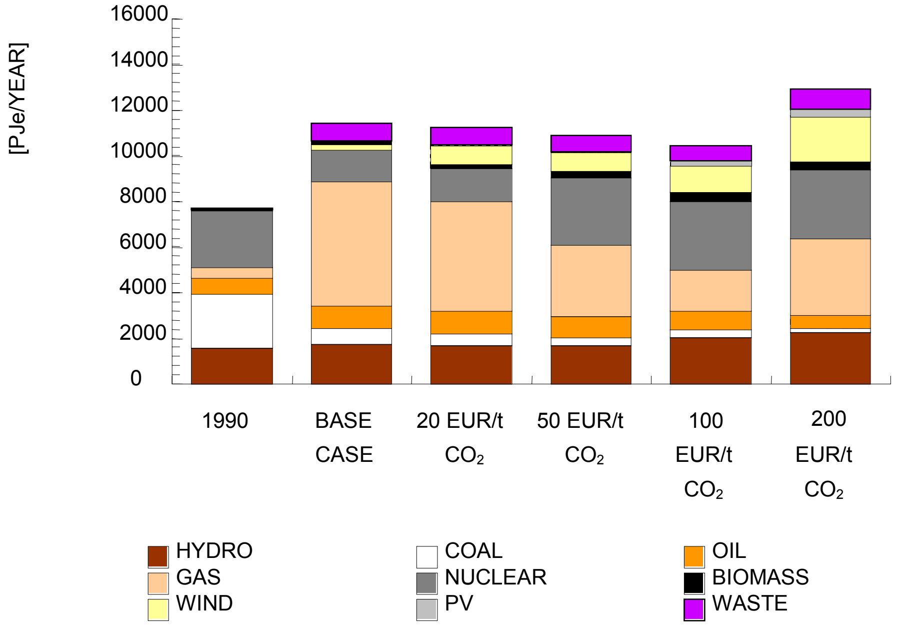


Figure 8.5 *Electricity production for increasing GHG permit prices, Globalisation scenario, 2030*

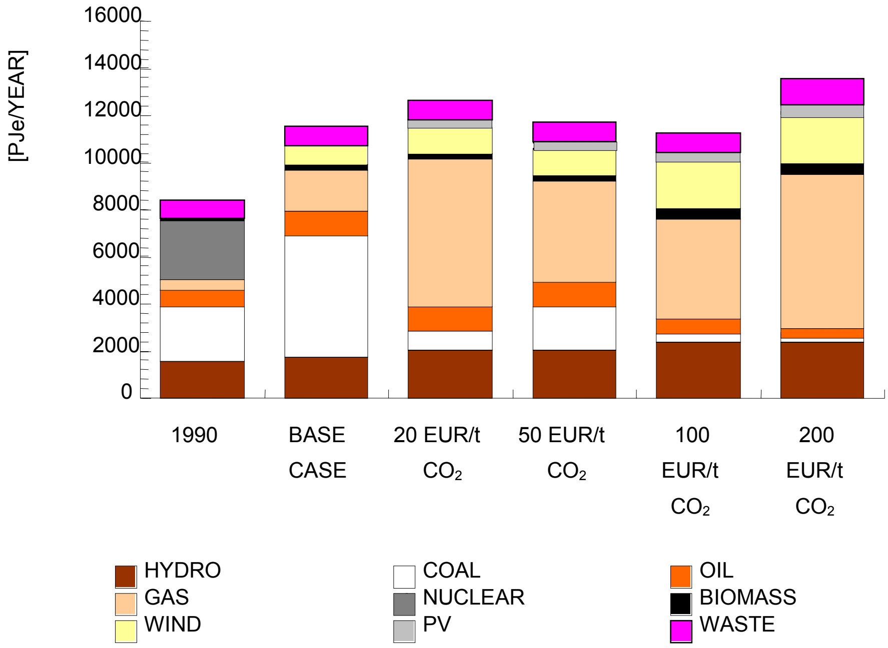


Figure 8.6 *Electricity production for increasing GHG permit prices, Fortress Europe scenario, 2030*

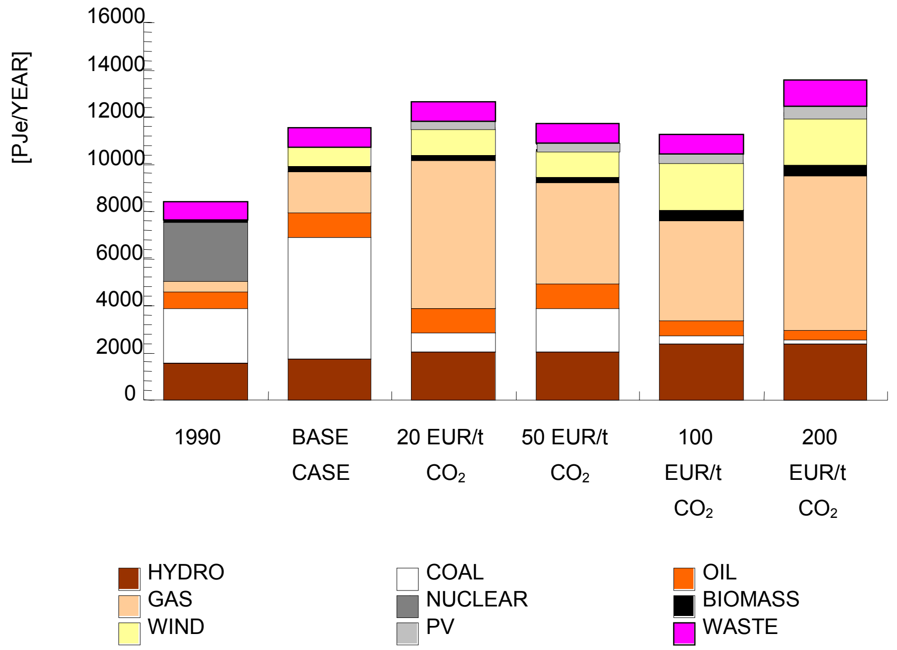


Figure 8.7 *Electricity production for increasing GHG permit prices, Sustain scenario, 2030*

Table 8.2 shows the benefit/cost ratios of different bioelectricity production technologies. The table shows that co-combustion is the most cost-effective strategy for bioelectricity production. At permit prices above 50 EUR/t, co-combustion in gas fired power plants (code BE2) is limited by the model bounds (this can be derived from the B/C in Table 8.2 being higher than 1.00). This is typically a strategy where the supply potential should be analysed in more detail in order to check the validity of the model bounds (see the sensitivity analysis in Chapter 10). These co-combustion units have the important value added that they can be equipped with CO_2 removal and underground storage, thus resulting in a bioenergy chain with negative CO_2 emissions: CO_2 is stored in trees and subsequently stored underground, while the energy content of the wood is recovered. This is shown in Table 8.2 through introduction of CO_2 removal technologies SQH and SQL at permit prices of 50 EUR/t upward. Note the decreasing benefit-cost ratio of the stand-alone gasifier BE3: its competitiveness decreases because the biomass price increases rapidly. Note also the decreasing competitiveness of co-combustion in coal fired power plants BE5, which can be explained by the same mechanism. Another important bioelectricity strategy is based on the energy recovery from residual lignin. The results show a switch from the current Tomlinson boilers to lignin gasifiers, which are characterised by a considerably higher energy efficiency.

Table 8.2 *Benefit/cost ratios for production of electricity, Globalisation scenario, 2030*

1 Production of electricity	*Base case*	*20 EUR/t*	*50 EUR/t*	*100 EUR/t*	*200 EUR/t*
BD1 Lignine boiler/large industrial cogeneration	0.43	0.36	0.32	0.26	0.26
BD2 Lignine gasifier/large industrial cogeneration	1.00	1.00	1.00	1.00	1.00
BE1 Industrial CHP unit (Total Energy (TE) Stirling engine)	0.57	0.60	0.62	0.57	0.62
BE2 Co-combustion in gas fired power plants 250 MW	1.00	1.00	1.00	1.05	1.05
BE3 Stand-alone wood gasifier-STAG 100 MW	0.38	0.63	0.69	0.35	0.19
BE4 Biomass gasifier/SOFC	0.63	0.70	0.78	0.70	0.90
BE5 Co-firing in coal fired power plant	0.74	0.54	0.43	0.16	0.25
BE6 IGCC with co-gasification	1.00	1.00	1.00	1.00	1.00
BE7 Biomass gas turbine CHP plant	0.38	0.40	0.48	0.20	0.31
BE8 Stand-alone straw gasifier-STAG 100 MW	0.37	0.66	0.82	0.76	0.95
SQG Wood chips for STAG without CO_2 removal	1.00	1.00	n.a.	n.a.	n.a.
SQH Wood chips for STAG with CO_2 removal	n.a.	0.64	1.00	1.00	1.00
SQK Wood chips for IGCC without CO_2 removal	1.00	1.00	n.a.	n.a.	n.a.
SQL Wood chips for IGCC with CO_2 removal	n.a.	0.66	1.00	n.a.	1.00

8.2.2 Biomass use for transportation fuels

The transportation market is the second important bioenergy market, following electricity. It represents approximately one third of the total energy market (expressed in primary biomass equivalents). The changes in the transportation market and their consequences for biofuel use are elaborated in Figures 8.8-8.10.

In all three scenarios, the results show a considerable growth in the transportation fuel demand from 1990 to the base case in 2030. There is a marked difference in transportation fuel demand in the three scenarios: in the Fortress Europe scenario, with emphasis on economic growth in the traditional sectors such as transportation, the demand is 50% higher. The total transportation fuel demand is hardly affected at permit prices up to 100 EUR/t, but declines significantly at a 200 EUR/t permit price. This reduction is the result of the combined impact of demand elasticities and the introduction of electric vehicles (losses in electricity production are not accounted for in Figures 8.8-8.10, so the impact is less pronounced on a primary energy basis).

The figures show that, in all three scenarios, some biomass is introduced if GHG permit prices are levied. In the Fortress Europe scenario, ETBE is introduced from a permit price of 20 EUR/t upward. In all three scenarios, ethanol is introduced from 50 EUR/t upward, and significant quantities of biodiesel from HTU oil are introduced at a 200 EUR/t permit price. In the Globalisation and the Fortress Europe scenarios, some methanol and DME are introduced at higher permit price levels, but the quantity is limited. Biodiesel based on RME or algae is not introduced in any of the scenarios due to the high costs compared to other alternatives.

Note that the quantity of biofuels in the total transportation fuels market is limited. At the 200 EUR/t permit price, the reduction in final demand is dominant, based on increased fuel efficiency, a partial switch to smaller cars and a reduction of transportation demand. Moreover, electricity and some hydrogen are introduced at higher permit price levels, resulting in a significant decarbonisation of the transportation fuel mix.

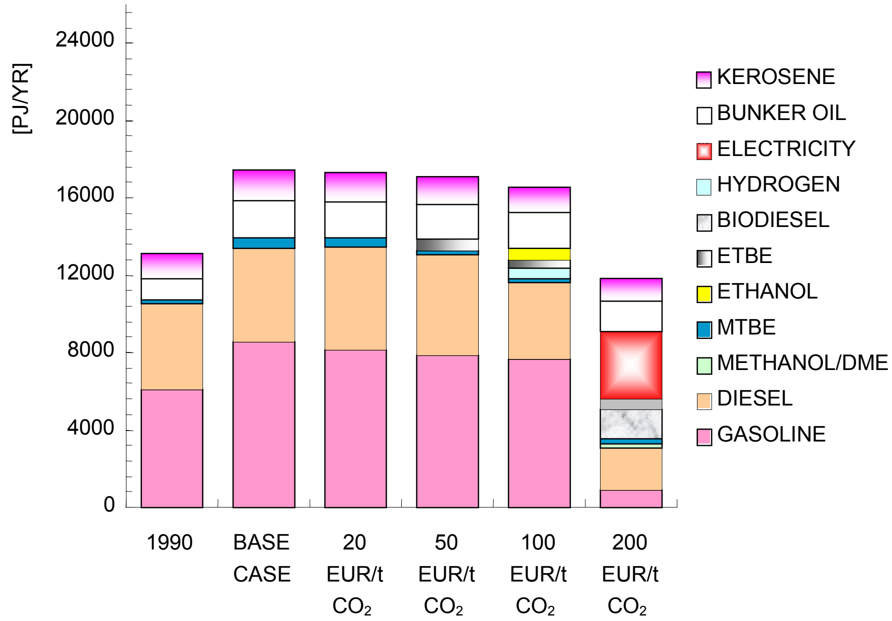


Figure 8.8 *Transportation fuels for increasing GHG permit prices, Globalisation scenario, 2030*

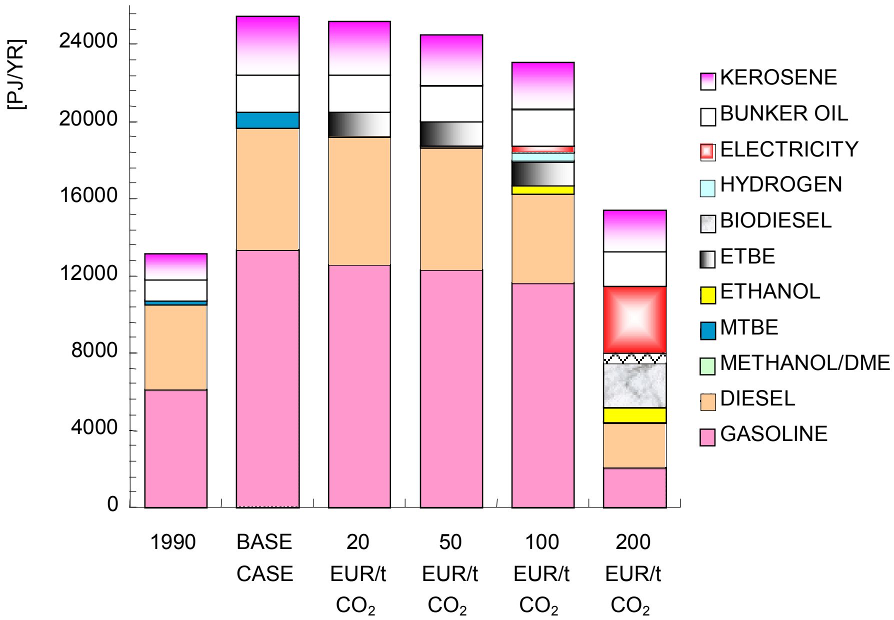


Figure 8.9 *Transportation fuels for increasing GHG permit prices, Fortress Europe scenario, 2030*

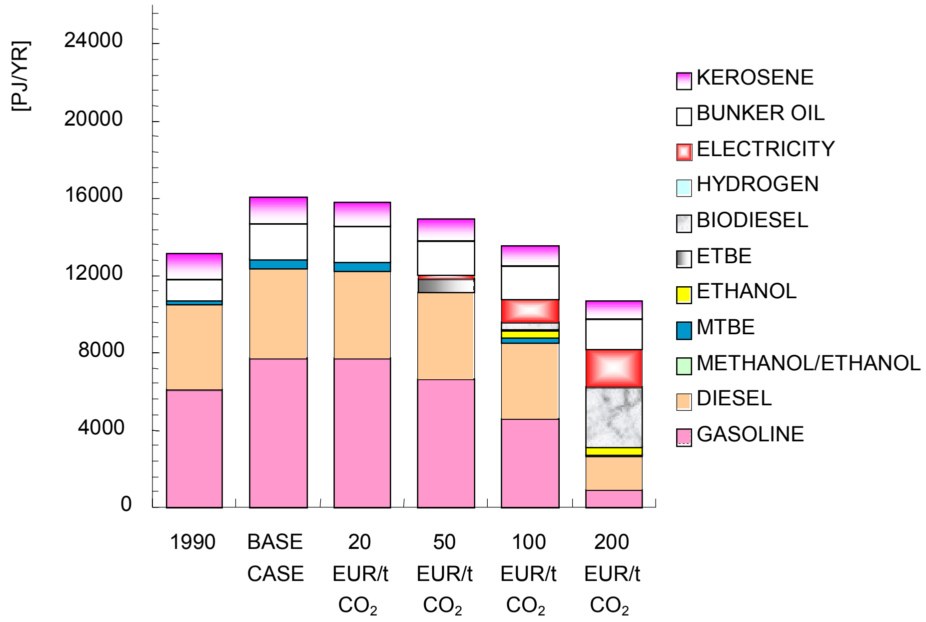


Figure 8.10 *Transportation fuels for increasing GHG permit prices, Sustain scenario, 2030*

Table 8.3 shows the benefit/cost ratios for biofuels in the Globalisation scenario in 2030. Note that methanol becomes cost-effective from 50 EUR/t upward. This includes methanol for MTBE production, a gasoline additive. Note also the production of HTU oil from 100 EUR/t upward. However, this HTU oil is not used in the transportation market, but as a naphtha substitute in the petrochemical industry (see the biomaterials, Section 8.3). Pyrolysis oil does not become cost-effective at any permit price level. On the supply side, straw from agricultural residues is the dominant feedstock.

Table 8.3 also shows the production of gaseous and solid fuels. Note that the production of synthetic natural gas does not become cost-effective, and neither does the production of charcoal as a coal substitute for iron production. Straw briquetting however, meets its upper model bound at a 50 EUR/t permit price. The logistic limitations and agricultural straw requirements deserve more attention.

Table 8.3 *Benefit/cost ratios for production of biofuels, Globalisation scenario, 2030*

1 Production of liquid fuels	*Base case*	*20 EUR/t*	*50 EUR/t*	*100 EUR/t*	*200 EUR/t*
BF1 Straw pyrolysis to methanol Batelle process	0.74	0.87	1.00	1.00	1.00
BF2 Wood chips pyrolysis to methanol Batelle process	0.65	0.72	0.71	0.72	0.65
BF3 Organic waste to methanol (BIOMETH)	0.16	0.17	0.17	0.22	0.28
BF4 DME from straw	0.46	0.58	0.76	0.93	0.91
BF5 DME from wood	0.41	0.48	0.54	0.67	0.69
BG1 RME from rapeseed	0.30	0.34	0.39	0.52	0.66
BH4 Ethanol 95% to 99%	n.a.	1.00	1.00	1.00	1.00
IN2 ETBE production	n.a.	n.a.	1.00	1.00	n.a.
SBA Ethanol 99% addition to gasoline	n.a.	n.a.	1.00	1.00	n.a.
T07 Ethanol 95% car	0.92	0.95	0.99	1.00	1.00
BI1 HTU oil production from wood	0.76	0.79	0.83	0.96	1.00
BI2 HTU oil production from lignin	0.74	0.69	0.68	0.71	0.76
BI3 Diesel from HTU oil	0.68	0.79	0.89	1.00	1.00
BI5 Naphtha substitute from HTU oil	0.66	0.79	0.89	0.93	0.96
BJ1 Diesel from algae lipids	0.88	0.98	1.00	1.00	1.00
BL2 Pyrolysis oil to diesel	0.40	0.47	0.55	0.67	0.70
BE9 Fischer Tropsch process	0.29	0.46	0.39	0.11	0.17
BO1 Sugar/starch from wheat	0.29	0.25	0.31	0.46	0.59
BO2 Sugar/starch from sugarbeet	0.19	0.18	0.24	0.33	0.50
BO3 Cellulose/hemicellulose from straw	1.00	1.00	1.00	1.00	1.00
BO4 Cellulose/hemicellulose from wood	0.95	0.76	0.52	0.59	0.67
2 Production of gaseous fuels	*Base case*	*20 EUR/t*	*50 EUR/t*	*100 EUR/t*	*200 EUR/t*
BM1 Hydro-pyrolysis to SNG	0.46	0.56	0.70	0.70	0.74
3 Production of solid fuels	*Base case*	*20 EUR/t*	*50 EUR/t*	*100 EUR/t*	*200 EUR/t*
BB1 Straw briquetting	0.67	1.00	1.10	1.17	1.16
IHB Charcoal from wood for iron production	0.10	0.19	0.30	0.34	0.45

8.2.3 Energy recovery from waste

Figures 8.11 and 8.12 show the energy recovery from waste in centralised MSW treatment plants. Figure 8.11 provides an overview of the total waste supply to these plants. Note the eight-fold increase from 1990 to the base case in 2030. This increase is driven by the combination of waste legislation, the increasing cost of waste disposal and the increasing energy recovery efficiency.

Figure 8.12 shows the energy recovery from waste wood. It is important to note that co-combustion of waste wood in large-scale electricity plants has not been considered because of pollution problems. Given that future incineration and gasification efficiencies are estimated in the range of 30-35%, the biomass input equals an electricity production of 0.8-1.0 EJ, equivalent to 10% of the total electricity production.

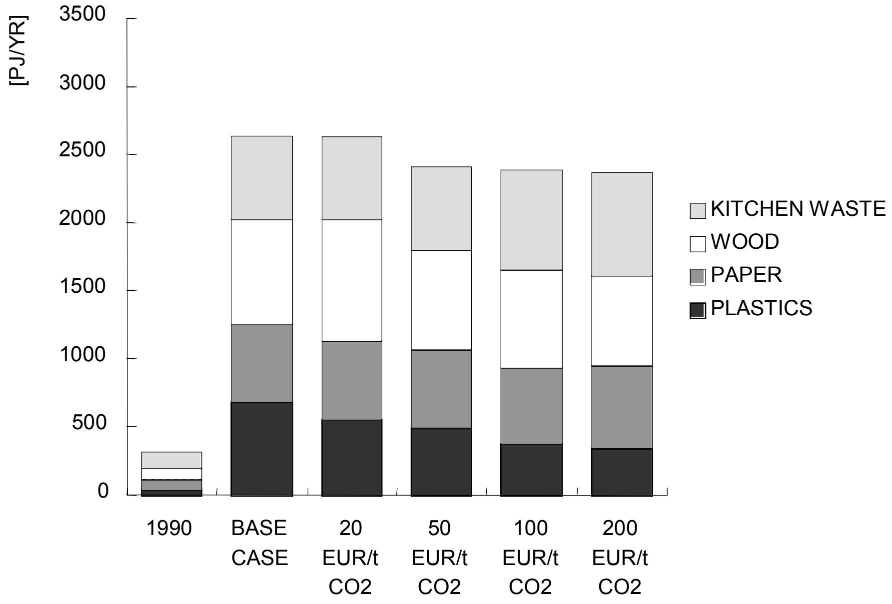


Figure 8.11 *Energy recovery from waste for increasing GHG permit prices in centralised MSW treatment plants, 3 scenarios, 2030*

Total energy recovery from waste biomass is not significantly affected by GHG permit prices. As a consequence, it seems a robust strategy to invest in these waste-treating technologies.

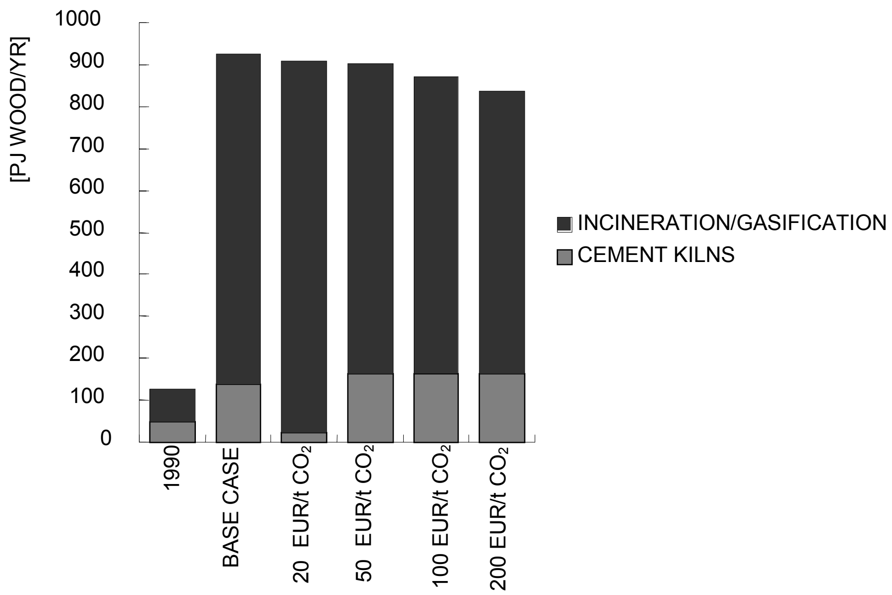


Figure 8.12 *Energy recovery from waste wood (wood waste input), centralised and co-combustion in cement kilns*

Table 8.4 *Benefit/cost ratios for energy recovery from waste, Globalisation scenario, 2030*

1 Energy recovery from post-consumer waste	*Base case*	*20 EUR/t*	*50 EUR/t*	*100 EUR/t*	*200 EUR/t*
DAA Methane recovery from disposal sites	0.41	1.00	1.00	1.00	1.00
DXK Anaerobic digestion kitchen waste	0.43	0.46	0.38	0.43	0.37
DXL Anaerobic digestion manure	0.40	0.54	0.74	1.00	1.07
EI1 Waste to energy (grate firing)	1.00	1.00	1.00	1.00	1.00
EI2 Waste to energy (Lurgi gasifier)	0.74	0.77	0.81	0.83	0.82
EI3 Waste to energy (Gibros PEC)	0.82	0.87	0.92	0.94	1.00
SUC Demolition wood incineration in cement kilns	1.00	0.84	1.06	4.22	2.78

Apart from the energy recovery from post-consumer waste, the energy recovery from manure must be mentioned. The results show 33 Mt anaerobic digestion of manure at a 50 EUR/t permit price, increasing to 200 Mt at 200 EUR/t (in 2030). Given that each Mt manure produces 1.5 GJ biogas, the biogas production increases from 50 PJ in the 50 EUR/t case to 300 PJ in the 200 EUR/t case. The driving force for this increase, is the gas production in combination with the assumption that N_2O emissions from treated manure (for fertilisation use) are lower than from untreated manure (only 1.25% of the nitrogen content compared to 2%). The value of 1.25% is similar to synthetic nitrogen fertiliser use. In monetary terms the value of this emission reduction equals 15 EUR/t manure at a 200 EUR/t permit price level. One must add that 200 Mt manure represents half of the total quantity of manure produced, so this is probably a high estimate of the potential (as significant quantities of manure cannot be collected and treated).

The relevance of co-production and cascading

Co-production and cascading have often been mentioned as important incentives for combined energy and materials biomass strategies in order to increase the biomass availability for energy recovery. Cascading is based on the concept: first use the biomass for materials (preferably with re-use) and next use the waste materials for energy recovery. This will increase the resource efficiency. An alternative approach is to produce biomaterials with a high value added, and use by-products as a cheap energy source. This study provides some insight into the relevance of these two issues.

Regarding cascading, energy recovery from waste is already important in the base case, driven by waste policies and increasing energy efficiencies of waste recovery technologies. Cascading strategies become important in this respect. However, this energy recovery strategy is not driven by the urge to increase the biomass penetration. The calculations show that biomass availability is not of primary concern, given the fact that such large agricultural areas are used for afforestation, while short rotation plantations could result in much higher yields. In conclusion, the relevance of cascading is of secondary importance.

The other side of the problem is the resource price. The production of bio-chemicals and wood construction materials (see Sections 8.3.1 and 8.3.2) results in significant quantities of cheap energy by-products which can be used for other purposes (the co-production strategy). The calculations show that this strategy is relevant to some extent. The use of bio-feedstocks and the production of bioethanol results in biomass energy by-products. However the production of sawn wood and pulp (two other materials whose production results in significant quantities of energy by-products) does not increase significantly because of GHG permit prices. The relevance of co-production is limited to less than 1 EJ bioenergy (through pyrolysis gasoline output from steam cracking and lignine by-product from ethanol with significant HTU oil production at the 200 EUR/t permit price). At lower permit price levels, its relevance is limited (around 200 PJ at a 50 EUR/t).

In conclusion the relevance of cascading is limited, co-production deserves more attention.

8.3 Biomass for materials

The biomass materials market can be split into bio-chemicals, construction materials and the pulp and paper market. First the aggregated results for materials will be discussed. Next, the three market segments will separately be discussed in more detail.

Figure 8.13 shows the biomaterials use in the Globalisation scenario. The figure shows an increase from approximately 120 Mt in the base case to 170 Mt in the 100 EUR/t case, and a subsequent decline to 150 Mt biomass at 200 EUR/t. This increase is largely accounted for by the increased biomass use as feedstocks for biochemicals production, as well as a limited increase of the biomass use for construction materials. At higher permit price levels (of 200 EUR/t) feedstocks decline again because now HTU oil is applied in the transportation sector instead of petrochemicals production.

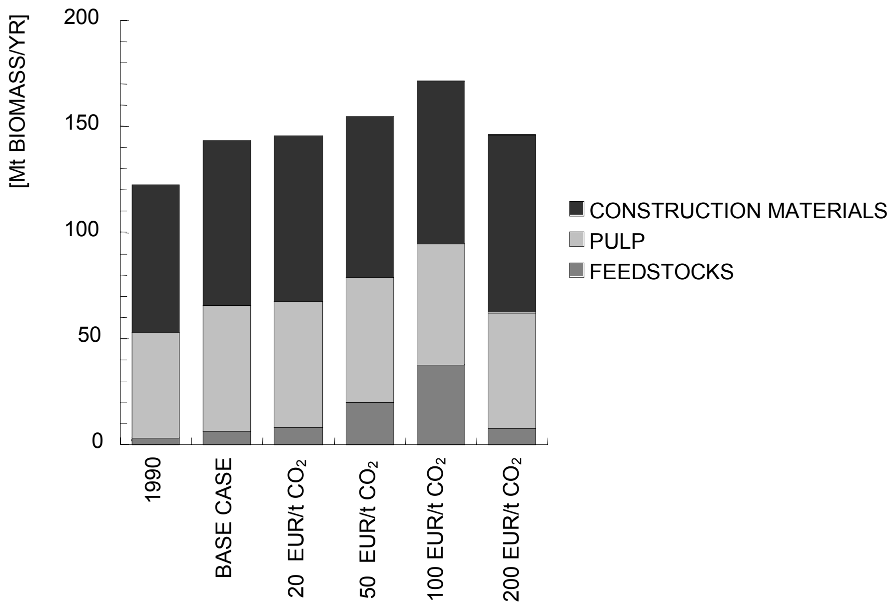


Figure 8.13 *Biomaterials use for increasing GHG permit prices expressed in primary biomass equivalents, Globalisation scenario, 2030*

Figure 8.14 shows the comparison of the three scenarios in the 100 EUR/t case. The results are rather similar (difference only 25 Mt biomass, 10%), with the highest amount of biomass used in the Sustain scenario. The differences are accounted for by the feedstocks market and the construction materials market. Figure 8.15 shows the impact on the use of some important materials. A significant decline in cement and glass consumption, a limited impact on polyethylene and aluminium, and an increase of the sawn wood consumption. These changes are the result of an interaction between materials substitution, increasing efficiency and a decline of product use because of increasing prices.

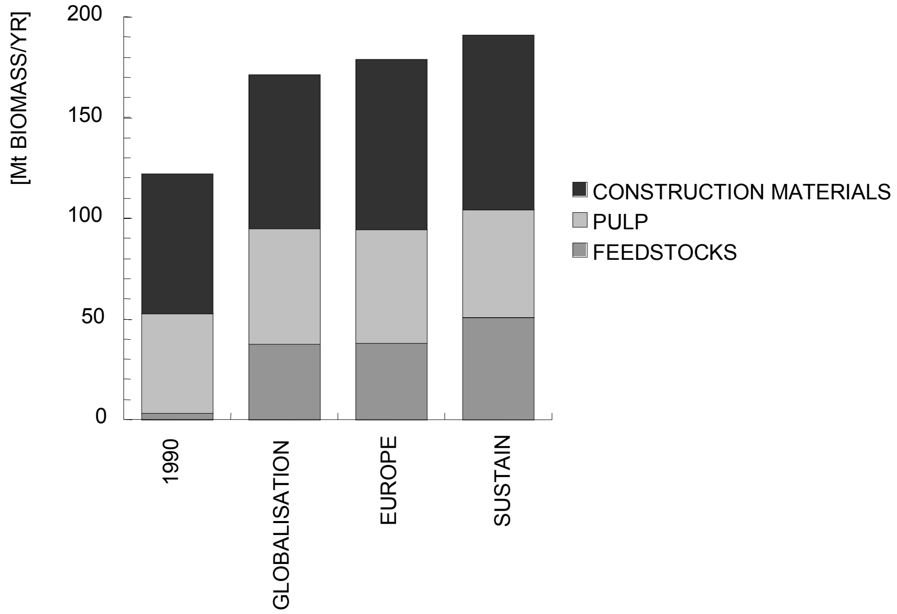


Figure 8.14 *Biomass use for materials in three scenarios, 100 EUR/t permit price, 2030*

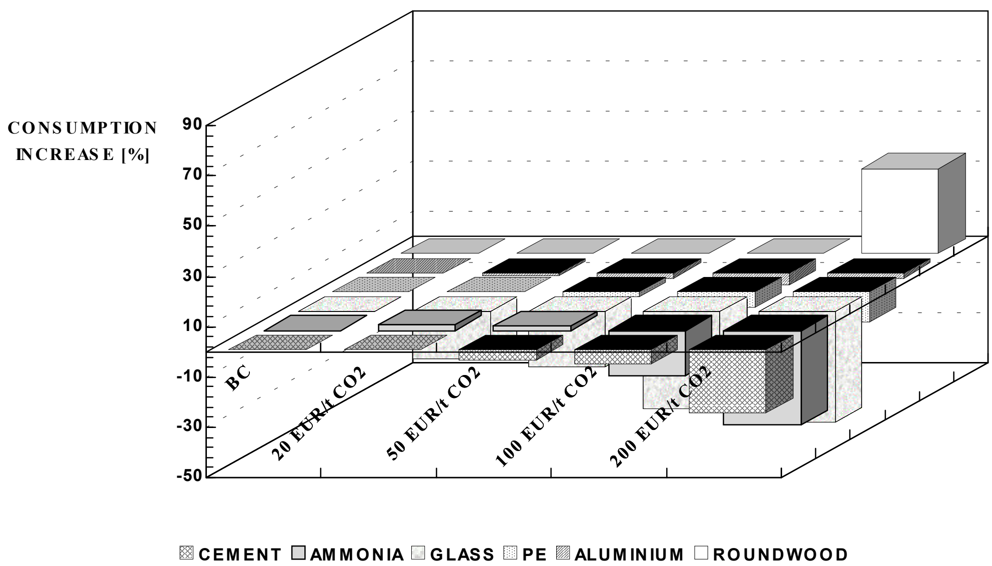


Figure 8.15 *The impact of GHG policies on the consumption of some important materials*

8.3.1 Bio-chemicals production

First the product mix of the petrochemical industry will be elaborated. The results for biomass consumption in this industry can only be understood if the changing product mix is considered. Figure 8.16 shows the petrochemical product mix for increasing GHG permit prices in the Globalisation scenario in 2030. The production of gasoline additives, methanol and ethanol has been allocated to the petrochemical industry. This is arbitrary; one could as well consider these processes as part of the refinery sector or as part of the agricultural or food industry sector (at least ethanol). The figure shows a total petrochemical production of approximately 100 Mt. Major changes are related to the fuel production. Established products such as plastics and other petrochemical products show a gradual decline in production volume due to decreasing demand and increasing recycling and reuse.

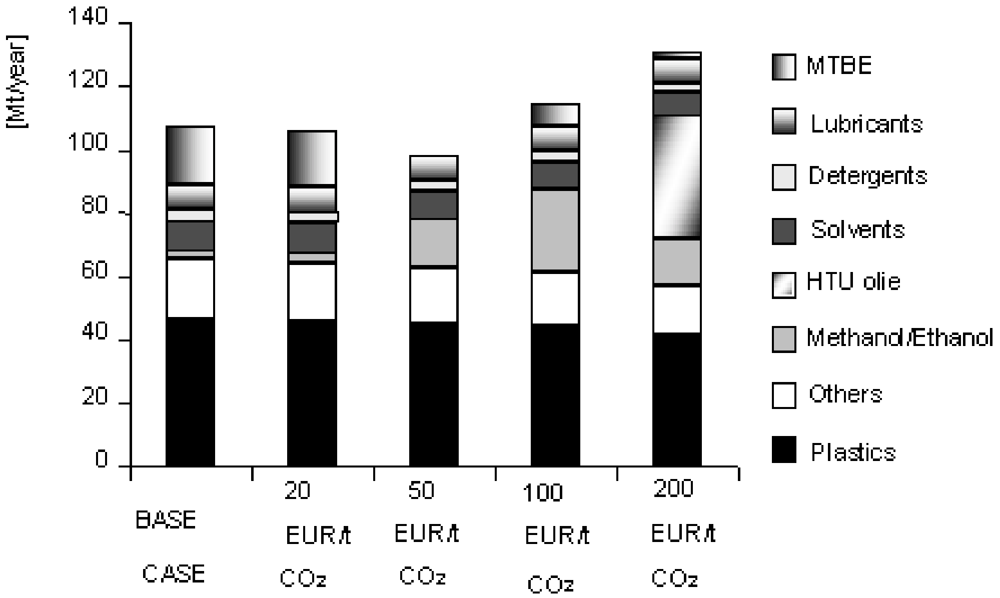


Figure 8.16 *Petrochemical production, 2030, globalisation scenario*

Figure 8.17 shows the energy use and (non-energy) feedstock use in the petrochemical industry. The figure shows that the total primary energy use declines at lower permit prices, but increases again by 50% from 4 to 6 EJ at higher levels. These changes are the combined effect of the changing product mix, the changing feedstock and energy carrier mix and the changing energy efficiency. Biomass is introduced as a substitute for oil and natural gas. Note the re-introduction of oil in the 200 EUR/t case. This is a typical systems effect, related to the changes in the refinery configuration that are caused by the changes in the transportation sector. Because more biomass is needed for production of transportation fuels, less biomass is available for production of bio-chemicals.

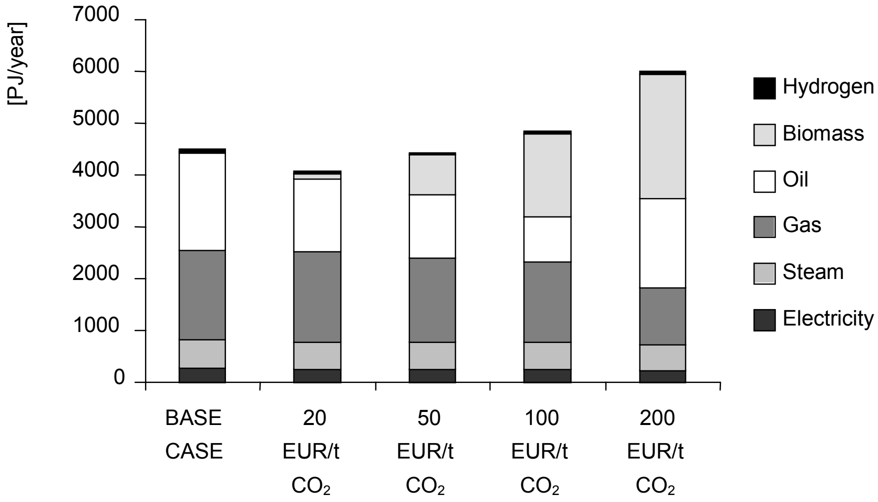


Figure 8.17 *Energy and non-energy use in the petrochemical industry, 2030, globalisation scenario*

Figure 8.18 elaborates the biomass use in the petrochemical industry. Five technologies are relevant: ethanol production, ethylene and butadiene production based on flash pyrolysis, methanol production and the production of biodiesel from HTU oil. Note that flash pyrolysis and HTU oil cracking are not yet proven on a commercial scale.

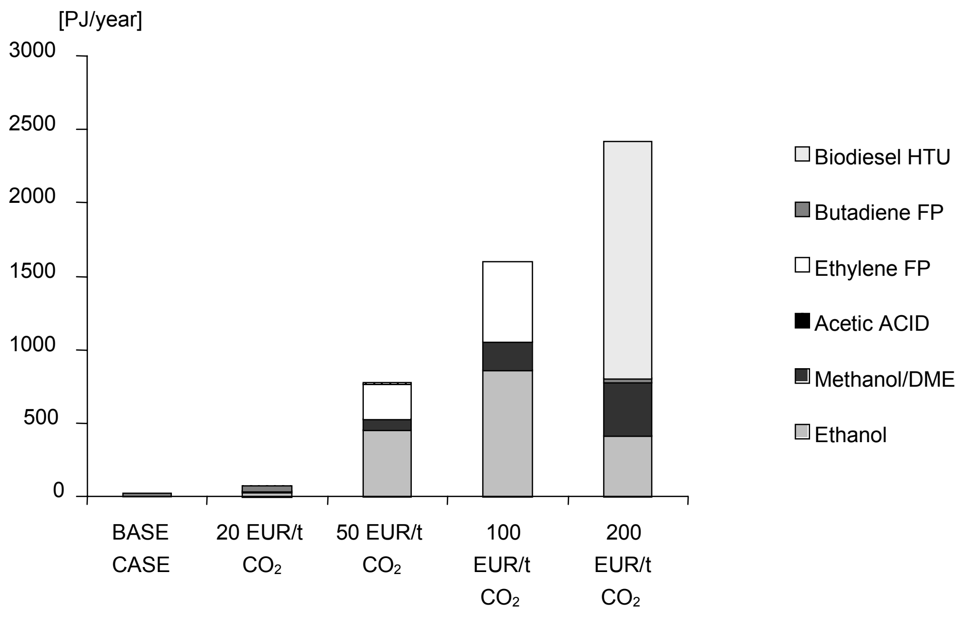


Figure 8.18 *Biomass use in the chemical industry for increasing GHG permit prices, Globalisation scenario, 2030 (FP = flash pyrolysis)*

Table 8.5 shows the benefit/cost ratios for different biochemical production technologies. The benefit/cost ratio of many production routes improves markedly at increasing permit prices, and some production routes become cost-effective. However, the quantities of biomass required for the production of many chemicals are small compared to the bulk commodities. As a consequence, these individual conversion routes are of secondary importance from a GHG emission mitigation point of view. For this reason they do not appear in Figure 8.18. However, given the added market volumes of potential minor routes, they do deserve attention.

Table 8.5 *Benefit/cost ratios for biochemicals, Globalisation scenario, 2030*

1 Production of petrochemicals	Base case	20 EUR/t	50 EUR/t	100 EUR/t	200 EUR/t
BK1 Synthetic lubricants from rapeseed oil	0.23	0.28	0.35	0.47	0.69
INE Ethylene/propylene/BTX from methanol pyrolysis (MTO process)	0.51	0.55	0.65	0.72	0.92
ING Ethylene from ethanol dehydrogenation	0.36	0.51	0.71	0.78	0.87
INH Ethylene/BTX from wood flash pyrolysis	n.a.	1.00	1.00	1.00	n.a.
IO3 Viscose for substitution of polyamide/PET	n.a.	n.a.	0.03	0.20	0.31
IO4 Cellophane production	0.34	0.36	0.38	0.49	0.58
IO5 Phenol through flash pyrolysis wood	1.00	n.a.	n.a.	n.a.	n.a.
IOP Acetic acid from biomass/synthesis gas route	0.93	0.97	0.99	1.00	1.00
IOQ Butanol/acetone from fermentation	0.74	0.89	1.00	0.31	0.45
IOR I-propanol from fermentation	0.55	0.73	0.87	1.00	1.00
IOS Butadiene from wood flash pyrolysis	1.00	1.00	1.00	n.a.	n.a.
IOT Phenol from lignin hydrotreatment	0.92	1.00	1.00	1.00	0.89
IOU Carbon black from wood	0.45	0.54	0.66	0.56	0.62
IOV Surfactant (AES) from palm kernel oil	0.73	0.84	1.00	1.00	1.00
IOX Marigold oil for solvents/resins in paint	0.68	0.69	0.71	0.73	n.a.
IOY PHB/PHV from sugar as PE substitute	n.a.	n.a.	n.a.	n.a.	n.a.
IPC PUR from lignin	1.00	1.00	1.00	1.00	1.00

Note that the direct biochemicals production (e.g. viscose, cellophane, marigold oil) does not become attractive. Instead, existing intermediates in the petrochemical chain (e.g. ethylene, butadiene) are produced from biomass. However within industry, most attention is currently focused on these dedicated production routes. This suggests that either the current model input data do not reflect the optimistic estimates of industry, or industry has not yet paid sufficient attention to the potential of biofeedstocks as substitute for oil and gas feedstocks for existing chemical products. More research is warranted to clarify the differences.

8.3.2 Biomass use for construction materials

Figure 8.19 shows the results with regard to wood products for building and construction. The figure shows approximately 65 Mt building and construction materials in 1990, increasing to 80 Mt in the base case in 2030. The total quantity increases to 85 Mt with increasing GHG permit prices. This increase is caused by a combination of a rapid growth of the sawn wood consumption and a decline of the particle board and MDF consumption. The sawn wood is used in the building sector, where wood substitutes concrete and other building materials. The board materials are mainly used in the furniture market, which is currently dominated by wood. As a consequence, the demand decline due to increasing prices dominates any positive substitution effect in this sector.

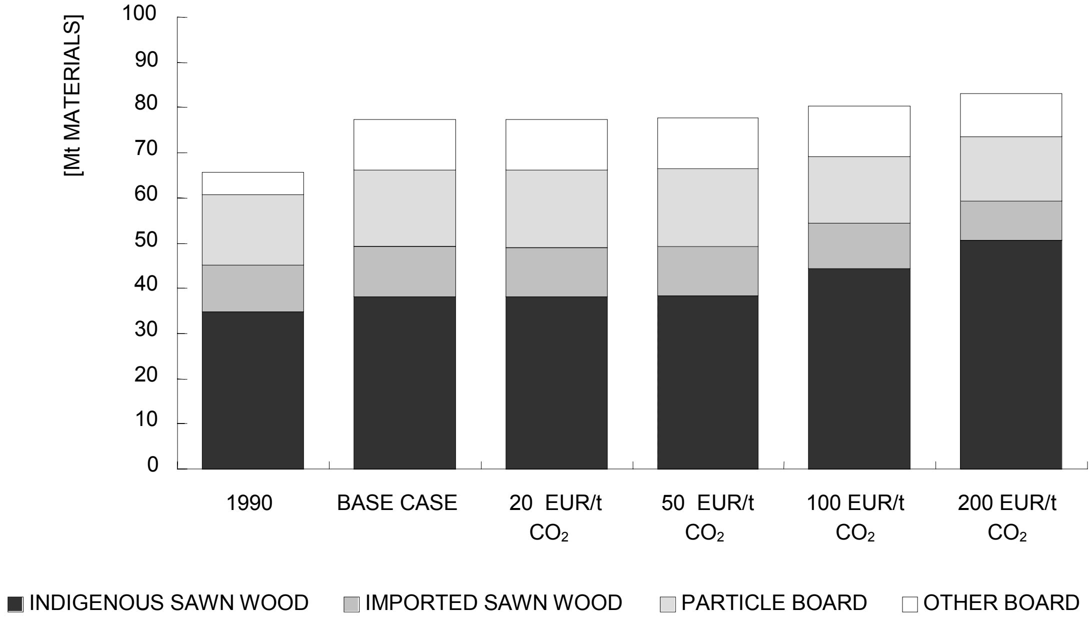


Figure 8.19 *Wood construction materials, Globalisation scenario, 2030*

Table 8.3 provides an overview of the benefit/cost ratios of wood products manufacturing. Small sawmills are replaced by large sawmills with higher cost-effectiveness. Tropical hardwood is substituted by engineered wood products from a permit price level of 100 EUR/t upward. Note that acetylated wood is only one example of a large family of potential substitutes.

Table 8.6 *Benefit/cost ratios for wood construction materials, Globalisation scenario, 2030*

1 Production of solid fuels	*Base case*	*20 EUR/t*	*50 EUR/t*	*100 EUR/t*	*200 EUR/t*
IXA Sawmill large Northern Europe	1.00	1.00	1.00	1.00	1.00
IXB Sawmill large Middle Europe	1.00	1.00	1.00	1.00	1.00
IXC Sawmill small Middle Europe	0.92	0.92	0.92	0.94	0.96
IXD Sawmill large Southern Europe	1.00	1.00	1.00	1.00	1.00
IXE Sawmill small Southern Europe	0.86	0.86	0.86	0.88	0.93
IXP Particle board production	1.00	1.00	1.00	1.00	1.00
IXQ MDF production	1.00	1.00	1.00	1.00	1.00
IXT Wood acetylation as tropical hardwood substitute	0.78	0.84	0.94	1.00	1.00
IXU PLATOnised wood as tropical hardwood substitute	0.25	0.31	0.40	0.52	0.68

8.3.3 Biomass for paper and pulp production

Figure 8.20 shows the paper consumption in the Globalisation scenario in 2030. A significant growth of paper consumption has been assumed, which is based on extrapolation of existing growth trends and the existing correlation between paper consumption and GDP growth. Note that GDP grows a factor 2.5-3, while paper consumption increases by a factor 1.5: a case of decoupling of GDP growth and physical demand, based on the assumption of increased electronic data traffic substituting paper use.

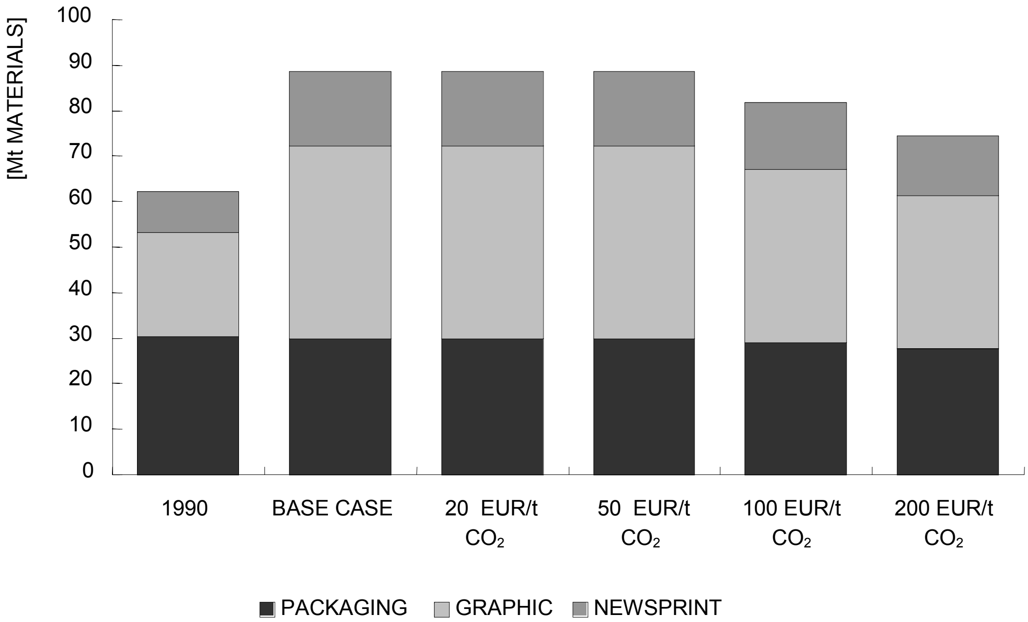


Figure 8.20 *Paper consumption, Globalisation scenario, 2030*

The ample biomass supply favours energy recovery from waste paper, thus requiring a growth in primary fibre supply. Figure 8.21 shows the results for the fibre supply (excluding the non-fibre paper additives). Paper recycling increases to 30 Mt per year (a 50% increase), chemical pulp production increases to 44 Mt per year (more than a doubling). The impact of GHG permit prices is limited. The recycling rate decreases from 40% in 1990 to 37% in the base case in 2030[38]. The driving force is in this case a co-production strategy: the lignin by-product from chemical pulp production can be used for energy recovery (with high efficiencies because of the new gasification technology). Moreover, energy can be recovered from waste paper.

[38] Note that the definition of paper recycling rate in this study is the recycled fibre consumption divided by the total fibre consumption for paper production. This definition differs slightly from other studies.

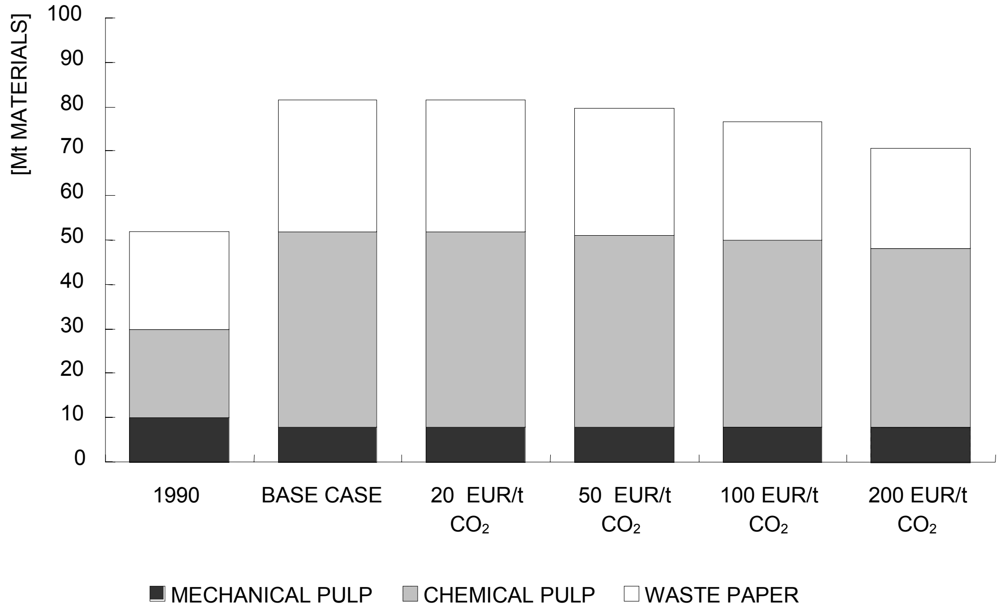


Figure 8.21 *Fibre supply for paper production, Globalisation scenario, 2030 (excludes approximately 10% non-pulp paper constituents such as kaolin etc.)*

8.4 Contribution of biomass strategies to GHG emission reduction

The quantity of GHG emission mitigation that can be attributed to biomass strategies depends to a large extent on the chosen reference system. Six reference systems can be considered:

1. The 'average' energy and materials system in the year 1990.
2. The 'marginal' production technology in the year 1990.
3. The 'average' base case energy and materials system in the year analysed.
4. The 'marginal' production technology in the base case of the year analysed.
5. The 'average' energy and materials system with permits (excluding biomass) in the year analysed.
6. The 'marginal' production technology with permits in the year analysed.

The term 'marginal' in this sense refers to the technology with the highest emissions per unit of product that is applied within Europe in the reference year. The term 'average' refers to the average emissions of all technologies that are applied for the manufacturing of a certain product. The following analysis is based on reference 5. Choice of references 1-3 will significantly increase the relevance of electricity production and of energy recovery from waste. The chosen reference implies that for 1990 the reference year is 1990, while for 2030, the reference year is 2030. In the base case, the reference is the average emission in the base case. In the case of emission permits, the average emission refers to the average emission in the case with permits. For example for electricity production, the average emissions are elaborated in Chapter 9. They decrease very significantly for increasing permit prices, thus decreasing the emission reduction potential through bio-electricity production from biomass.

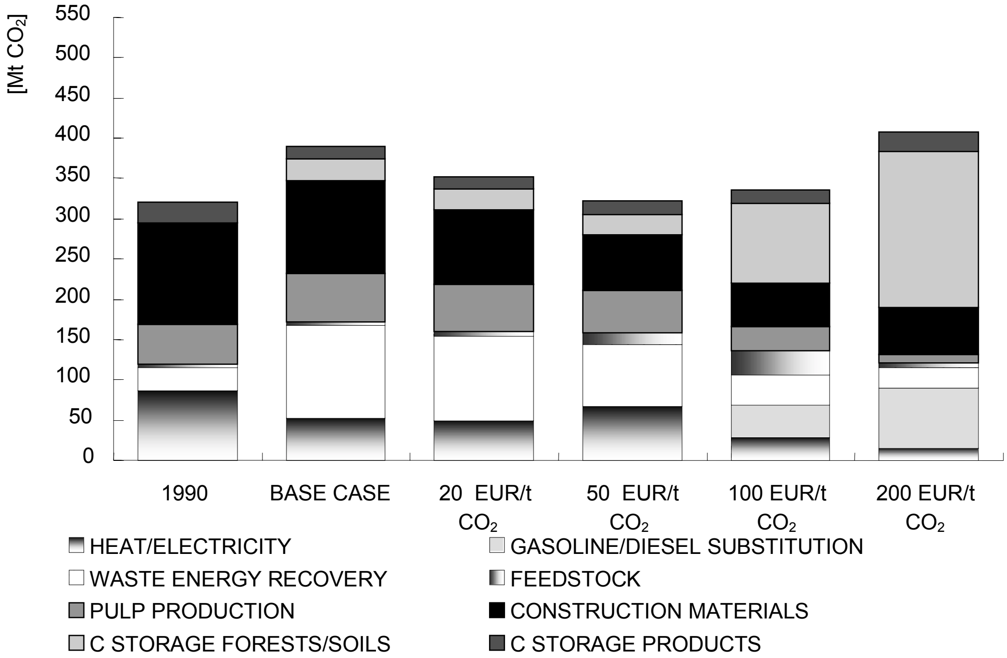


Figure 8.22 *Contribution of biomass strategies to GHG emission reduction, 2030, Globalisation scenario*

Figure 8.22 shows the contribution of biomass strategies in the Globalisation scenario in 2030. Biomass already has a very significant emission reduction effect in the base case, both in 1990 and in 2030. However, as the emission reduction increases for the whole energy and materials system, the introduction of more biomass strategies merely balances the reduced emission reduction per unit of biomass applied (especially in the heat/electricity and building materials market). Only at a high permit price level of 200 EUR/t, the contribution of biomass improves markedly through afforestation, from 300 to 400 Mt emission reduction. This analysis shows the importance of accounting for the changing reference system. Without such consideration, the relevance of biomass strategies would be grossly over-estimated (see also the estimates in Chapter 3).

Another approximation of the contribution of biomass can be derived from a model run where additional biomass availability is reduced to zero. In model terms, this has been achieved through high export prices for poultry and roundwood, and high prices for residual straw for other applications. As a consequence, no surplus resources are available for biomass strategies. The GHG emission mitigation in these model runs without biomass is compared with the mitigation in the globalisation model runs and the difference is attributed to the biomass strategies.

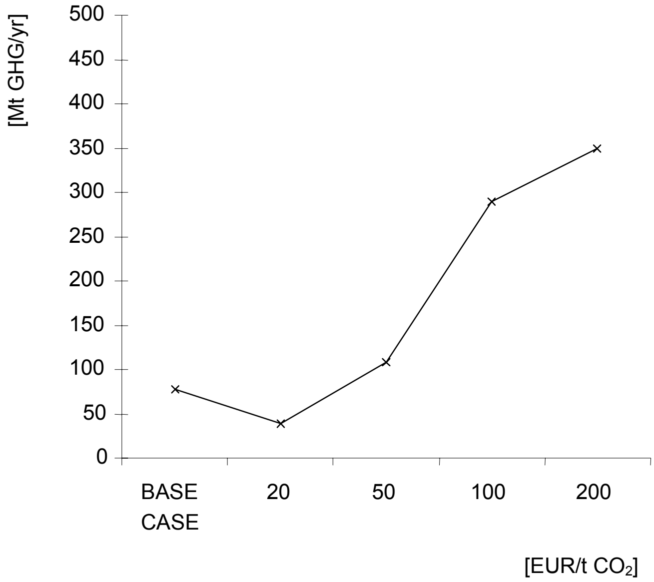
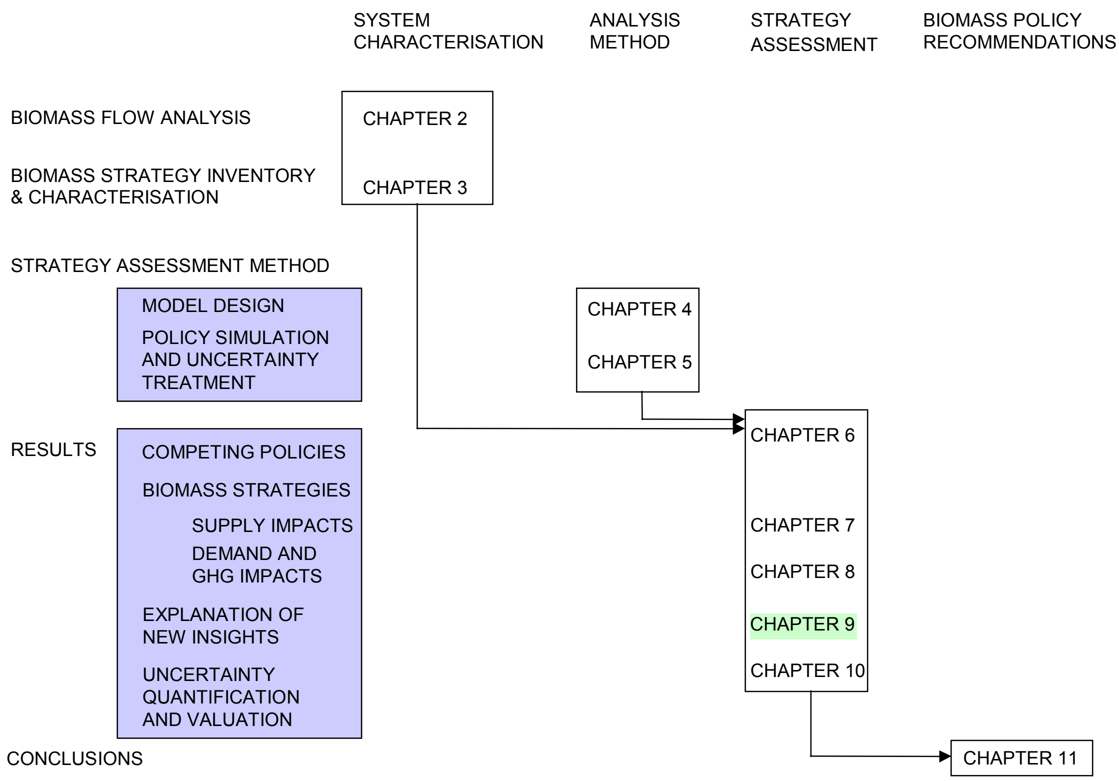


Figure 8.23 *Estimation of biomass strategy contribution to GHG emission mitigation, based on MARKAL model runs*

Figure 8.23 shows the result: a very modest contribution of biomass strategies at permit prices up to 50 EUR/t. From 100 EUR/t upward, the contribution of biomass strategies rises to 300-350 Mt. Significant differences exist between Figure 8.22 and Figure 8.23. At lower permit price levels, the contribution of biomass is significantly higher in Figure 8.22. However Figure 8.23 shows much higher growth in biomass use at higher permit price levels. The differences can be attributed to a different reference system selected. In Figure 8.22, the reference is the base case situation without any biomass (thus excluding pulping, wood construction materials and waste energy recovery). Figure 8.23 does not account for the positive contribution of biomass in the base case. Another important difference is that Figure 8.23 is based on marginal effects, while Figure 8.22 is based on the average reference system emissions (e.g. relevant for electricity). Finally, Figure 8.23 accounts for indirect GHG effects in the agricultural food production, which are not accounted for in Figure 8.22. Figure 8.23 is a more reliable estimate than Figure 8.22. The differences between both figures show the complexity of proper accounting of GHG impacts in bottom-up accounting, one important reason why an integrated modelling approach is required.

9. THE IMPACT OF THE METHODOLOGY CHARACTERISTICS FOR THE STRATEGY SELECTION: SOME EXPLANATIONS



The selection of emission reduction strategies in MARKAL is based on least cost system optimisation with endogenised environmental costs (on the basis of the emission permit price). This approach has consequences for the selection procedure. These consequences will be elaborated for biomass. Three strategies for agricultural land use for GHG emission reduction are compared:

- afforestation,
- high yield crops and production of transportation fuels,
- high yield crops and production of electricity.

These three strategies are compared because the MARKAL MATTER 4.2 results show remarkable differences compared to other studies in the sense that afforestation is preferred over electricity production and biofuel production (see Chapter 8). Earlier studies have advocated the production of electricity. The difference can be explained on the basis of the model input data and the methodological differences with other studies. The following elements will be discussed in Sections 9.1-9.4:

- the changing reference system emissions,
- the impact of cost optimisation,
- the impact of discounting,
- the impact of accounting for competing resource use options.

9.1 The impact of the changing reference system

The impact of the changing reference system must be considered in a proper analysis of emission mitigation potentials. Biomass competes with a large number of other emission mitigation options, which are gradually introduced as more stringent emission reduction targets are introduced. As a consequence, the GHG emission reduction potential of biomass declines compared to the current reference system. The most drastic changes occur in electricity production and in materials production. The first one is very relevant for the analysis of bio-electricity production, a strategy that is currently widely promoted as being the best biomass strategy. The reduction of emissions in the production of competing materials is very relevant for the analysis of the potential emission mitigation through introduction of wood based products.

Other biomass strategies are less dependent or even independent on changes in the reference system configuration. For example, the CO_2 effect of carbon storage in afforestations is independent of any other option (at least if competing land use options are neglected). The substitution of petrochemical feedstocks and transportation fuels are other examples where carbon content is essential (the model calculations suggest that competing CO_2 free electricity and hydrogen for transportation fuels do not affect the carbon content of the (marginal) reference transportation fuels, see also Section 8.2.2). As a consequence, the relative attractiveness of these strategies will increase if the changing reference is considered. This is a very important explanation of the results shown in the preceding chapters. In order to illustrate this point, Figures 9.1 and 9.2 illustrate the average CO_2 intensity of electricity production and the average GHG intensity of materials production.

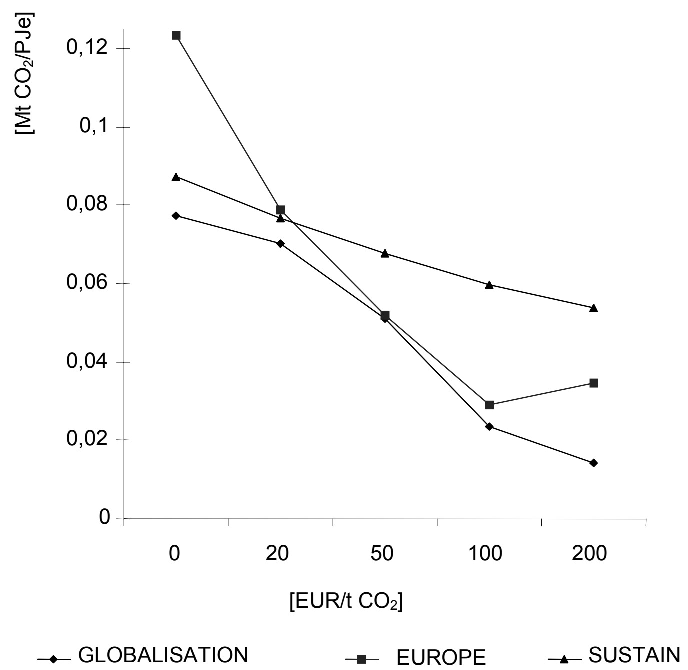


Figure 9.1 *Average GHG intensity of electricity production, 3 scenarios, 2030*

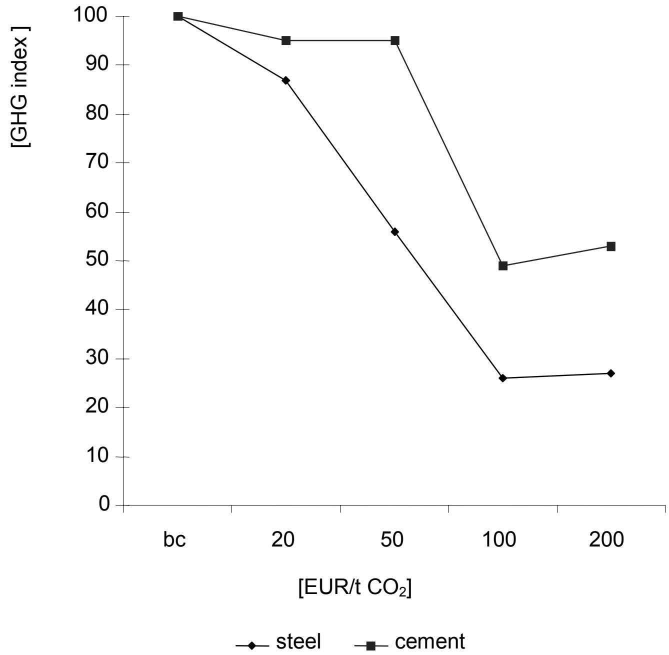


Figure 9.2 *Average GHG intensity of materials production compared to the base case (BC=100), Globalisation scenario, 2030*

9.2 The impact of cost optimisation

The MARKAL algorithm is based on cost minimisation[39]. Considering costs has important consequences for the selection of biomass strategies. The analysis in Chapters 6-8 has shown that due to cost considerations, the emission mitigation strategies with the highest GHG impact are not necessarily cost-effective strategies as well.

The cost dimension can also explain why strategies that affect the beginning and the end of the product life cycle are more cost effective than strategies that affect the middle of the product life cycle. Figure 9.3 shows the cost structure of the product life cycle of a wooden window frame, split into a GHG sensitive part and a GHG insensitive part. The further one proceeds from roundwood to the final product, the smaller is the GHG cost sensitive fraction (labour and capital costs make up for the difference). As a consequence, the impact of a GHG permit price on the product price decreases. A small price increase will not induce any change. Waste (at the end of the product life cycle) can be considered as a natural resource substitute. As a consequence, the GHG sensitivity is high (similar to the GHG sensitivity of natural resources).

[39] Which is equivalent to the maximisation of the consumer/producer surplus.

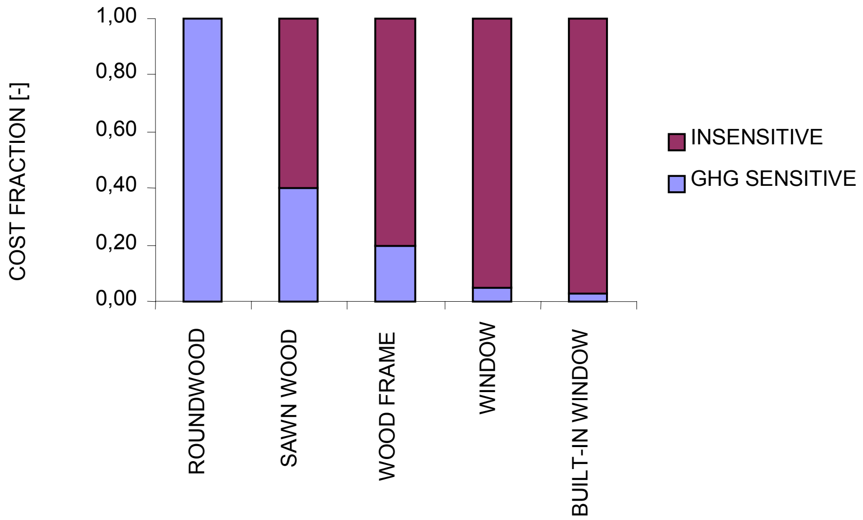


Figure 9.3 *Cost structure of a wood window frame*

9.3 The impact of discounting

This section will elaborate the impact of discounting on the MARKAL MATTER biomass strategy selection. The optimal use of 1 ha of land will be elaborated. The following comparison is based on a time period of 50 years, the rotation time span for afforestation in the model.

Afforestation with poplar

The assumptions are:

- Afforestation costs: 1000 EUR/ha.
- Life plantation: 50 years.
- Yield after 50 years: 450 t roundwood.
- Annual carbon storage: 14 t CO_2/ha/year (incl. soil and litter).
- Release after 50 years: 700 t CO_2/ha/year.
- Value roundwood: 190 EUR/t.
- CO_2 emission reduction roundwood use via methanol production: 0.073 t CO_2/GJ methanol (0.8 t CO_2/t wood).

Methanol production from miscanthus

The assumptions are:

- Plantation and harvesting costs: 1000 EUR/ha/year.
- Annual yield: 500 GJ/ha.
- Efficiency methanol production: 62.5 %.
- Average biomass transportation costs to the methanol plant+storage costs: 2.5 EUR/GJ.
- CO_2 emission reduction: 0.073 t CO_2/GJ methanol (substitution of gasoline).
- Methanol production costs: 6 EUR/GJ methanol (excl. investments).
- Methanol plant investment: 30 EUR/GJ methanol capacity/year.
- Value methanol: 4.5 EUR/GJ (diesel/gasoline production cost).

Electricity production from miscanthus

The assumptions are:

- Plantation and harvesting costs: 1000 EUR/ha/year
- Annual yield: 500 GJ/ha.
- Average biomass transportation + storage costs: 2.5 EUR/GJ.
- Efficiency of electricity production from biomass: 50%.

- CO_2 emissions reference electricity production: 0.1 t/GJ in base year, 3 and 7% reduction per year over the next 50 years.
- Electricity plant investment costs: 75 EUR/GJ electricity/year.
- Value electricity: 12 EUR/GJ.

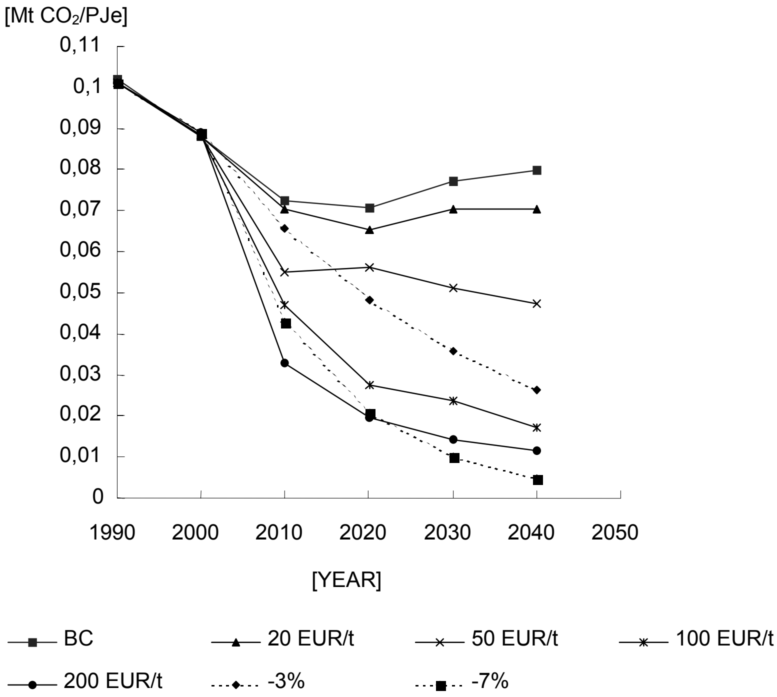


Figure 9.4 *Average CO_2 intensity of electricity production for increasing GHG permit prices, Globalisation scenario, 2030, in comparison to 3% and 7% average annual improvement from 2000 onward*

The CO_2 emissions related to the reference electricity production depend on the competing emission mitigation strategies. MARKAL MATTER model results show a very significant emission reduction in electricity production if GHG emission mitigation strategies are introduced (see Figure 9.4). Other strategies (such as CHP, new high efficiency gas fired power plants, renewables such as wind energy, CO_2 removal and underground storage and nuclear energy) will reduce the emissions in electricity production by a factor 10, if permit prices from 100 EUR/t upward are introduced (see Section 9.1). This emission reduction is accounted for through the 3% and 7% annual emission reduction in electricity production from the Western European average level of 0.1 GJ/t (comparable to the emission for a gas based modern power plant without CHP).

The net present value (NPV) of the projects is calculated as the difference of revenues and costs. All costs and all revenues are first converted into EUROs of the year of investment. This is basically the same comparison made in the MARKAL algorithm.

Figure 9.5 first illustrates the GHG impact of the different strategies. The figure shows that the emission reduction per hectare is significantly higher for methanol production than for afforestation (1275 vs. 350 Mt CO_2/ha). Based on this comparison, methanol should be preferred. This is the typical LCA or energy chain analysis approach.

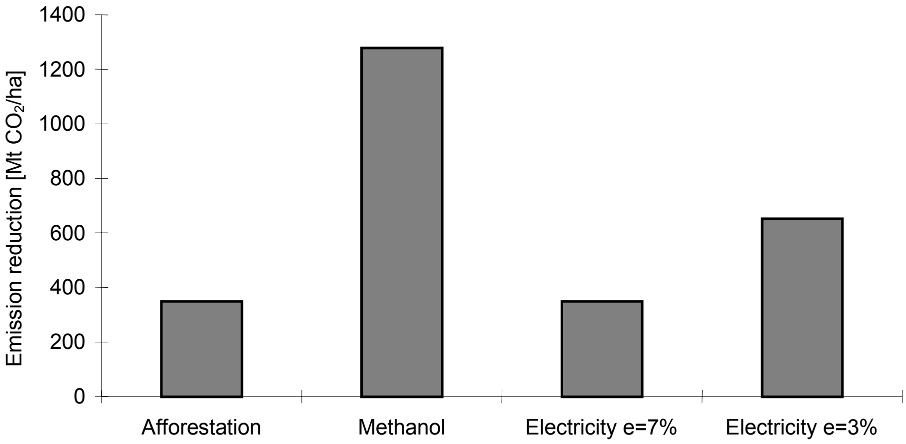


Figure 9.5 *Aggregated impact on CO_2 emissions over a period of 50 years (e=annual GHG intensity reduction in the reference electricity production)*

However the MARKAL optimisation shows a very different picture. One of the main causes is discounting. Figure 9.6 shows the cost efficiency of these projects according to the MARKAL algorithm (including discounting) for an emission permit price of 200 EURO/t CO_2.

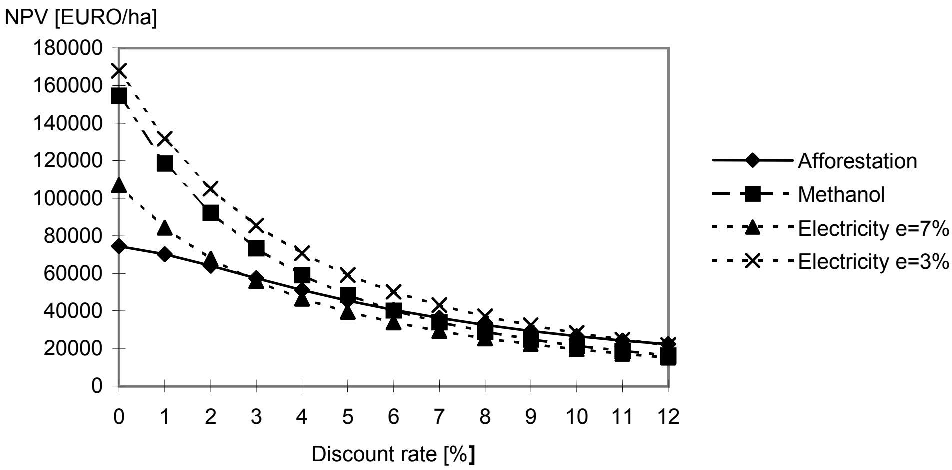


Figure 9.6 *Net present value of different land use options for GHG emission mitigation as a function of the discount rate. Project time span 50 years. Emission permit price 200 EUR/t*

Figure 9.6 shows that:

- The NPV can vary a factor 8, depending on the discount rate 0-12%.
- Afforestation is the worst project at 0% discount rate, but the best project at 12% discount rate.
- The most significant differences in NPV occur at low discount rates. At 0% discount rate, the NPV of the best project is 2.2 times the NPV of the worst project. At 12% discount rate, the NPV of the best project is 1.5 times the NPV of the best project.
- The NPV of electricity production depends critically on the rate of emission reduction in the reference system (the competing technologies). The neglect of this change in other analyses is not correct and can result in wrong conclusions.
- The 7% improvement rate is more in line with MARKAL results than the 3% improvement rate. As a consequence, electricity production has a lower NPV than the production of transportation fuels.

- At lower discount rates, the selection of biomass use for transportation fuels and electricity production will be preferred to afforestation (in the MARKAL model calculations).
- Financial data must be considered in the selection of GHG emission mitigation strategies, emission mitigation data alone are not sufficient.
- The difference between the MARKAL results and other studies with regard to optimal biomass strategies can to a large extent be explained by two factors. First, the consideration of the changing GHG intensity of the reference electricity production (considering all competing emission mitigation strategies) and second, the selection of strategies on the basis of discounted project life cycle costs.

9.4 The impact of competing resource use options

Biomass options compete for the limited quantity of biomass available at a certain price level. In analyses, it is often neglected that biomass prices will increase if a GHG tax is applied, driven by competing biomass applications. However this effect is not negligible as shown by MARKAL results. Figure 9.7 shows this effect. The gasoline price increases because of the related GHG emissions. The price for ethanol from biomass also increases, but because of the increasing demand for biomass and the increasing land costs (see Figure 7.5). Other analyses would compare the gasoline price at a certain permit price level and the ethanol price without permit price (the horizontal line). Ethanol would become cost-effective if this method is applied. Figure 9.7 shows however, that the production cost gap between gasoline and wood based ethanol remains approximately constant at a level of 40 EURct/l. Introduction of wood based ethanol is only cost-effective in case this gap is closed by cheaper production processes, based on new R&D.

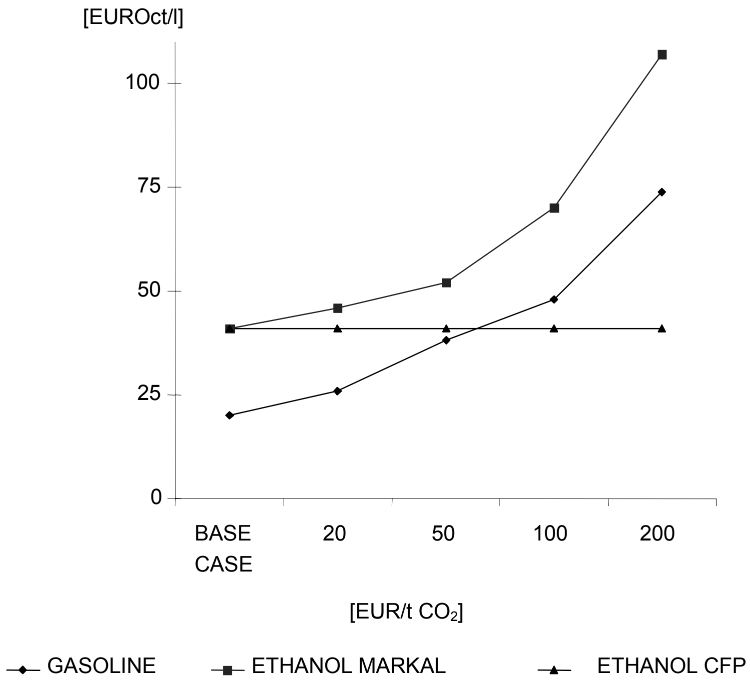
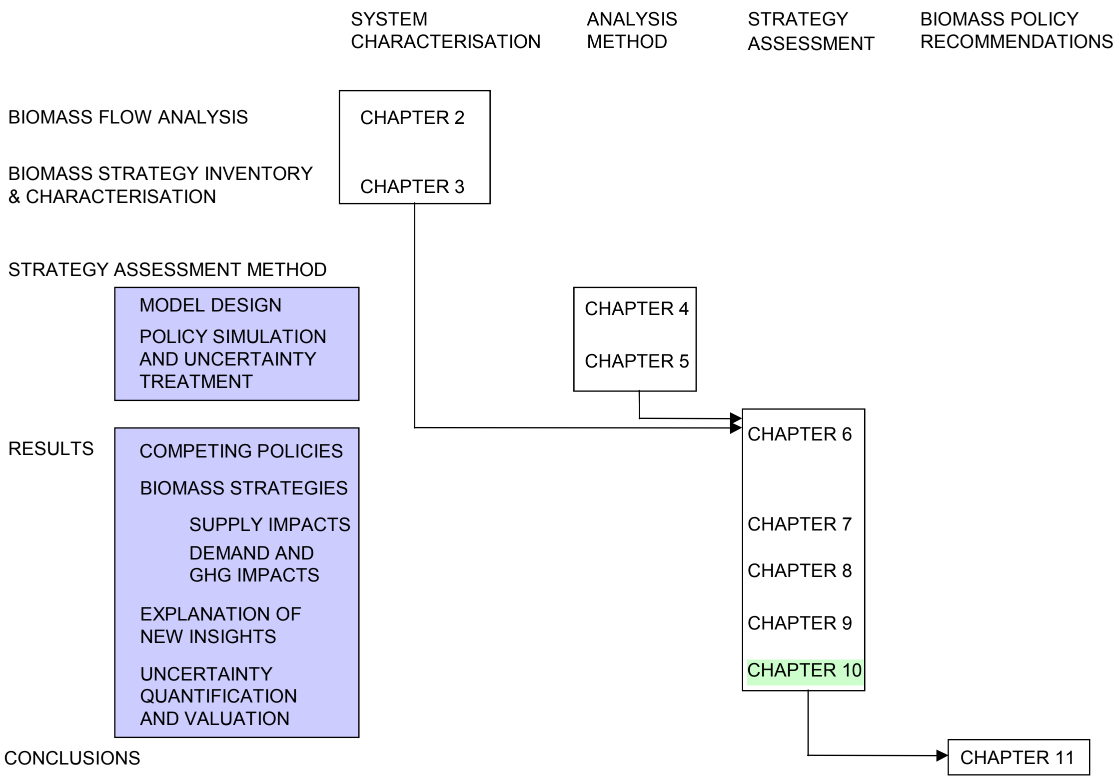


Figure 9.7 *The price of gasoline and bio-ethanol in relation to the GHG reduction incentive (CFP=Constant Feedstock Price)*

10. UNCERTAINTY ANALYSIS



10.1 Heuristic uncertainty analysis: expert comments

In order to get feedback, the preliminary modelling results have been presented at the following meetings:

- Environment and Climate programme meeting, Darmstadt, June 1998.
- LCA conference, Brussels, December 1998.
- Conaccount workshop, Amsterdam, December 1998.
- Biomaterials conference, Bonn, March 1999.
- Agrires colloquium, ministry of environment, Paris, May 1999.
- Two internal ECN workshops, April and July 1999.
- Meeting with EWAB program management, Novem, Utrecht, August 1999.
- IEA bioenergy implementing agreement task 25 workshop, Gatlinburg, USA, 27-30 September 1999.
- Biofuels conference, Brussels, October 1999.
- Meeting with the members of the scientific committee of the Environment and Climate programme, Brussels, 28 October 1999.
- IEA-ETSAP workshop, Bergen, the Netherlands, 3-4 November 1999.
- Biomass conference, Graz, Austria, November 1999.
- Renewable energy conference, Noordwijkerhout, the Netherlands, November 1999.

The following important uncertainties have been encountered in the past year during project discussions and during presentations for the parties mentioned above. They have been categorised into three categories:

- policy simulation,
- technology/resource availability,
- methodological issues.

Policy simulation

- Other environmental policies have not been considered (e.g. regarding sustainable development, waste, spatial planning, eutrophication).
- The impact of other policies is not considered (taxation and subsidies, labour).
- The impact of the extension of the European Union with central European countries is not considered.
- The GHG policy scope (European boundaries and/or end-use related system boundaries).

Technology/resource availability

- Additional imports of biomass for energy and materials from other regions are not considered.
- Future agricultural productivity increases based on new technology (is considered, but the figures are uncertain).
- The impact of changing global agricultural commodity markets.
- Quality issues have not been detailed (e.g. different cheese or beef meat qualities for biological farming).
- It is not clear to what extent the data for buildings represent a realistic average for the whole sector.
- The impact of climate change on the productivity of agriculture and forests.
- The accounting of carbon storage in forests planted before 1990 and biomass carbon storage in products and in waste disposal sites is still unclear.
- The feasibility of many new process routes, especially for feedstock substitution, is uncertain as of yet.
- Costs and efficiencies of new biomass conversion technologies are based on exogenous assumptions. No endogenous learning curves are included in this model version.
- Parameters for competing technologies may be under- or overestimated.
- The GWP time horizon can differ.

Methodological issues

- Other environmental impacts have not been considered (e.g. NO_x, SO_2 and hydrocarbon emissions in the transportation sector).
- Lifestyle changes are not modelled explicitly as improvement option (some lifestyle differences are part of the scenario characteristics).
- The modelling of CH_4 and N_2O emission mitigation options for agriculture is still incomplete.
- The multi functionality of forests (for recreation, rainwater catchment function, etc.) is not considered in the wood cost analysis.
- The model is a crude representation of Western Europe. The match of regional supply and demand is only considered on the scale of the regions (North, Middle and South) while supply and demand may not match on a more detailed scale. The same problem may apply to large scale CHP units.
- The model contains one single electricity grid. Electricity production in Northern Europe for the Middle or Southern regions with long range transportation does not seem a viable option.
- Materials only compete on the basis of price to a limited extent.
- The real market is not an ideal market.
- The wood industry, for example, uses its own residues. Credits for the use of renewable wood energy should be allocated to the wood chain.
- The current model formulation excludes non-linear equations. For example: investment costs or process efficiencies will often depend on the scale of operations, which is a non-linear effect. These effects cannot be analysed with MARKAL.
- No detailed analysis has been made of future land costs.

A number of key parameters has been varied in the scenarios (see Chapter 5), such as fossil fuel prices, discount rates, food demand, GDP growth, structural changes, future of nuclear power, trends in the global agricultural market and CO_2 storage potentials. Table 10.1 provides an overview of other important uncertainties. This list is based on a combination of back of the envelope calculations and insights from model sensitivity analyses that are not reported separately.

Table 10.1 *Key uncertainties*

Policy simulation	
1	Renewable energy targets
2	Spatial planning (e.g. regarding land use)
3	Lacking international GHG policy agreement
4	Other environmental policies[40]
5	Labour policies
6	Extension central/eastern European countries
7	Policy scope: IPCC emission accounting guidelines adjustment
8	Subsidies and taxes (agriculture)
Technology/resource availability	
9	Changing global agricultural commodity markets
10	Biomass imports
11	Agricultural productivity trends (genetic engineering etc.)
12	Agricultural structural change (higher product quality etc.)
13	Heating energy demand wood frame buildings
14	The impact of climate change on the productivity of agriculture and forests
15	GWP time horizon
16	Length of rotation for afforestation
17	Technological uncertainty for biomass
18	Characteristics competing technologies, based on other resources
19	Future demand for physical products (including food)
20	Future land costs
Methodological issues	
21	Other environmental impacts
22	CH_4 and N_2O emission mitigation for agriculture
23	Learning curves
24	Multifunctionality of forests
25	Matching regional biomass supply and demand
26	Matching regional electricity supply and demand
27	Market characteristics
28	Allocation residue credits
29	Non-linearities regarding investment costs
30	Representation buildings sector
31	Addition of more regional detail
32	Rebound effects
33	Expansion of temporal system boundaries

Based on insights from sensitivity analyses and based on literature study most attention in the sensitivity analysis has been paid to policy simulation and the availability of technologies and resources. Methodological issues are thought to be of secondary importance. Table 10.2 provides a brief characterisation of the sensitivity analyses that have been done within this study. The selection in Table 10.2 is based on a combination of the perceived impact and the feasibility of model analysis. Regarding the methodological uncertainties, these are the most difficult to analyse, as they would often require the use of completely different methodologies, a laborious task beyond the project scope.

[40] Europhication, energy, biodiversity, acidification, waste, nature reserves

Table 10.2 *Key parameters for sensitivity analysis (numbers in column 1 refer to numbers in column 1, Table 10.1)*

Policy simulation	
1. Renewable energy target	Minimum 25% of primary energy use
2. Spatial planning	Minimum 15 Mha high yield biomass crops
2. Spatial planning	5 Mha maximum bound afforestation Southern Europe
3. Lacking international GHG emission reduction agreement	GHG policies focusing on sitting ducks (excluding industry)
4. Waste policies	Waste disposal 50 EUR/t (down from 185 EUR/t)
4. Biodiversity/nature policies	Extensification (lower yields)
5. Labour policies	Labour costs 10-20 EUR/t
Technology/resource availability	Range/approach
10. Cheap import potential from South America/Russia (liquids)	3 EJ/yr HTU oil (South America) and 3 EJ/yr ethanol (Russia)
11. Future agricultural productivity	20% higher
13. Heating energy demand wood frame buildings	20% lower
14. Climate change impacts on productivity	Mixed; see Annex 1
15. Time horizon for global warming potentials	20 years GWP (instead of 100 years)
16. Rotation length afforestations	20-50 years
17. Upper bounds co-combustion gas fired power plants	No bounds (instead of 25 Gwe)
17. Upper bound straw pelletisation	No bounds (instead of 250 PJ)
17. Fischer-Tropsch biodiesel	Yes (not considered in reference calculations)
17. HTU oil production	Failure of development
18. No electric vehicles	Failure of development

To some extent the impact of methodologies (actually the impact of a much broader scope of methodological differences) can be derived from the comparison with the results from other studies in Section 10.4. Section 10.4 discusses the results of this study in comparison to other studies based on other methodologies. The bulk of the differences can be attributed to methodological differences, thus the comparison provides a measure for the impact of methodological issues on the results. However, the comparison is not clear-cut in the sense that input data can also differ and cause part of the differences. Moreover, time horizons and scenario characteristics are not identical. More research is recommended (see also Chapter 4 for a discussion of methodological issues).

10.2 Sensitivity analysis results: the impact of the policy dimension

10.2.1 Regulation instead of pricing: a target for renewable energy

The European Union has formulated a White Paper for a Community Strategy and Action Plan: Energy for the future: Renewable sources of energy (European Commission, 1997b). The White paper aims for a 12% contribution from renewable sources of energy to the European Union's gross inland energy consumption by 2010. Heatpumps and combustion of plastic waste are not considered as part of the renewables target, but a significant contribution from biomass is considered. The European renewables target needs to be translated into a model constraint for a minimum fraction of renewables. For a start, the target has been extrapolated to a 24% contribution in 2030, and stabilisation afterwards (as fraction of the total primary energy requirement[41]). The bound on renewable energy is shown in Figure 10.1. Large hydro (whose renewable character is currently still debated) is included in the category renewables. A 50% efficiency has been assumed for the reference electricity production from fossil fuels.

[41] Because primary energy use increases between 2030 and 2050, the minimum quantity renewable energy increases accordingly

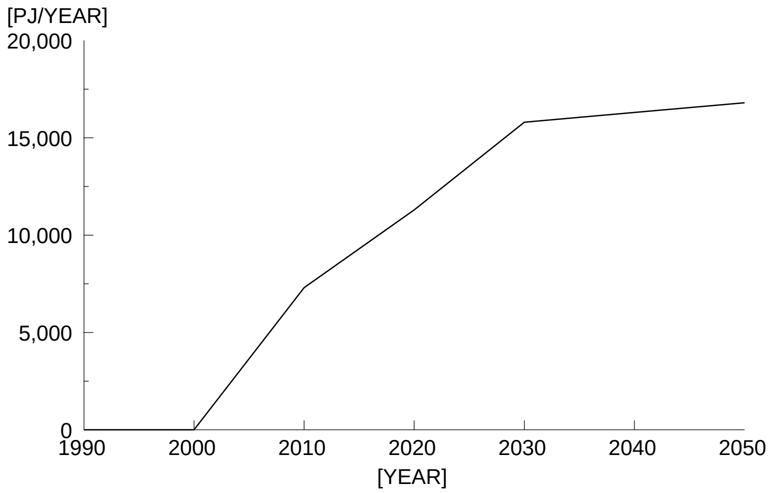


Figure 10.1 *Minimum quantity of renewable energy in the regulation scenarios, expressed in gross energy consumption equivalents*

Because of this renewable energy target, GHG emissions decrease by 340 Mt in the Globalisation scenario in 2030 (i.e. 8% decrease compared to the base case). The loss of consumer/ producer surplus is 32 billion EUR, indicating average emission mitigation costs of 94 EUR/t CO_2 (well above the marginal cost curve in Figure 6.7). Biomass use increases significantly: 3 EJ additional primary biomass use (compared to the base case without such a target). This result is comparable to the 200 EUR/t case (see Chapter 7). Therefore this is considered a feasible, but a costly policy approach with limited impact.

10.2.2 Regulation instead of pricing: minimum 15 Mha biomass crops

A minimum bound of 15 Mha for biomass crops reflects a situation where governments try to establish increased biomass use, e.g. based on covenants with the agricultural sector. In the base case (with a 15 Mha crop area bound), the results show 7 Mha Eucalyptus and poplar and 4 Mha sweet sorghum in South Europe and 4 Mha poplar and willow in Middle Europe.

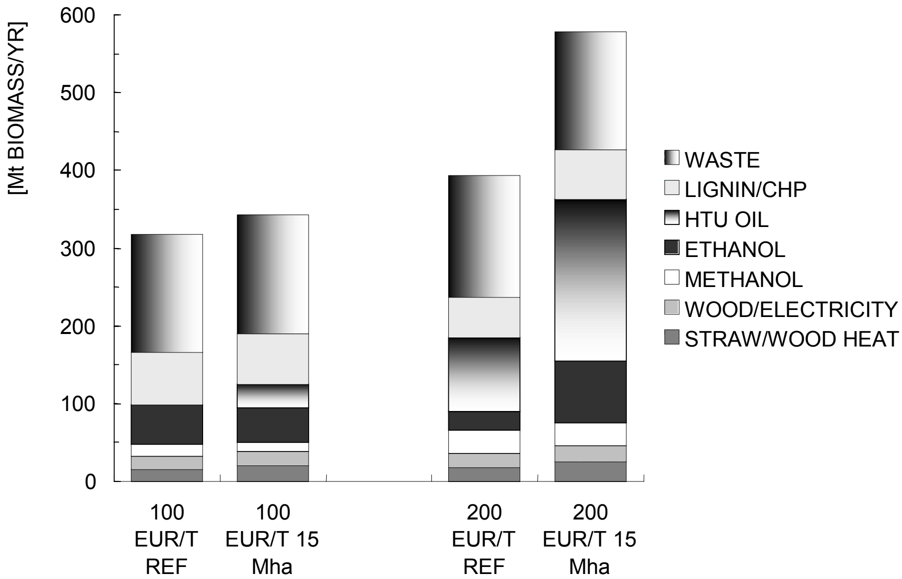


Figure 10.2 *Biomass use for energy, Globalisation scenario, minimum bound 15 Mha biomass crops, compared to reference scenario, 2030*

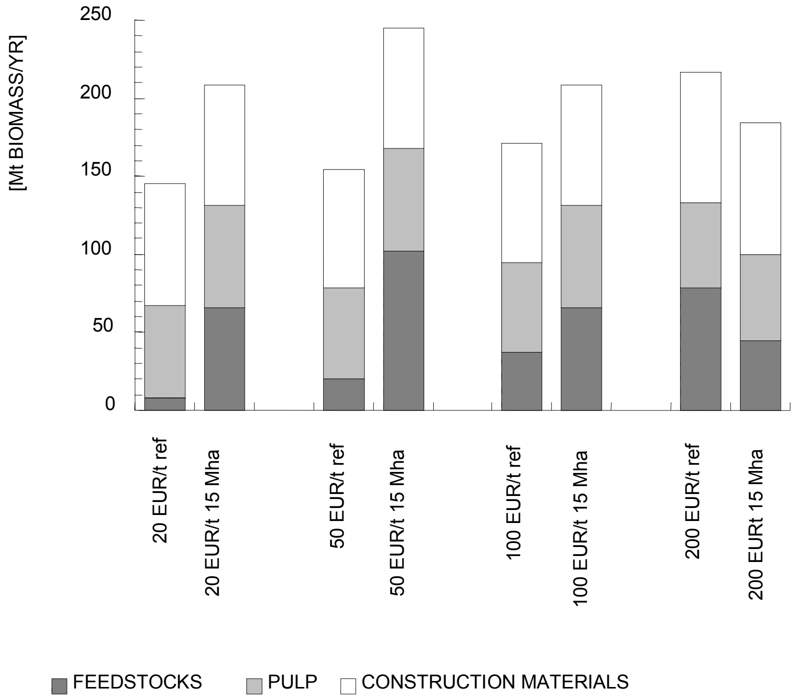


Figure 10.3 *Biomass use for materials, Globalisation scenario, minimum bound 15 Mha biomass crops, 2030*

Figures 10.2 and 10.3 show the biomass use for energy and materials in a situation with a minimum bound on biomass crops. The results differ significantly from the reference calculations (Figures 8.3 and 8.12). The bioenergy use is higher, especially in the 200 EUR/t case (580 Mt vs. 390 Mt). Especially more HTU diesel is introduced in the transportation market. At 50 EUR/t, the use of biomass for feedstock applications shows a peak of 250 Mt (compared to 150 Mt on the reference calculations) which declines at higher permit price levels (in line with the reference calculations). Especially the use of biomass for feedstocks is markedly higher. The total GHG impact is most pronounced in the 20 EUR/t and 50 EUR/t cases: approximately 100 Mt lower emissions in 2030.

10.2.3 Exclusion of exposed sectors

The industry sector is subject to international competition, a so-called 'exposed sector'. Earlier analyses (see e.g. Gielen, 1999c) have shown that the production costs will increase significantly due to GHG permit prices in the 50-200 EUR/t range. In fact the rise in production costs is such, that foreign producers can produce at lower costs, thus substituting for European producers if the foreign producers are not subject to the same policies. One way to solve this problem is the exemption of these producers from the GHG policy regime. This policy strategy has significant consequences for the biomass strategies, which is shown in Figures 10.4 and 10.5.

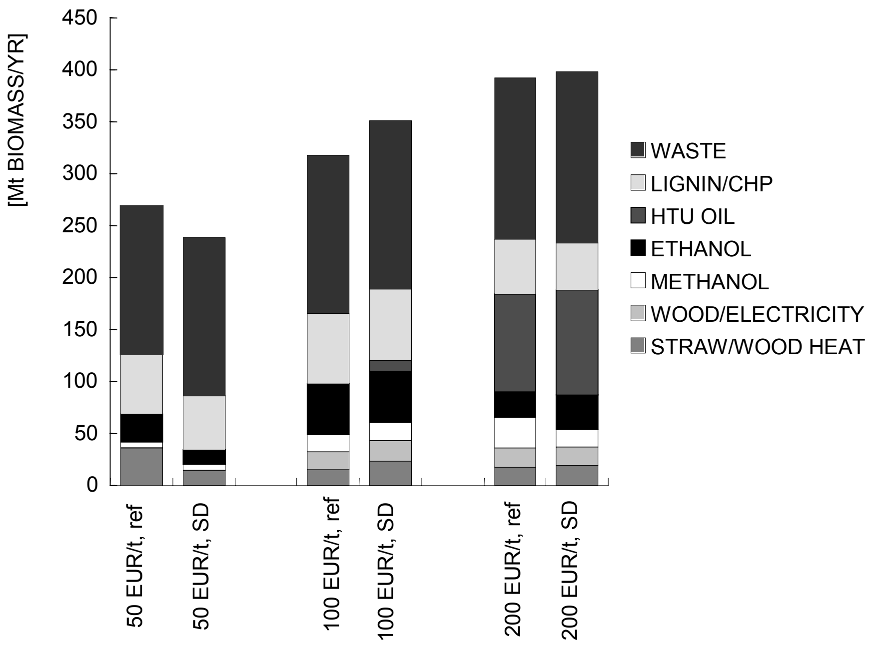


Figure 10.4 *Biomass use for energy, Globalisation scenario, excluding exposed sector from GHG policies, 2030*

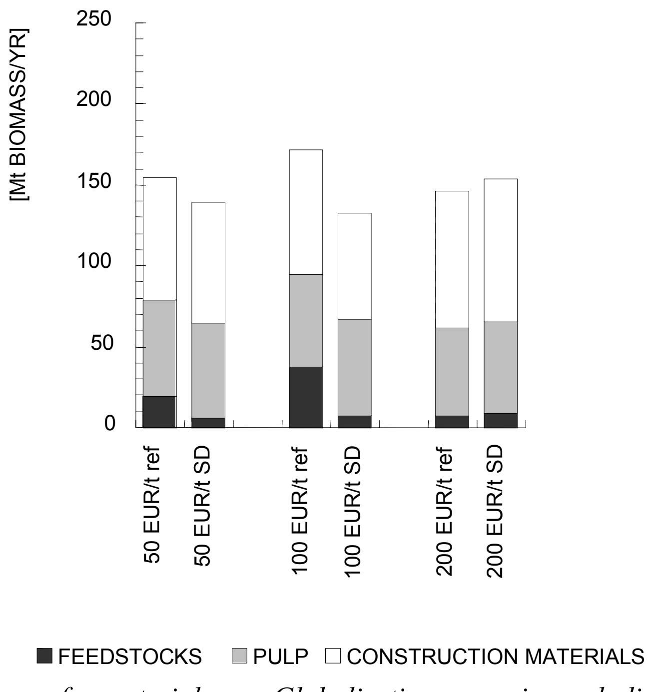


Figure 10.5 *Biomass for materials use, Globalisation scenario, excluding exposed sectors, 2030 (SD = only penalties for 'Sitting Ducks')*

Biomass use for energy applications is almost the same, but feedstock substitution does not take place on a significant scale (compare Figure 8.12). This effect is a logical consequence of the exclusion of the exposed petrochemical industry from GHG policies. As a consequence of the exclusion of industry, the emission reduction potential is reduced significantly: from 3400 Mt in the reference case at a permit price level of 200 EUR/t to 2800 Mt in the situation where the exposed sectors are excluded. However this can only to a very limited extent be attributed to biomass strategies. In fact, biomass strategies are hardly affected, which is an important added value compared to strategies that do affect the exposed sectors.

10.2.4 Environmental policies: extensification

Extensification has been modelled through a combination of lower crop yields (either 20% lower or stabilised compared to current crop yields) and more emphasis on extensive methods for animal raising (a ban on bio-industry for pork and beef in large parts of Europe). The results show a limited impact on land use (see Figure 10.6). At 100 EUR/t, the area for biomass crops and afforestations is significantly reduced, while at 200 EUR/t the impact is limited. However this figure does not show the significant increase of fodder imports: 90 Mt additional imports of soy and tapioca at a permit price of 200 EUR/t. In other words: extensification in Europe at the cost of other regions.

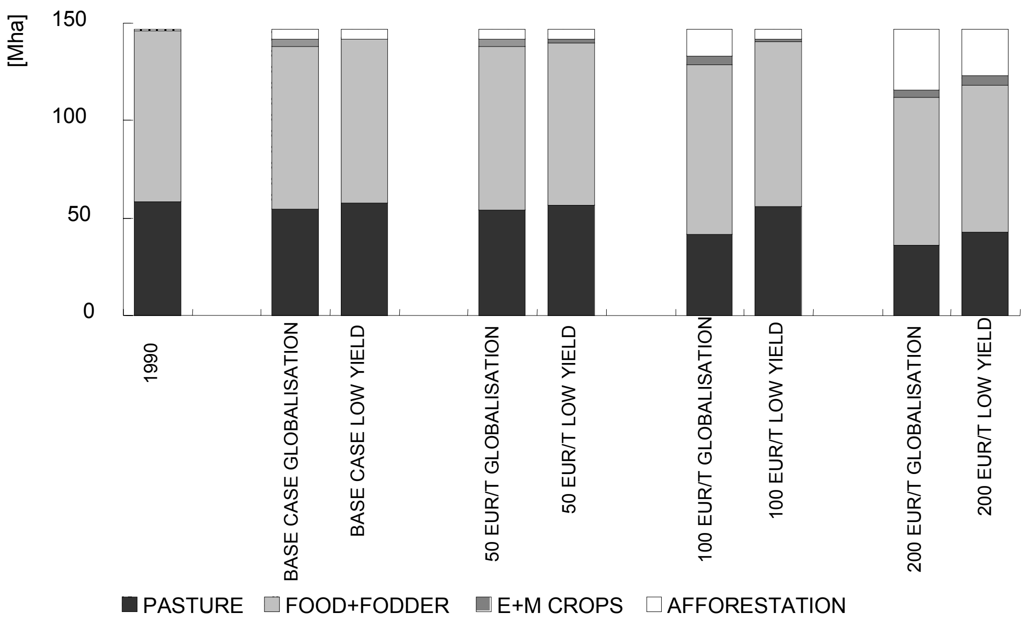


Figure 10.6 *Impact of extensification on land use, 2030*

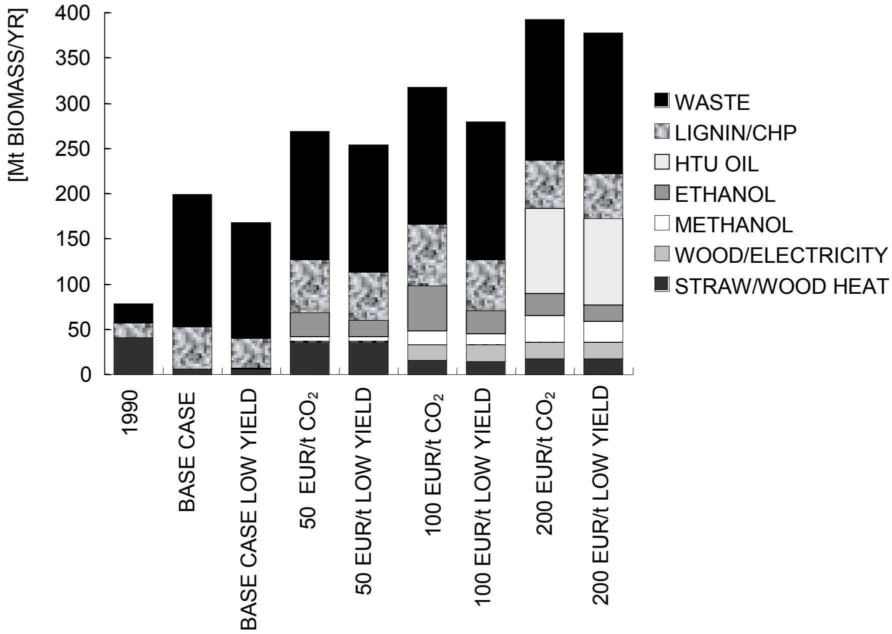


Figure 10.7 *Impact of extensification on bioenergy, 2030*

Figures 10.7 and 10.8 show the impact on bioenergy and biomaterials. In both cases the impact is limited and the most significant changes occur at a permit price of 100 EUR/t. The impact is negligible at lower and higher permit price levels. However, the impact on GHG emissions is substantial at higher emission permit prices: 130 Mt higher in the 100 EUR/t scenario, 180 Mt higher at 200 EUR/t.

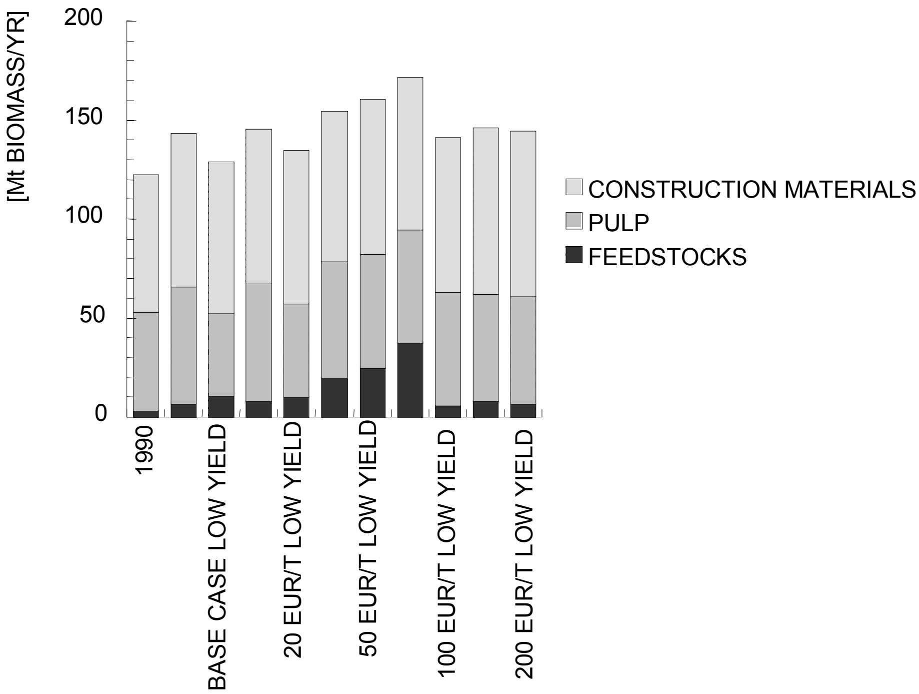


Figure 10.8 *Impact of extensification on biomaterials, 2030*

10.2.5 Waste disposal fees

The waste disposal costs have been varied. Waste disposal costs in the reference calculations increase to 150 EUR/t waste in 2010 and to 185 EUR/t in 2030 (current disposal costs in Europe range from 15 to 100 EUR/t). In this sensitivity analysis the disposal fee increases to 50 EUR/t in 2010 and stabilises afterwards.

The results show significantly different waste handling in the case of low disposal fees. Especially in the year 2010 at limited GHG policy goals, the differences are significant (e.g. the Kyoto target of -8% corresponds with the 20-50 EUR/t CO_2 range). The difference in biomass waste incineration amounts to 25 Mt, resulting in a GHG emission reduction of 20 Mt CO_2. The results for 2030 are not sensitive to this different disposal fee. The maximum reduction of GHG emissions compared to the case with high permit prices is 25 Mt in the 50 EUR/t case in 2030, but this difference is related to changes in plastic waste management.

10.2.6 Labour policies

The labour costs have been raised by 50%. However the results show a negligible impact. The main reason is probably the incomplete representation of labour requirements. The model shows an increase of 33.000 jobs between the base case and the 100 EUR/t case, compared to a European labour force of more then 100 million, thus a negligible effect. Given the impact on GDP (see Chapter 6), the representation of the labour market in MARKAL requires further detail before sound conclusions can be drawn.

10.2.7 Spatial planning: bounds on afforestations

The reference calculations for the Globalisation scenario show an afforestation in Southern Europe of up to 23 Mha. Such a significant change in land use can face major opposition by local residents. For this reason, a sensitivity analysis was done where this afforestation in the Southern low yield region was limited to 6 Mha. The results show that total afforestation declines from 23 Mha to 14 Mha in 2030 in the 200 EUR/t permit price case (so more afforestation in the North, Middle and South high yield regions). At the same time, the grassland area increases from 42 Mha to 49 Mha. All changes are concentrated in the Southern region. The impact on GHG emissions is limited: 10 Mt higher in the 200 EUR/t case.

10.3 Sensitivity analysis results: technologies and resource availability

10.3.1 Cheap imports liquid biofuels

Two import options have been added to the model: HTU oil from South America at 4 EUR/GJ and a maximum of 3 EJ (approximately 100 Mt) in 2030; and ethanol (99% pure) from Russia at 15 EUR/GJ and a maximum of 3 EJ (approximately 125 Mt) in 2030. Note that these are very significant import potentials (together approximately 20% of the primary oil import). The model results show that HTU oil imports are not attractive in the base case. However, they become attractive in the 50 EUR/t case and reach the maximum of 3 EJ and remain at this high level at increasing permit prices. Ethanol import becomes attractive at 100 EUR/t (0.3 EJ) but declines to 0.1 EJ at the 200 EUR/t permit price level. The HTU oil is applied in the transportation market and as a feedstock for the petrochemical industry. HTU oil and ethanol substitute diesel and gasoline in the transportation sector. These imports have a significant impact on the emission reductions: 200-250 Mt additional emission reduction from 50 EUR/t upward. Since the impact on the endogenous biomass is limited, these reductions are add-on. In conclusion, imports deserve special attention.

10.3.2 Future agricultural productivity

Figures 10.9-10.11 show the impacts of a 20% higher agricultural productivity. The figures show that higher yields can have a significant impact on biomass crops, especially in a 200 EUR/t permit price. The area of biomass crops increases from 4 to 9 million hectares.

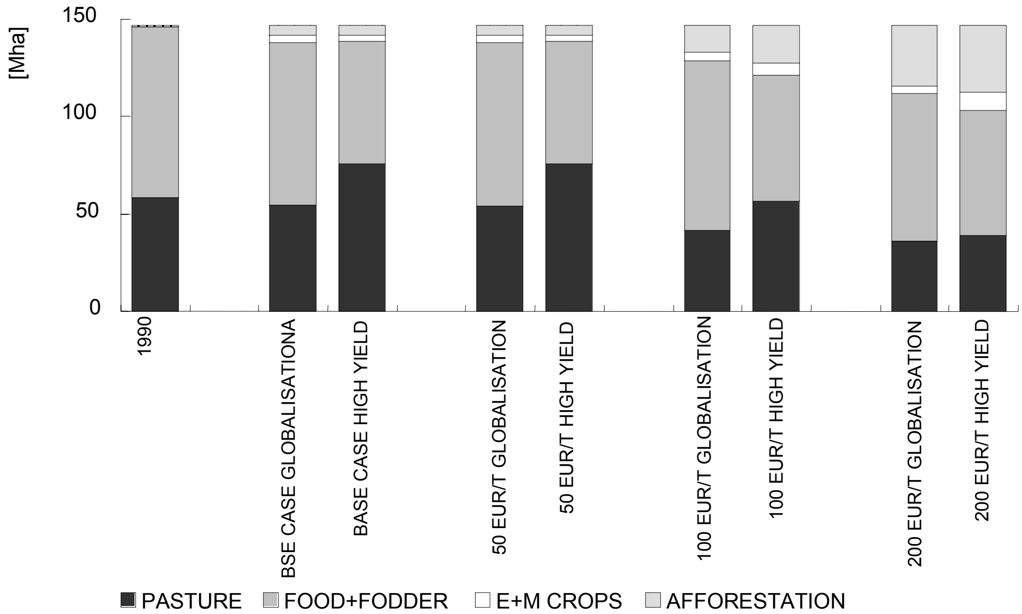


Figure 10.9 *Impact of 20% higher product yields on agricultural land use, globalisation scenario, 2030*

Figures 10.10 and 10.11 show the impact on bioenergy and biomaterials, respectively. Especially in the 200 EUR/t case, the impact on bioenergy is substantial: 130 Mt additional primary biomass use, especially for the production of HTU oil. This results also in 125 Mt additional emission mitigation.

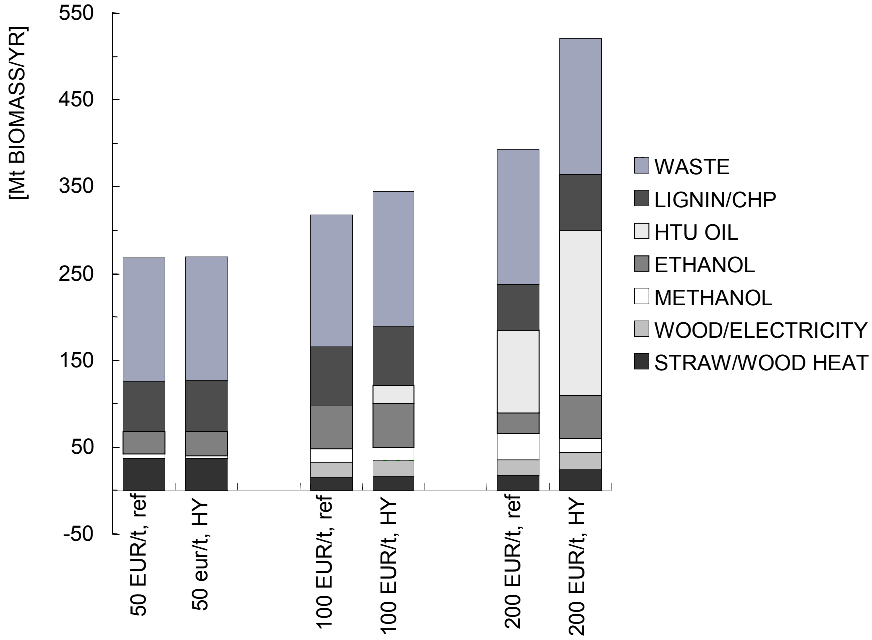


Figure 10.10 *Impact of 20% higher product yields on bioenergy use, globalisation scenario, 2030*

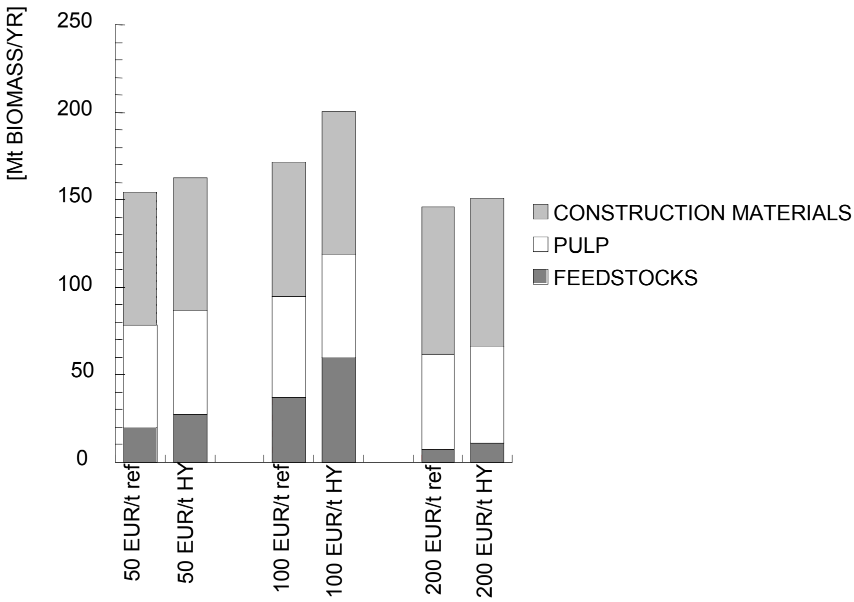


Figure 10.11 *Impact of 20% higher product yields on biomaterials use, globalisation scenario, 2030*

10.3.3 Heating energy demand wood frame buildings

The GHG balance of buildings is to a large extent determined by the heating energy demand. There is a significant interaction between the materials selection and the heating demand. One of the often quoted advantages of wood frame buildings is their better insulation and lower thermal mass. As a consequence, their heating energy demand is lower.

Table 10.3 *Heating energy demand, reference calculations and sensitivity analysis*

Building type	Reference building Brick/concrete [GJ/100 m^2/yr]	Wood frame Standard [GJ/100 m^2/yr]	Wood frame Sensitivity analysis [GJ/100 m^2/yr]
Multi family dwelling Middle Europe	30	32	28
Single family dwelling Middle Europe type 1	19	20	17
Single family dwelling Middle Europe type 2	34	34	30

The results for 2030 show an increased wood product use of 5 Mt (+6%). At the same time GHG emissions are reduced by 30 Mt. The difference is accounted for by the introduction of the wood frame multi family dwelling in the sensitivity analysis.

10.3.4 Climate change

The climate change scenario parameters are elaborated in Annex 1. The main impact is related to the use of biomass feedstocks for the petrochemical industry. In the climate change scenario, the biofeedstocks increase by 37 Mt at a 100 EUR/t permit price in 2030. This increase has a significant impact on GHG emissions, which are 80 Mt lower. In conclusion, climate change is not always detrimental to sustainable development on a regional scale.

10.3.5 Time horizon for GWP

The global warming potential depends on the time horizon considered. The Kyoto Protocol states that the 100 year time horizon must be applied. In order to quantify the GHG impact of this choice, the 20 year time horizon has been analysed in a sensitivity analysis (see Table 10.4).

Table 10.4 *The impact of the time horizon on GWP*

Substance	GWP 20 years	GWP 100 years
CO_2	1	1
CH_4	56	21
N_2O	280	310
CF_4	4400	6500
C_2F_6	6500	9200

The results show remarkable differences at higher permit price levels. If the 20 year time horizon is applied,, CO_2 emissions are 75 Mt lower in the 200 EUR/t case in 2030 (approximately 7% compared to the remaining CO_2 emissions in this scenario). The main reason is the 1 EJ additional production of HTU oil. This production is related to a doubling of biomass crops from 5 to 10 Mha, coupled to decreased afforestation and decreased fodder production.

These changes are related to the high methane intensity of existing meat production practices. These practices are more affected by permit prices in case of a 20 year time horizon, resulting in increased meat imports and increased land availability in 2020. This results in the selection of a different technology trajectory, resulting in a different industry structure in 2030. In conclusion, the choice of the 100-year time horizon has significant consequences for the biomass use.

10.3.6 Rotation length afforestations

Three afforestation lengths have been considered for the Southern low yield area: 20, 50 and 100 years. The investment costs have been kept constant, the annual carbon storage is 20% higher for the 20-year rotation and 20% lower for the 100-year rotation.

The results show a preference for the 50-year rotation, with only limited areas of 100-year plantations. The 20-year rotation is not selected in any of the cases. This shows that a shorter of longer rotation does not make sense from a CO_2 storage point of view.

10.3.7 Considering Fischer-Tropsch

The additional consideration of Fischer Tropsch synthetic gasoline and diesel co-production (with liquid product yields 56% gasoline, 10% diesel, 34% other fuels, in combination with CHP, based on slurry reactor design (Van Ree, Moonen, Lako and Mozaffarian, 1999; Van Paasen, 1999) has no consequences for the results because the process is not cost-effective in any of the globalisation scenario runs which have been analysed (in 2030 B/C ratios range from 0.46 in the 20 EUR/t case to 0.1 in the 100 EUR/t case).

10.3.8 Upper bound straw pelletisation/co-combustion in gas fired power plants

The results in Table 8.2 and 8.3 show that the benefit/cost ratio for co-combustion in gas fired power plants BE2 and for straw briquetting BB1 exceed 1, indicating that additional biomass use via these processes is limited by model constraints. It is difficult to estimate the constraints with accuracy, but it is possible to check the impact of these constraints through a set of model runs where these constraints have been removed.

The results show a significant increase of biomass use for both processes. Co-combustion increases to 800 PJ (up to 92 GW_e co-combustion capacity, corresponding to approx. 20 GW_e biomass capacity on the basis of 25% biomass energy input). Straw briquetting increases up to 1.5 EJ from an upper bound of 0.3 PJ in the globalisation scenario. GHG emissions are reduced by 30 Mt in the 200 EUR/t scenario. This is a limited impact.

10.3.9 Failure of HTU development

A model run without HTU oil shows that the impact on GHG emissions is small, but the impact on sector structure and sectoral emissions is substantial. In the petrochemical industry, HTU oil based ethylene production is replaced by flash pyrolysis based ethylene production. In the 200 EUR/t case, a shift occurs from HTU use for biodiesel to flash pyrolysis based ethylene production (thus a shift from bioenergy to biomaterials production). The GHG emission reduction switches from the transportation sector to the petrochemical industry. However, the impact on total GHG emissions is limited: an increase of approximately 30 Mt. In conclusion, the system as a whole is robust regarding the uncertain development of this technology because of the availability of substitutes.

10.3.10 No electric vehicles

The results in Section 8.2.2 show that in case of a 200 EUR/t permit price, electric vehicles are introduced on a large scale in the transportation market. However, the most recent trends suggest that fuel cell cars seem the most promising technology (see e.g. Hanisch, 1999). Fuel cells can be fuelled with ethanol or methanol from biomass, so this would pose an important market opportunity. In order to check the impact of this assumption, model calculations were done without electric vehicles. However these calculations show no large-scale shift to biomass transportation fuels. Instead, more gasoline is used. Total GHG emissions are approximately 400 Mt higher. In conclusion, the introduction of biomass is not affected by the uncertainty regarding electric vehicle development.

10.4 Comparison of BRED and other study input and results

A comparison is made with the following studies:

- UN-ECE Timber trends V study,
- EU Atlas study,
- Recent Primes work,
- US FARM model.

These studies have been selected because they provide sufficient detail on a Western European level. Other scenario studies such as IMAGE (Alcamo, 1994), SRES (IPCC, forthcoming) are so general in character that a proper comparison with the results from this study is not possible. The following discussion provides an overview of the main conclusions of the selected studies, relevant to this project.

UN-ECE Timber Trends V study

The UN-ECE/FAO Timber Trends V (UN-ECE/FAO, 1996) provide a scenario analysis of forestry and forest products in the world until 2020, with special emphasis on Europe. The study states that European demand for forest products will continue to grow, not fast but steady. The European forests will be required to increase the volume of wood it supplies. The projected level of removals in 2020, although a third more than that of the early 1990s, is still only 70 per cent of the net annual increment. European production of forest products is projected to grow between 1990 and 2020, assuming constant real prices and costs, by 25-35 per cent for sawnwood, 20 per cent for wood-based panels, 30 per cent for pulp and around 50 per cent for paper. In addition, 35-45 Mt more waste paper would be recovered and processed. The waste paper recovery rate is expected to rise from 37 per cent to 49 per cent in 2020. Net imports will increase. An increase of self-sufficiency is only possible on the basis of large areas of intensively managed forests in parts of Europe with good growth conditions. The area of exploitable forest is expected to grow by just under 5 million hectares. The consumption of wood for energy (including waste wood) is expected to grow steadily to 2020, increasing by about 1.5 per cent a year. The authors state that the relation between different parts of the forest and forestry products sector and between that sector and others is a complex one. It is important to develop a coordinated outlook for the future, explicitly considering interactions between the sectors, and placing decision and policy making in this context.

The rising consumption is not reflected in this study. Similarities exist with regard to the competitiveness problems for existing forests. The Timber Trends indicate increasing imports, while this study indicates increasing wood plantations as substitutes. The increasing wood use for energy is not reflected in this study. The main difference is that GHG policies are not considered in depth in the Timber Trends. This suggests that implicitly such policies are not considered as relevant issue.

EU Atlas study

According to the EU ATLAS project, the focus for biofuels is on ETBE, bioethanol and RME (ETSU, 1997b). HTU biodiesel and methanol have not been considered. The authors of the study state that biofuels could contribute to a 20-50% CO_2 emission reduction. There is a very attractive technology potential for both biodiesel and bioethanol of 12% of market share by the year 2020, which equates to 1.9 EJ. A policy target exists of 0.5 EJ biofuels in 2005, which will be difficult to achieve. The main problems are costs and feedstock availability. Costs for bioethanol from lignocellulose crops will be reduced from 0.35 EUR/l in 1995 to 0.25 EUR/l in 2010 (equivalent to 9.6 EUR/GJ). Bioethanol and ETBE can significantly contribute to a reduction of emissions of aromatic compounds.

With regard to heat, a growth is forecasted from the current level of 0.8 EJ to 1.3 EJ in 2010 (EU-12, current level 50% higher for the whole of Western Europe). This growth is for the 'proposed policies' scenario (no growth in the BAU scenario) (ETSU, 1997c). With regard to electricity production, stand-alone IGCC units and co-combustion in coal fired power plants have been considered. Co-combustion in gas fired power plants has not been considered because it is considered to be too far from realisation. Scenarios for 2010 are based on WEC data (97 PJe in 2010). This production capacity will be concentrated in the Scandinavian countries.

The optimism regarding biofuels is not reflected in this study but for high emission permit price levels. The emphasis on heat production is also not reflected in this study. The differences can be attributed to methodological differences. A number of technologies that appear to be attractive in this study have not been considered in the ATLAS study.

Recent primes work
The most recent Primes model analysis (Capros, Mantzos, Vouyoukas and Petrellis, 1999) provides a framework for the comparison of the general outcome of the study on a European level. The results show an increase of primary energy use 57 EJ in 1995 to 67 EJ in 2020 (a significant decoupling of GDP and energy use, except for electricity).This growth is accounted for by natural gas (in the electricity sector) and by oil products (in the transportation sector). The electric capacity in 2020 is 870 GW, 45% is gas based. Renewables (especially wind) in the electricity sector grow by 50% between 1995 and 2020 (to 158 GW in 2020). As a consequence of decoupling and the switch to gas, CO_2 emissions grow from 3037 Mt in 1995 to 3508 Mt in 2020. Emissions in 2020 are reduced by more than 1200 Mt at a CO_2 permit price of 100 EUR/t CO_2. Despite the very different model configuration these results are well in line with the results from this study (which shows a base case CO_2 emission of 3430 Mt in 2020 and 1250 Mt CO_2 emission reduction at 100 EUR/t CO_2, well within the uncertainty range).

US FARM model
The US Department of Agriculture has developed the Future Agricultural Resources Model (FARM) for the assessment of the impacts of climate change and primary production from land (Van Kooten and Folmer, 1997). This model endogenised crop substitutions, links climate projections of land and water resources, simultaneously estimates the impacts of climate change on crop and livestock production and forestry, and integrates these land-use activities within a global model that accounts for all market-based activity. The model contains a general equilibrium model of the global economy. It has eight regions, six land categories and 11 sectors producing 13 commodities. Prices are determined in competitive and international markets. Future yield increases, CO_2 fertilisation and climate-induced technical change are neglected. The model limits substitutability of production factors (e.g. fertiliser for land). On the other hand, it is optimistic about the potential to expand agricultural production into new areas. Changing land classes are taken into account (e.g. Northern European land that becomes suitable for corn).

A key assumption is the impact of climate change. The input data are derived from general circulation models (GCMs) that predict a decline in yield of approximately 25% for all important crops. Cropland is forecast to increase (by 2020) from 78 to 83 Mha (EU-12). Pasture decreases from 55 to 52 Mha, forestry increases from 54 to 56 Mha and other land use declines from 36 to 31 Mha. It is logical to expect that an increase in crop land would also lead to greater incomes, but this is not the case. European wheat production falls by an average 11.6% (from a base of 80 Mt), production of non-grains falls 10.6% (from 279.9 Mt) and livestock numbers decline by 1.5%. Production of other grains rises by an average 24.5% but from a lower base of 25 Mt. Forestry output increases by 3.2% from a base of 171 Mm^3. Although more crop land is brought into production, the land is used less intensively as a result of economic signals from elsewhere in the economy and from other regions in the world and because the land is simply less productive. Commodity prices are projected to increase for all commodities except forest products and other grains. Revenues accruing to three factors of production (land, labour and capital) are expected to decline, with the owners of land experiencing the largest reductions in income.
These results are very different from the results of the present study. The assumptions for crop yield impacts of climate change are very different and land price trends are different. One important difference is that the agricultural sector is analysed as a stand-alone system, contrary to

the integrated analysis in this study. Moreover the changing technology dimension, a key issue in this study, is neglected. The changes are less dramatic than the ones that are calculated in this study.

10.5 The consequences of the uncertainties for the conclusions

Table 10.5 provides an overview of the results of the model sensitivity runs. A comparison of these figures and the figures in Table 10.1 suggests that the expert estimates of uncertainties were too high. This indicates that the results are more robust than was thought beforehand. Based on the results of the uncertainty analysis and the results of the expert review workshop, a qualitative characterisation of the robustness of the results is provided in Table 10.6.

Table 10.5 *Overview of results of model sensitivity analyses*

	Δ GHG 200 EUR/t [Mt CO_2/yr]	Δ Cost 200 EUR/t [bln. Eur/yr]	Δ Biomass 200 EUR/t [t biomass]	Remarks
Policy				
Regulation instead of pricing	-340	32	+300	compared to base case
15 Mha crops	0 - -100	na	+150	
Exclusion exposed sectors	+ 600	na	-10	
Extensification	+180	na	0	
Waste disposal fee 50 eur/t	0 - -25	na	0	
Labour policies	0	0	0	
Spatial planning: maximum afforestation	+10	na	0	
Technology/resource availability				
Cheap imports	-250	na	+300	
Future productivity	-125	na	+100	
Heating demand WFD	-30	na	+5	
Climate change	-80	na	+40	100 eur/t result
Time horizon GWP	-75	na	+80	
Rotation length afforestations	0	0	0	
Bounds co-combustion/pelletisation	-30	na	+150	
Fischer-Tropsch	0	0	0	not selected
HTU yes/no	+30	na	0	
No electric vehicles	+400	na	0	no impact on biomass

Table 10.6 *Robustness of the main conclusions*

Biomass will be important	Robust
No dedicated bioelectricity	Robust
No heat from biomass	Not robust
Biofuels in the transportation sector	Robust
Biochemicals	Policy dependent
250-650 Mt biomass	Robust (excl. in case of imports)
Contribution up to 350 Mt GHG emission reduction	Robust
Technology selection	Generally not robust
Crop selection	Eucalyptus robust; others not
>10 Mha afforestation	Not robust

Figure 10.12 shows another way to aggregate the data and use them for quantification of uncertainties. The loss of consumer/producer surplus is shown as a function of the GHG emission reduction for the reference case (i.e. the globalisation scenario) and for a number of uncertainty analyses. The spread of the results is a measure of the uncertainty: horizontally for the GHG emission mitigation that can be achieved, and vertically for the uncertainty regarding the costs for emission mitigation. The figure suggests a cost uncertainty of 100 billion Euro or an uncertainty in the emission mitigation potential of 500 Mt CO_2 equivalents. Note that not all of this potential can be attributed to biomass (e.g. the exclusion of the exposed sector 'sitting ducks' encompasses the emission reduction potential in the steel and cement industry etc.).

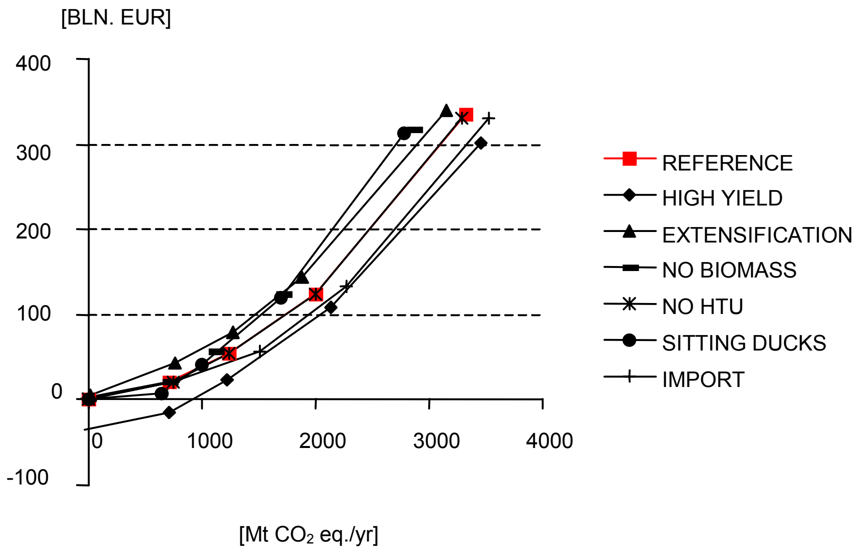


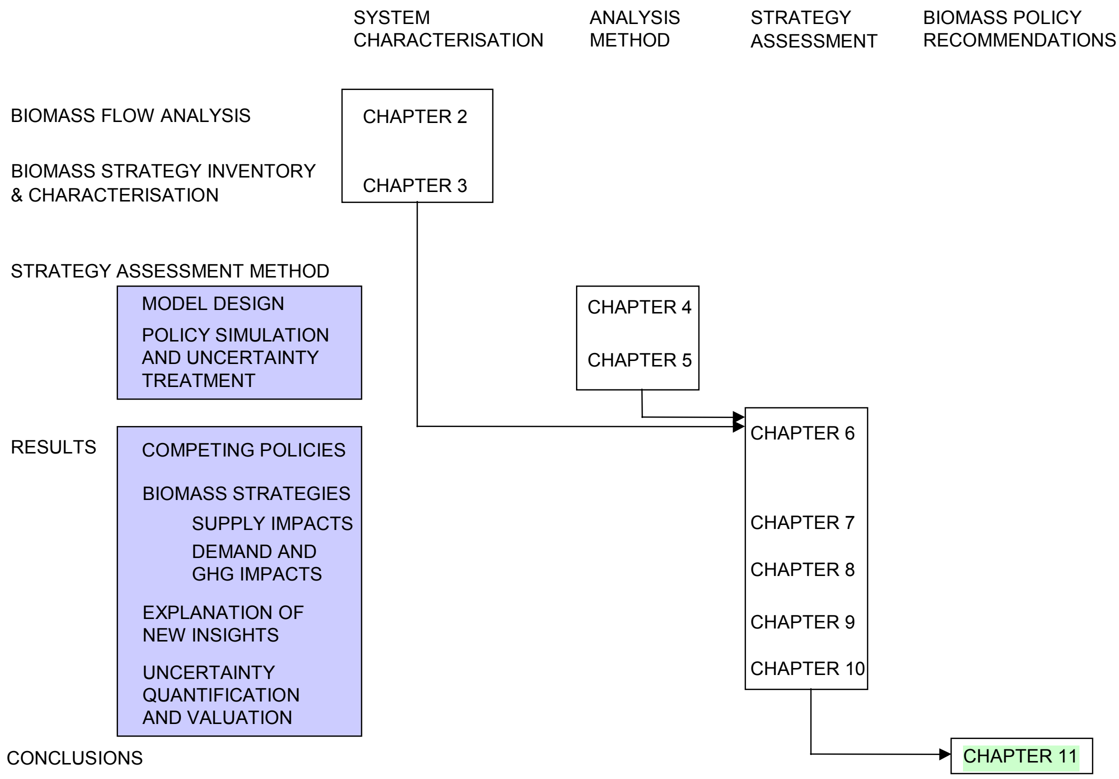
Figure 10.12 *Loss of consumer/producer surplus as a function of the GHG emission mitigation for sensitivity analyses, 2030*

The following conclusions can be drawn from this sensitivity analyses:

- The policy dimension is more important than the technological parameters, cost parameters and possible impacts of climate change.
- Selection of policy instruments is very relevant. Regulation can increase biomass use dramatically, but at a considerable expense.
- Comparing the estimates in Table 10.1 and the results of the model runs in Table 10.5, the system and the model conclusions seem more robust than thought at first sight on the basis of expert opinions. This can be explained by the fact that the system consists of a very large number of processes, so it contains many resource alternatives and many emission reduction alternatives. As a consequence, a single sub-optimal policy decision is not likely to be fatal. Moreover, market forces seem a better approach than regulation for long-term GHG policies, given the difficulty of making the right technology selections.
- A significant interaction of GHG policies, energy policies, agricultural policies and industry policies must be considered. Integrated policy making will increase the efficiency and effectiveness of GHG policies significantly.
- The results from this study differ to a considerable extent from other important scenario studies. Some of the differences can be explained by the differing input parameters. Afforestation has been considered, which is not considered in the other studies. Biomaterials have also not been considered on other studies. Moreover this study considers new technology explicitly, which is not considered in a number of the other studies. It is felt that these expansions are very relevant for the analysis, and do not add to the uncertainty for this study.
- This study assumes a long time perspective and very ambitious GHG policy targets, beyond the scope of most of the other scenario studies. This is probably the single most important uncertainty: will such policies really be developed? If not, the role of biomass will be limited (except for the situation with sustainability policies, e.g. ambitious renewable energy targets).
- Regarding technology selection, the results are in most cases based on literature estimates. Sufficiently reliable data for selection are lacking. As a consequence, the results for induvidual technologies should be considered with care.
- Regarding methodological uncertainties, the ideal market hypothesis is probably the most far-reaching simplification. It is unclear to what extent long term developments approach ideal market conditions. The ongoing liberalisation makes this approach more realistic as more elements are liberalised.

- Regarding relevant strategies, the main uncertainty is related to the feedstock market segment, as its development depends on the policy scope, future availability of cheap resources and technology which is not yet proven on a commercial scale.

11. CONCLUSIONS AND RECOMMENDATIONS



A number of research questions have been raised in Chapter 1:
1 What are current biomass flows in the Western European economy (Section 11.1)?
2 Which strategies exist to reduce GHG emissions with biomass (Section 11.1)?
3 What are the techno-economic characteristics of biomass supply and demand (Section 11.1)?
4 What is the potential of these biomass strategies to reduce GHG emissions (Section 11.1)?
5 Which technologies must be developed for these strategies (Section 11.2)?
6 What is the impact of the changing reference system for GHG emission reduction (Section 11.1)?
7 Can an integrated energy and materials biomass strategy increase the penetration of bio-energy (Section 11.1)?
8 What policies should be initiated (Section 11.3)?
9 How should uncertainties be treated in decision making (Section 11.4)?

This Chapter discusses the answers to these questions, based on the analyses in Chapters 2, 3 and 6-10. Section 11.5 provides recommendations for further research.

11.1 Biomass for energy or materials

Current biomass flows and autonomous trends

Agriculture and forestry constitute a very important element in the existing Western European economy, especially if the flows are expressed in weight or energy units. Total annual commercial plant biomass production amounts to approx. 1200 Mt (dm), which equals 15-20 EJ. This is equivalent to 25-30% of the total Western European primary energy use (but this sustainable resource is largely neglected in energy statistics). The bulk of this biomass is used for non-energy purposes: food and materials. The total physical biomass flow is more significant than the flow for key commodities such as steel, cement and oil. Approximately 900 Mt agricultural products can be allocated to the food chain. 200 Mt wood is used for products such as pulp, paper and construction materials. Some agricultural residues, residues from wood processing and fuel wood are applied for energy purposes (total approximately 150 Mt). Post consumer waste incineration and anaerobic digestion are processes in the end of the chain which are relevant from an energy point of view. The energy content of the post-consumer biomass is 2 EJ per year.

Food demand is stabilising in Western Europe. An important trend is the ever increasing yield of crops and the increasing efficiency of conversion processes. As a consequence of stabilising food demand and increasing productivity, a surplus supply potential exists for agricultural products. This poses an important incentive for increased bioenergy and biomaterials production. However, the significant efforts have up till now not resulted in major new crop developments. Instead, a trend towards extensification can be discerned, driven by increased consumer quality demand, increasing environmental concerns and the need to reduce agricultural surpluses.

Biomass strategies for GHG emission reduction
Biomass strategies can contribute to GHG emission reduction. A number of strategies can be discerned:
- Afforestation,
- carbon storage in soils,
- carbon storage in products,
- substitution of fossil energy carriers with clean biomass,
- substitution of materials,
- increased efficiency of production,
- energy recovery from waste,
- recycling and reuse.

Each of these strategies encompasses a large number of options that can be characterised on the basis of different technologies, different biomass types and different product markets. It is important for proper assessment of their GHG emission mitigation potential to account three types of GHG emissions: CO_2, CH_4 and N_2O.

The technology dimension
During the last centuries the trend has been a (relative) decline of biomass use in favour of other energy carriers and other materials which are less costly, easier to handle and possess superior quality. In order to face this competition and in order to develop the full potential of the biomass resource, new technology development has been widely accepted as a key issue. The detailed BRED assessment studies (see Chapter 1 and Chapter 3) have shown that a number of technologies are currently being developed that can reverse the negative biomass trends. Promising technologies can be found on the biomass supply side (e.g. fast growing biomass crops, generally higher agricultural yields, improved biomass logistics) and on the consumption side (e.g. gasification, efficient production of transportation fuels, biochemicals, engineered wood products). Given the inherent uncertainty of technological progress, not all developments will succeed. However given the broad range of technologies which has been encountered and given the increasing need for an improved use of the biomass resources, it is likely that technological change will affect the economic structure.

Supply: techno-economic characteristics
The supply of biomass for energy and materials is constrained by physical supply constraints: land availability and biomass yield per hectare of land. Apart from the technical constraints, biomass costs have been considered in the analysis of the attractiveness of these strategies. The modelling results show that the demand for biomass will not increase significantly compared to

the current situation in a situation without GHG policies. However once the right incentives are introduced (e.g. a tripling of the crude oil price through introduction of a 100 EUR/t CO_2 emission permit price), the demand for biomass increases significantly, which results in increasing biomass prices. As a consequence the biomass supply increases.

The supply can be split into four categories:
- agricultural biomass crops,
- agricultural residues from food and fodder production,
- forestry,
- waste materials and kitchen waste.

The most important biomass supply potentials exist for agricultural crops, followed by residues, wood from forests and waste materials. Figure 11.1 shows the relevance of different supply options at increasing emission permit prices. The main growth can be attributed to increased recovery of agricultural residues, increased wood recovery from existing forests (roundwood, forestry residues and bark) and short rotation wood plantations. Each category will be discussed separately.

Modelling results suggest a biomass supply potential of approximately 200-400 Mt primary biomass for the year 2010, while the potential for the year 2030 ranges from 250 to 650 Mt (depending on the scenario). The technical potential is even much higher, but the competing afforestation strategies seem more effective. Not physical constraints but costs limit the supply. Especially the development in the global food markets and biomass markets and the future agricultural productivity are important variables.

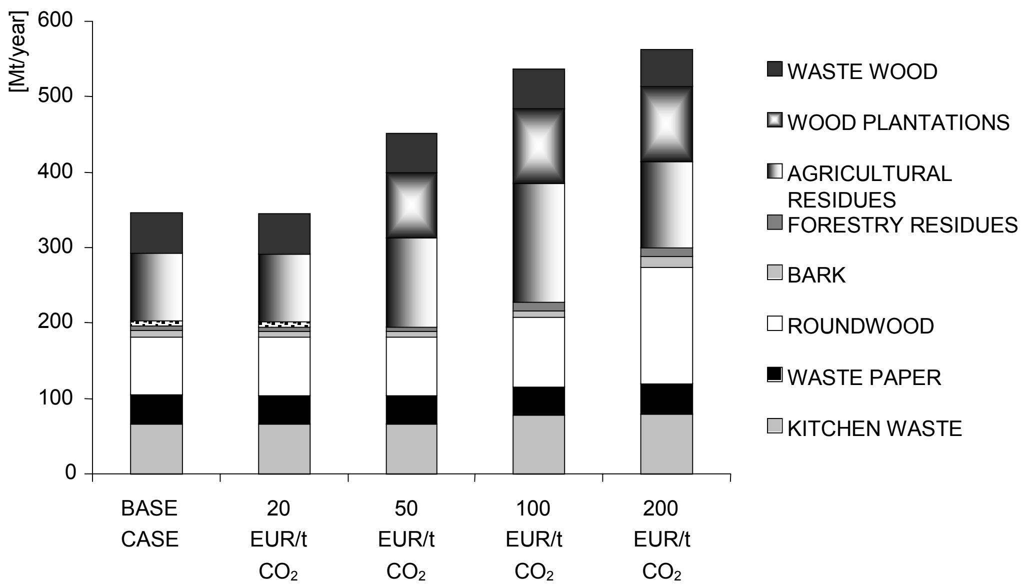


Figure 11.1 *Relevance of biomass supply options at increasing emission permit prices, Globalisation scenario, 2030*

Bioenergy and biomaterials production in short term rotations must compete with afforestation for carbon storage. Biomass from afforestations will become available for energy and materials applications on the long term, but it will delay the introduction of biomass on the short term. The model results show a considerable land use for afforestation, much higher than for biomass crops.

The main reason is the comparatively low GHG emission reduction costs of afforestation, especially compared to energy and materials applications (even if the opportunity cost of agricultural land are taken into account). Afforestation strategies have no decreasing efficiency because of the changing reference situation. Bioenergy and biomaterial strategies on the other hand must face significant emission reductions in the reference system. For example in electricity production, CO_2 removal, other renewables and increased efficiency in electricity consumption pose attractive competing emission reduction strategies.

The crops that are applied are the high-yield crops: especially Eucalyptus, poplar and a limited area of sweet sorghum and miscanthus. These crops can achieve yields in the range of 20-35 t dm/ha/year in 2030. Note that Eucalyptus is the only of these crops which covers a significant area at this moment, the data for the other crops are speculative and uncertain as of yet. The model calculations suggest the most significant changes due to GHG policies will take place in Southern Europe. In the calculations, a 20-30% increase of yields has been assumed between now and 2030 for given fertiliser gift levels. Such improvements can be achieved though improved plant material, improved irrigation, etc..

An agricultural land availability in the range of 10-20 Mha and a biomass yield in the range of 250-500 GJ/ha suggests a biomass production potential from dedicated crops in the range of 2.5-10 EJ. The calculations in this study represent an optimistic estimate in the higher range.

The potential for wood recovery from existing forests is also considerable. The current recovery represents only two thirds of the annual regrowth. The additional harvest potential is limited to 100-150 Mt wood, equal to 1.5-2.5 EJ per year. A comparison of these figures for existing forests and the figures for the agricultural yield potential shows that the supply potential is of secondary importance. Model calculations suggest that wood recovery from existing forests declines significantly in the base case in favour of forest plantations. A high GHG permit price can keep the wood recovery on a high level and can even result in increased recovery.

Waste from food and fodder production poses another important potential biomass source. Out of a total agricultural plant biomass production of approximately 900 Mt, 50-100 Mt is not harvested (e.g. straw from cereals). Another 300 Mt (dm) manure is recycled as natural fertiliser. Part of this manure is collected from stables (approximately 200 Mt), another part is directly applied through animals in the field. Approximately 225 Mt products (dm) are delivered to the consumers. The output of kitchen waste represents another 35 Mt (dm). The remainder (approximately 190 Mt) ends up in the sewage system. Part of this is recovered in sewage treatment systems. The amount of sewage sludge is approximately 25 Mt (dm). In conclusion, the total amount of waste from food and fodder where energy recovery could be applied is approximately 500 Mt (dm), equal to 6-8 EJ per year. However the potential for recovery of this energy is limited by the high water content of some of this biomass.

Waste materials can be split into waste wood materials and waste paper and board. Energy recovery from wood processing (saw dust, chips, etc., approx. 40 Mt dm in total) and energy recovery from black liquor (chemical pulp production, 25 Mt dm) represent important bioenergy sources. Post consumer wood waste represents a biomass quantity of 34 Mt, waste paper and board approximately 65 Mt. Approximately 50% of the waste paper is recycled. Some post consumer wood is recycled into particle board or re-used in buildings (approximately 5-10 Mt). In conclusion, approximately 140 Mt waste materials are either disposed or incinerated. This represents a potential of 1.7-2 EJ.

Addition of these potentials suggests a biomass availability of 900-1100 Mt, equivalent to 11.8-22.5 EJ in 2030. This is equivalent to 16-32% of the primary energy use in 2030 (energy use defined according to energy statistics).

Demand: techno-economic characteristics

The biomass applications can be split into energy applications and materials applications. These applications must compete with land use for food production and with land use for carbon storage. The model calculations suggest little change in a base case without GHG policies: the land is simply used at a sub-optimal efficiency level. However if GHG reduction strategy is aimed for, the use of biomass will increase significantly in case of ambitious policy targets (i.e. an emission reduction of more than 50% in the year 2030, compared to the base case). This increased biomass use will simultaneously increase the sustainability of the economy. However, this implies that more biomass services are produced with the same amount of land. This implies an intensification, especially of agricultural production.

With regard to the biomass applications the results show remarkable differences with earlier studies:

- The market for transportation fuels from biomass will only develop at comparatively high emission permit values (100 EUR/t and higher). The difference with earlier studies not showing transportation fuels can be explained by new emerging production routes for transportation fuels from biomass (not considered in most preceding studies).
- Moreover, the market prospects in the electricity market have deteriorated because of the rapid technological progress with regard to gas fired power plants and the still improving supply prospects for this fossil fuel. This progress is generally neglected in other studies, while it is crucial for proper assessment.
- MARKAL modelling results show that Western European biomass availability is no constraint at emission permit price levels up to 100 EUR/t CO_2. As a consequence, no competition occurs between bioenergy and biomaterial applications. On the contrary: the production of biomaterials result in an increased availability of process waste and post consumer waste that can be used for energy recovery. Only at emission permit price levels above 100 EUR/t CO_2, a trade-off between both applications will occur.
- At all permit price levels, considerable quantities of biomass (up to 175 Mt) are used for materials applications. Biomaterials applications constitute approximately one third of the total biomass use for energy and materials.
- Electricity production is limited to energy recovery from waste, lignin gasification and co-combustion in gas fired power plants. The production of heat from biomass does not reach an important position in any of the scenarios. However, energy-from-waste strategies are already introduced in a situation without GHG policies and dominate in the bioenergy market up to permit price levels of 50 EUR/t. Significant efficiency improvements can be expected for these technologies, hence more energy services will be produced with the same amount of biomass.
- Substitution of petrochemical feedstocks is another important category that has received little attention as of yet. However, the relevance of this strategy depends on the biomass availability (only attractive in scenarios with ample biomass availability). The costs are comparatively high (especially relevant at emission permit prices of 100 EUR/t and higher). However the current R&D developments result in many new biochemical process routes and new biochemicals, characterised by superior product quality and lower costs. The model does not reflect the full potential of this development. Consideration of these market niches will result in an even stronger penetration of biomass in the petrochemical market.
- The production of building and construction materials does not become attractive in any of the scenarios. The main reason is the comparatively high costs of this strategy. Moreover, its theoretical potential is limited because of the limited building materials market (in physical terms, when compared to e.g. the energy market).
- Cascading of wood materials is of secondary importance, the main reason being the ample biomass potential availability. Increased cascading is introduced in the sense of increased energy recovery from waste materials and residues.
- The combination of biomaterials and bioenergy strategies results in additional biomass use for energy production, in the form of by-products from materials production (especially lignin and by-products from pyrolysis processes can be used for energy recovery). Structural wood products with a long product life can contribute to energy recovery after a product life of decades. Increased recycling and energy recovery of biomaterials poses an important op-

tion that can simultaneously substitute fossil fuels and reduce methane emissions from disposal sites. The energy recovery will increase due to waste policies and new waste incineration technologies with increased efficiency. In case of a 100 EUR/t emission permit price, the results for 2030 show an additional bioenergy use in the order of 1 EJ, which can be attributed to the use of by-products from biomaterials.

The impact of the competing food market
Land availability depends on the demand structure, foreign trade and trends for food and crop yields. Considerable flexibility exists with regard to agricultural productivity depending on the crop type, the use of fertilisers, the application of genetic engineering, etc.. The productivity of agriculture as a whole also depends on the structure of the sector, especially the fodder crop types and the animal type. For example a switch from beef to poultry reduces fodder demand considerably (see e.g. Gielen, Bos, De Feber and Gerlagh, 1999). Changing lifestyle potentially poses an important strategy, but this is a no feasible road for policy making. Lifestyle trends pose also a source of uncertainty in the analysis: for example the recent problems with British beef, Belgian chicken meat and French prepared fodder may have affected the lifestyles.

A price increase of more than 100 EUR/t is an indicator that imports from other continents may become competitive. Given the sheltered and heavily regulated European agricultural market, this is not a new threat. However, the results suggest that the problem may become more pronounced because of GHG policies. Most affected products are beef, chemical pulp, graphic paper, sawn timber and board materials. Also wheat and mechanical pulp are close to a 100 EUR/t price increase at permit price levels of 200 EUR/t CO_2. The deteriorating competitive position for agricultural products is one of the main obstacles for an ambitious European GHG policy, in case other regions do not develop similar policies.

The impact of competing non-biomass strategies
Biomass strategies must compete with a large number of non-biomass strategies. Especially in the electricity market, the heating market and the materials markets these competitors must be considered. The high relevance of competitors can be estimated if the technical potentials and the economic potentials in Table 11.1 are compared. Competition is less relevant for feedstock substitution and carbon storage strategies, an important advantage for these strategies.

The GHG impact of biomass strategies
Table 11.1 shows the relevance of the individual strategies in different scenarios. The second column shows the technological potential, based on the bottom-up estimates in Chapter 3. Substitution of materials has the highest relevance (up to 500 Mt CO_2 equivalents in 2030), followed by the substitution of energy carriers (400 Mt CO_2 equivalents) and afforestation (180 Mt CO_2 equivalents). The other strategies are of secondary importance by themselves, but amount together to 405 Mt CO_2 equivalents.

Table 11.1 *The relevance of biomass GHG strategies: techno-economic potentials, 2030*

Strategy	Technological potential[42] [Mt CO_2 eq]	Economic potential[43] [Mt CO_2 eq]
Afforestation/soil carbon	180	150
Carbon storage in products	105	25
Energy substitution	400	100
Materials substitution	500	100
Increased production efficiency	100	<25
Energy recovery from waste	100	25
Recycling/reuse	100	<10

However it is not correct, to add these GHG emission reduction potentials for two important reasons. First, the supply of biomass is limited by the land area available for biomass production and by the biomass yield per hectare. Second, the biomass strategies must not be compared to the emissions in the current reference energy and materials system. Instead they must be compared to all competing GHG emission reduction strategies for proper assessment of their relevance from a national and European point of view (see Section 9.1). The MARKAL MATTER 4.2 model calculations suggest a significantly reduced potential if these effects are accounted for. The column economic potential in Table 11.1 (based on the analysis in Section 8.4) shows a total potential of approx. 400 Mt, of which afforestation and materials substitution pose the most significant part of this potential.

11.2 R&D recommendations

Based on the model calculations, a number of technologies seems attractive, while others seem less attractive. A combination of benefit/cost ratios and market volumes has been used as a criterion for the categorisation in Tables 11.2 and 11.3 (in attractive, limited relevance and not attractive options). The category 'not attractive' is used for technologies whose benefit/cost ratio is significantly below 1 at all permit price levels. The category 'limited relevance' includes technologies whose benefit/cost ratio approaches 1 only at high permit price levels, or whose market potential represents less than 5 Mt GHG emission mitigation (less than 0.1% of the total GHG emissions). Finally, the technologies that are selected in the base case or at permit prices below 200 EUR/t and with significant market potential are categorised as 'attractive' options. The results are shown in Table 11.2 and Table 11.3.

Table 11.2 *Selection of supply options*

Attractive	Limited relevance	Non attractive
Eucalyptus	Poplar	Willow
Residual straw recovery	Sweet sorghum	Algae
Straw briquetting	Miscanthus	Wheat
Afforestations		Rape
		Corn
		Sugarbeet

[42] Estimated on the basis of 10 Mha biomass crops, current reference system, not considering costs or interactions.
[43] Characterised by the contribution at a permit price of 200 EUR/t CO_2.

Table 11.3 *Selection of conversion technologies*

Attractive	Limited relevance	Not attractive
Lignine gasification	Gibros PEC for waste	TE Stirling engine
Gasification/co-combustion in gas fired power plants	Phenol from wood flash pyrolysis	Stand alone biomass gasifier/CC
100% ethanol	Acetic acid	Co-firing in coal steam cycle
ETBE	Butanol/acetone fermentation	Stand alone biomass gasifier/SOFC
Co-combustion cement kilns	I-propanol fermentation	Methanol from waste
Butadiene from wood flash pyrolysis	Phenol from lignin hydrotreatment	RME
PUR from lignin	Natural surfactants	Pyrolysis/diesel
New fibre construction materials	HTU oil/petrochemicals	Hydro-pyrolysis to SNG
Advanced integrated waste incineration plants	Straw to methanol/DME	Charcoal
Tropical hardwood substitutes	Increased sawn wood use for buildings/constructions	Lurgi gasifier for waste
HTU oil/diesel		Fischer-Tropsch biofuels
Ethylene from wood/flash pyrolysis		Bio-lubricants
Anaerobic digestion manure		MTO
		Ethanol dehydrogenation
		Viscose/cellophane
		Carbon black from wood pyrolysis
		Dedicated solvent crops
		Bioplastics Biopol, starch based etc.
		Anaerobic digestion waste
		Wood stoves

These results are sensitive with regard to the input parameters. Many technologies are not yet proven on a commercial scale, economic data are also uncertain. The R&D recommendations are considered to be valid on the general level (e.g. 'flash pyrolysis is attractive' and 'transportation fuels are attractive'). However the sensitivity analyses and scenario analyses show that the optimal technology depends on many factors. For this reason, it is recommended to 'let the market make the selection' and provide R&D support to a broad range of technologies.

11.3 Policy recommendations

11.3.1 Recommendations for EU policies

Energy policies

The European Union has a policy target for 12% renewable energy in 2010. The European Union has formulated a White Paper for a Community Strategy and Action Plan: Energy for the future: Renewable sources of energy (European Commission, 1997b). The White paper aims for a 12% contribution from renewable sources of energy to the European Union's gross inland energy consumption by 2010. A significant contribution from biomass is considered. The biomass use should increase by 3.8 EJ. This contribution is split into 1.3 EJ wood and agricultural residues, 0.8 EJ transportation fuels, 1.1 EJ solid bio-fuels, and 0.6 EJ biogas (including recovery of landfill gas). The model calculations suggest that such a target is in principle feasible, but a high price tag is attached to this target (32 MEUR per year). Sufficient supply potential exists to set even more ambitious policy targets for the period beyond 2010. A policy target of 10% biomass in 2030 should be feasible. However such a target only makes sense in case ambitious policy targets for sustainability and GHG emission reduction are set. If this is not the case, competing improvement options are more cost-effective and no further expansion of biomass use (compared to the autonomous trends, mainly initiated by waste regulations) should be aimed for.

There is a danger that specific regulatory approaches of biomass strategies do not take the changing reference system into account properly, resulting in costly and inefficient emission reduction strategies. Especially too ambitious targets for renewable energy obscure the potential for cost-effective emission reduction measures on the demand side and in materials production and consumption. For this reason, it is recommended to apply generic pricing policy instruments that endogenise environmental impacts into the prices of products.

The model calculations are in accordance with the policy mix selected for renewable energy in 2010. The only exception is the use of biomass as feedstock substitutes for the petrochemical industry, which is not considered in this target (non-energy use). It is recommended to include this market segment into future policy targets.

Environmental policies
The GHG problem is a very different kind of environmental problem than the previous ones because it is closely related to the physical throughput in the economy, and it cannot be solved by end-of-pipe measures alone. Integrated policy making is required, that covers the economy as a whole. A sector approach will result in sub-optimal solutions.

Ambitious long term GHG policy should be set. However some conditions must be met that are discussed in the industry policy section (see below). The GHG policy problem can be solved, based on other resources and new technology.

A large number of biomass related technologies are currently being developed. It is difficult to say beforehand which developments will succeed, and what the best technologies will be. It is recommended to consider this technology dimension for long term policies.

GHG policies and sustainability are closely related issues that relate to bulk flows in the economy. Biomass strategies that reduce GHG emissions are often also beneficial from a sustainability point of view. It is recommended to consider both policy areas together.

Waste policies will be affected by GHG policies. According to the model calculations energy recovery is the best option for waste wood and for waste paper. The interactions between GHG policies and waste policies should be taken into account.

Changing lifestyle poses another potentially important strategy e.g. with regard to the meat consumption. However, this is a sensitive area for policy making and seems a less promising approach.

Regarding biomass, the results from this study are conflicting with earlier studies. The differences show that governments can determine the future of biomass strategies by setting out the ‘rules of the game’. However, proper attention should be paid to the accounting method for project evaluation. Special attention should be paid to:
- the definition of the reference situation,
- the definition of spatial and time system boundaries,
- the definition of costs and the discounting problem.

The current statistics regarding agriculture, forestry, materials, waste and energy use different definitions and different units. The GHG policy issue is closely related to flows in physical terms. It is recommended to develop a new integrated statistic in mass terms for these sectors, in order to facilitate the development of integrated policies.

Agricultural policies and forestry policies
Agricultural policies can influence the productivity and the sector structure and thus policy makers can exert considerable influence on the future applicability of biomass strategies. Current policies with regard to sustainable agriculture (Commission of the European Communities, 1999) contain conflicting policy targets, especially with regard to biomass strategies for GHG policies on one hand and extensification and protection of the existing rural land use on the

other hand. Especially the marginal soils will become available for non-food crops. However these are the regions where the policies are aiming for preservation of the existing practices. It is recommended to make clear choices.

The introduction of GHG policies will affect both agriculture and forestry significantly. If generic pricing policy instruments are selected that treat agriculture and forestry emissions and sinks equally to energy related emissions, prices of agricultural products and forestry products will increase significantly. This effect is on one hand caused by the emissions in the life cycle of these products. On the other hand, the rent of agricultural land will increase because of the competing land use for afforestation. Especially in the case of ambitious emission targets (and high emission permit prices), afforestation becomes a strong competitor. Because of these increased opportunity costs, the revenues of landowners will increase significantly. Prices for some animal products increase two- or threefold. Such price increases will result in increased competition from foreign producers that are not subject to such stringent policies, which results in an imminent carbon leakage threat. Increase food product prices will also reduce the demand for these products, but the elasticity of demand is rather low so this effect is of secondary importance.

For the agricultural and forestry sector as a whole, the endogenisation of GHG emissions in the product prices will result in significantly improved economics. Moreover, market volumes increase because the non-food market will increase significantly: total output may increase from 1200 Mt to 1750 Mt plant biomass.

The improved economics allow the reduction of subsidy schemes. The agricultural policy targets regarding supply security and sustained agriculture will be met by the increased product demand. The increased product prices result in an increased profitability of agriculture. It remains to see whether the benefits are transferred to the agricultural labour force or to the land owners. However other policy goals such as protection of existing landscape and increased biodiversity may become threatened by this intensification. More funds or regulations are required to balance potential negative secondary effects of GHG policies. It is recommended to formulate agricultural policy targets and different environmental policy targets clearly and separately. The model calculations indicate that such targets are often conflicting and require a balanced assessment.

The value of land will rise dramatically in case ambitious GHG policy targets are set, and afforestation project GHG benefits are accounted. It is recommended for governments to acquire surplus agricultural land as long as prices are low and to make regulations that prevent speculation.

Industry and R&D policies

Current agricultural policies and GHG policies are characterised by considerable uncertainties regarding long term policy goals over a period of decades. The concept of sustainability that is set as a policy goal in the Amsterdam treaty lacks detail and is too vague as a guideline. It is even unclear as of yet if the Kyoto agreement will be binding. GHG policy targets for the period beyond the Kyoto time horizon are as of yet unclear.

Industry is in principle willing to contribute to the achievement of policy targets such as sustainability and GHG emission reduction, but a number of conditions must be met by policy makers:

- Long term policy goals must be clear, ambitious, generic and unambiguous.
- A level playing field must be set.
- Policy makers should not favour technologies. Instead, the optimal selection should be left to the market forces.
- The right price signals must be given to the market.

These conditions are not met by the current policies. An adjustment of these policies is recommended.

11.3.2 Recommendations for national governments

The model runs indicate differing trends for North and middle Europe on the one hand and Southern Europe on the other hand. The results suggest that the highest impact of GHG policies on agricultural land use can be expected in Southern Europe. This region can be split into a high yield section (well suited for high yield crops) and a low yield section (well suited for afforestation). However this implies a significant change from current agricultural practices. Oil crops and extensive animal farming are substituted. The increased emphasis on perennial biomass will change the landscape. The increased biomass use will increase transportation requirements.

Food and fodder crops production decreases, coupled to increased imports. On the other hand food and fodder production increases in Middle and (to a limited extent) Northern Europe. Biofuels will be imported from Northern Europe and from Southern Europe into the North-western European region with high population densities. Regarding bio-chemicals, production of solid and liquid intermediates and final products close to the biomass production sites and subsequent transportation to the existing petrochemical complexes seems the most obvious method for integration. This production will be located in the Northern European region and in Southern Europe.

Regarding afforestation, the split between landowners and land users is in many countries a barrier for a shift to perennial crops or even a shift to permanent afforestation. Moreover once the land is turned into forest, its designated use changes in many countries to forestry. Such a change results in a significant value loss. This is typically a major barrier for farmers to change the land use. The best way to handle this problem is government or government related institutions buying the land and handling afforestation projects. It is recommended to keep afforestation projects outside the market mechanism.

11.4 Strategic consideration of uncertainties

MARKAL imposes certain limitations with regard to the conclusions that can be drawn from the modelling results. The model is based on an assumed ideal market, rational behaviour, perfect foresight, a fixed demand and a closed system. All five conditions are only valid to a certain extent. This is probably a better representation for most energy conversion and materials producing industries (the first part of the life cycle) than for household consumption and waste handling (the middle and end parts of the life cycle). Consequently, the results may underestimate certain barriers for emission reduction. For example: car sales are price driven to a limited extent only.

Another important limitation is that the decisions in the model are based on full life cycle costing. In reality, decisions are often taken on the basis of purchasing costs. Taxes and subsidies are neglected in the model, while they may determine 75% of the product price in extreme cases such as gasoline. Especially for the assessment of biofuels, this is a very important issue. The implicit assumption is in this case that biofuels will be taxed in the same way fossil fuels are taxed (as far as taxation or generation of government revenues is concerned).

The comparison of this study and other studies shows that methodological issues determine the results to a large extent. This study considers some aspects that are not considered in other studies such as technological change, discounting, the consideration of competing emission mitigation options and cost optimisation. It is up to the decision-maker to decide whether these aspects should be considered, but the results show that they can determine the outcome to a large extent.

A comparison of the results for the pilot study and the BRED study allows some conclusions regarding the validity of the conclusions based on MARKAL. More detail and a more thorough analysis have resulted in the identification of new types of improvement options and also in more substantial improvement potentials. Comparison of model input data for both studies shows little change of input data for some model sections, and significant differences for others. The set of technologies differs significantly for certain parts of the model. These differences can be attributed to a more thorough search for data, more expertise, and easier data accessibility though the internet and new literature databases. Another part of the differences can be attributed to new R&D results and R&D trends during the last two years. The data for biofuels production for the transportation sector have improved significantly.

If the insights can change significantly in a period of two years, this raises questions concerning the sense of a model for a period of 50 years. It also raises the question how the modelling process can be improved. More attention should be devoted to the compilation process for model parameters. Experience has shown that publications tend to emphasise the positive aspects of new technologies. Publications focusing on problems or disadvantages are much harder to come by. The lesson to be learned is to treat reports regarding technological breakthroughs with caution if the modelling results are used for planning purposes. One important advantage of quantitative models is the increased ratio in the R&D funding allocation process that considers many aspects that are not considered in more simple assessment methods. Another advantage is the forced process data description in a standard format, allowing comparison of very different types of technologies. The dataset that has been developed for the MARKAL model can also be used for other environmental chain analysis studies.

Data regarding future crop yields are one of the main uncertainty sources. The model calculations indicate that the new, prospective high yield crops are the most attractive ones. However these are typically the crops whose yield figures may be too optimistic, even by a factor 2. The uncertainty regarding biomass availability if further complicated by the sensitivity for future food production trends. Due to climate change, yields may increase in many parts of Europe by 10-20% for C3 crops, but yield reductions of 10-20% may occur for C4 crops (such as Miscanthus and corn) and for crops on in Southern Europe where water availability becomes a limiting factor. Model calculations suggest that the net impact is limited, at least within the time horizon considered.

Certain biomass strategies are less dependent regarding changes in the reference system configuration than others. For example, the CO_2 effect of carbon storage in afforestations is independent of any other option (at least if competing land use options are neglected). The substitution of petrochemical feedstocks and transportation fuels are other examples where carbon content is important. As a consequence, the relative attractiveness of these strategies will increase if the changing reference is considered. The uncertainty of the GHG impact of these strategies is independent of the future reference energy and materials system configuration.

The uncertainty analysis shows that the impact of policy decisions is by far more important than the uncertainty regarding technology and regarding costs. The selection of policy instruments, the selection of target sectors, the definition of GHG emissions, etc. are issues with major consequences that should be evaluated thoroughly. The diversity on the technology side and on the biomass supply side reduces the relevance of uncertainties regarding these issues.

11.5 Methodological issues and recommendations for further research

The results from this study differ to a considerable extent from the results of earlier biomass assessment studies. The differences can be explained because of methodological differences:

- This study selects on the basis of cost-effectiveness with endogenised environmental impacts (contrary to e.g. LCA, which selects on the basis of environmental impacts alone).

- Costs are discounted.
- Technological change is considered.
- The changing reference system is considered (equivalent to: the whole energy and materials system is optimised as one system for a period of 90 years).
- Market volumes are considered.
- The food production competition for land use is considered.

The relevance of these issues for the quality of the decision making depends on the topic and the policy goals. Given the global scale of the GHG problem and the long term planning horizon for significant emission mitigation, the issues are of special relevance for GHG policy making and for sustainable development. It is recommended to elaborate this approach further for analysis of biomass strategies. For other environmental problems, the time horizon may be shorter and the characteristics of the total energy and materials system may be of secondary importance. In such cases, straightforward existing LCA, MFA or technology assessment methodologies may be more appropriate.

Recommendations for further modelling research (not in order of importance):

- Consider EU expansion with Central European countries.
- Consider biomass imports from outside Europe.
- Develop the model as a tool for objective evaluation.
- Pay more attention to transportation distances and transportation optimisation for biomass and biomass products.
- Expand the model with other environmental impacts but GHG emissions.
- Model CH_4 emission reduction and N_2O emission reduction in agriculture in more detail.
- Analyse the straw supply potential in more detail, especially the competition for organic soil improvement.
- Analyse the potential for new bio-chemicals in more detail.
- Use building energy models for detailed analysis of the interaction of building materials selection and energy use during the building use stage.
- Analyse the environmental impacts of co-combustion of post-consumer wood waste in more detail though thorough literature review (especially dioxins).
- Validate the data with industry experts and use the comments for new model runs.
- Develop a comprehensive LCA database for wood buildings and buildings from competing materials.
- Analyse the impact of carbon leakage and changing trade patterns of agricultural products and forestry products in more detail, based on a global systems engineering model.
- Develop an internet version of the model engineers and policy makers can use themselves.
- Integrate the MARKAL approach in EU R&D strategy development.

ANNEX A. QUANTIFICATION OF A CLIMATE CHANGE SENSITIVITY ANALYSIS

Climate change can influence biomass yields though various mechanisms (Beniston and Tol, 1998):
The climate effect must be split into annual crops and perennial crops.

- Increased CO_2 concentrations can increase the growth rate of plants, especially the C3 crops. For C4 crops (such as maize and miscanthus), the effect is much smaller.
- Higher temperatures can reduce the water availability and will increase the transpiration. Water availability problems may be mitigated regionally by irrigation schemes. Water availability may be reduced in Southern Europe, but water availability may increase in Northern Europe.
- As a result of increasing air temperatures in winter, the risks associated with damaging frosts will be reduced as a whole. This will allow expansion of winter cereals and probably other winter crops in southern Scandinavia. Increasing spring temperatures will extend suitable zones for summer crops (e.g. sunflower, grain maize).
- Weeds, pests and diseases may increase due to increase precipitation and increased CO_2 concentrations. However these effects may be mitigated by weed and pest control.
- The impact on forestry is not clear. Some sources suggest a strong relocation to Northern latitudes and an increased growth rate. Others suggest limited change.

Some results from modelling studies are listed in Table A.1.

Table A.1 *Results from modelling studies (European Commission, 1997a)*

Year (CO_2 concentration)	Region	Crop	UKTR model [%]	GFDL model [%]
2023	South	Wheat	+1	+5
(454 ppmv)		Grapevine	+3	+13
		Sunflower	-21	+16
	Middle	Wheat	+5	+5
		Onion	+10	+10
2064	South	Wheat	+39	+18
(617 ppmv)		Corn	-11	-7
		Sunflower	-8	-8
	Middle	Wheat	+20	+28
		Onion	+17	+21

Assuming that the CO_2 concentrations increase 70-150% (500 ppmv-700 ppmv), and assuming that Southern Europe becomes drier and Northern Europe becomes wetter, the impact of temperature increases, and of increased pests and weeds can be neglected, a scenario has been developed where agricultural crop yields change (Tables A.2-A.4).

Table A.2 *Middle and Northern Europe, 2030*

Crop	Reference no climate change (% change compared to 1990)	Climate change scenario [% change]
Grass [t/ha]	5.3 (+5)	+10
Grass + fertilizer [t/ha]	6.3 (+5)	+10
Wheat (whole plant) [GJ/ha]	197 (+27)	+10
Wheat + fertilizer [GJ/ha]	283 (+50)	+10
Miscanthus [GJ/ha]	434 (+22)	0
Maize (whole plant) [GJ/ha]	315 (+18)	0
Maize + fertilizer (whole plant) [GJ/ha]	357 (+33)	0
Rape [GJ/ha]	171 (+28)	+10
Sugarbeet [GJ/ha]	141 (+8)	+10
Fodder [t/ha]	11.0 (+11)	+10
Sunflower [GJ/ha]	156 (+22)	+10
Willow [GJ/ha]	256 (+49)	+10
Vegetables [t/ha]	26.3 (+0)	+10
Fruit [t/ha]	9.6 (+0)	+10
Afforestation coniferous [t wood/ha]	5.0 (+0)	+10
Afforestation non-coniferous [t wood/ha]	5.0(0)	+10
Willow North [GJ/ha]	97 (+13)	+10
Poplar Middle [GJ/ha]	193 (+42)	+10

Table A.3 *South Europe High Yield, 2030*

Crop	Reference no climate change (% change compared to 1990)	Climate change scenario [% change]
Grass [t/ha]	5.3 (+5)	+10
Grass + fertilizer [t/ha]	6.2 (+5)	+10
Wheat (whole plant) [GJ/ha]	363 (+25)	+10
Miscanthus [GJ/ha]	500 (+20)	-10
Sorghum [GJ/ha]	500 (+14)	-10
Sugarbeet [GJ/ha]	123 (+8)	+10
Fodder [t/ha]	1.1 (+11)	+10
Vegetables [t/ha]	26.3 (+0)	+10
Fruit [t/ha]	9.6 (+0)	+10
Afforestation coniferous [t wood/ha]	5.0 (+0)	+10
Afforestation non-coniferous [t wood/ha]	5.0 (+0)	+10
Poplar South [GJ/ha]	254 (+49)	+10

Table A.4 *South Europe Low Yield, 2030*

Crop	Reference no climate change (% change compared to 1990)	Climate change scenario [% change]
Grass [t/ha]	4.0 (+25)	-25
Afforestation coniferous [t wood/ha]	2.5 (+0)	-25
Olives South [GJ/ha]	40 (+0)	-25

Apart from changing crop yields, some demand categories may change. As the climate becomes wetter in Northern Europe and snow conditions deteriorate, there is a marked increase in air transportation for vacations (demand for air traffic +25%). Demand for residential heating decreases by 5% as temperatures increase. Some of the main waterways (such as the Rhine) become less navigable due to increased droughts in the summer. This increases the demand for truck transportation (+10 %). The demand for cooling in Southern European offices increases by 50%.

REFERENCES

Alcamo, J. (ed.) (1994): *Image2.0: Integrated modelling of global climate change.* Kluwer Academic Publishers, Dordrecht, The Netherlands, 1994.

APME (1993): *European Municipal Solid Waste Combustors and Associated Energy Recovery Survey.* Brussels, Belgium, 1993.

APME (1995): *Plastics consumption and recovery in Western Europe in 1994.* Brussels, Belgium, 1995.

Beek, R. van (1997): *Comparison of household waste figures for various countries in Europe.* Ministry of Housing, Spatial Planning and Environment, The Hague, The Netherlands, 1997.

Beniston, M., R.J. Tol: Europe (1998): In: R. Watson, M. Zinyowera, R.H. Moss, D.J. Dokken*: The Regional Impacts of Climate Change. An Assessment of Vulnerability,* pp. 148-185, Cambridge University Press, UK, 1998.

Börjesson, P., L. Gustavsson: *Different ways to use forest for greenhouse gas mitigation. Wood versus concrete buildings in a life-cycle perspective.* Energy policy, forthcoming.

Bos, A.J.M. (1991): *De CO_2-verdiensten van biomassa.* IVEM, Groningen, September 1991.

Bos, A.J.M. (ed.) (2000): *Biomass for greenhouse gas emission reduction. Task 9: workshop proceedings.* ECN, Petten, The Netherlands.

Böswald, K. (1998)*: Present and future options of forests and forestry for CO_2 mitigation in Germany.* In: G.H. Kohlmaier, M. Weber, R.A. Houghton (eds.): Carbon dioxide mitigation in forestry and wood industry. Springer Verlag, Berlin, Germany, 1998.

Capros, P., E. Kokkolakis, S. Makris, L. Mantzos, Y. Antoniou, J.-F. Guilmot (1995): *Energy Scenarios 2020 for European Union. Volume 1: Results for European Union.* Brussels, Belgium, October 1995.

Capros, P., L. Mantzos, L. Vouyoukas, D. Petrellis (1999): *European Energy and CO_2 Emissions to 2020.* Paper presented at IEA/EMF/IIASA Energy Modelling Meeting, Paris, France, 16-18 June 1999.

CEPI (1994): *1994 Annual Statistics.* Brussels, Belgium, 1994.

Commission of the European Communities (1999): *Directions to sustainable agriculture.* COM(1999) 22 final. Brussels, Belgium, 27 January 1999.

Confederation of European Paper Industries (1994): *Annual Statistics.* Brussels, 1994.

Cornelis van Kooten, G., H. Folmer: *Economic Instruments and the Pasture-Crop-Forest Interface.* In: W.N. Adger, D. Pettenella, M. Whitby (eds.): Climate Change Mitigation and European Land-Use Policies, pp. 113-128, CAB International, Wallingford, UK, 1997.

Crabtree, R. (1997): *Policy Instruments for Environmental Forestry: Carbon Retention in Farm Woodlands.* In: W.N. Adger, D. Pettenella, M. Whitby: Climate Change Mitigation and European Land-Use Policies. CAB Publishers, Wallingford, UK, 1997.

Department Of Energy DOE (1999): *Carbon Sequestration. State of the Science.* Washington, February, 1999

Dewar, R.C., M.G.R. Cannell (1992): *Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples.* Tree physiology 11, pp. 49-71.

Diamantidis, N.D., E.G. Koukios (1999): *Biomass for greenhouse gas emission reduction Task 4-6: Techno-economic characterisation of biomaterials production.* NTUA, Athens, Greece, 1999.

Duin, R. van (1997): *Production and consumption of materials in Western Europe in the year 2000. An overview of materials with CO_2 relevance.* Bureau B&G, Emst, The Netherlands, July 1997.

ETSU (1997a): *Atlas project: Renewable energy sector overview.* European Commission, Thermie programme, Brussels, 1997.

ETSU (1997b): *The ATLAS project - Renewable energy. Liquid biofuels.* Energy Technology Information Base 1980-2010, 1997.

ETSU (1997c): *The ATLAS project - Renewable energy. Biomass Electricity.* Energy Technology Information Base 1980-2010.1997.

European Commission (1997a): *Climate change and agriculture in Europe. Assessment of impacts and adaptations.* EUR17470. Luxembourg, 1997.

European Commission (1997b): *Energy for the future: Renewable sources of energy.* White paper for a community strategy and action plan. COM(97)599 final, 26/11/1997: http://europa.eu.int/comm/dg17/599fe_en.pdf.

European Environmental Agency (1999): *Annual European Community Greenhouse Gas Inventory 1990-1996.* Kopenhagen, May 1999.

Faaij, A. (1997): *Energy from biomass and waste.* PhD thesis, Utrecht University, The Netherlands, September 1997.

Feber, M.A.P.C. de, D.J. Gielen: *Biomass for greenhouse gas emission reduction. Task 7: Energy technology characterisation.* ECN-C--99-078, Petten, The Netherlands.

Fraanje, P. (1997): *Cascading of pinewood.* Resources, Conservation and Recycling 19, 1997, pp. 21-28.

Franssen, S. (1999): *MATTER 3.0: Relaxing the Demand in the MATTER model.* ECN, Petten, The Netherlands, June 1999.

Gaouyer, J.-P (1997): *French policy and the programmes for liquid biofuels.* Paper presented at the conference 'Use of biofuels for transportation', 29 September-1 October 1997, Stockholm, Sweden.

Gerlagh, T. (1998a): *Biomass for greenhouse gas emission reduction. Land availability for Western European biomass production.* ECN-I--98-051. Petten, The Netherlands, November 1998.

Gerlagh, T. (1998b): *Biomass for greenhouse gas emission reduction: Western European Land Availability.* ECN-C--98-109. ECN, Petten, The Netherlands, December 1998.

Gerlagh, T., D.J. Gielen (1999): *MATTER 2.0. A module characterisation for the agriculture and food sector.* ECN-C--99-048, Petten, July 1999.

Gielen, D.J. (1995): *Wood for energy or materials applications - Integrated energy and materials system optimisation for CO_2 reduction.* In: A. Frühwald, B. Solberg (eds.): Life-cycle analysis - A challenge for forestry and forest industry. EFI proceedings no. 8, pp. 149-168, 1995.

Gielen, D.J., J. van Doorn (1995): *Biomassa voor de Nederlandse energiehuishouding. Beoordeling van conversieroutes met MARKAL.* Novem, report no. 9504. ECN, Petten, The Netherlands, February 1995.

Gielen, D.J., P. Koutstaal, T. Kram, S.N.M. van Rooijen (1998): *Post-Kyoto. Effects on the Climate Policy of the European Union.* ECN-C--98-040. Petten, The Netherlands, June 1998.

Gielen, D.J., P. Lako, L. Dinkelbach, R. van Ree (1998): *Prospects for bioenergy in the Netherlands. A MARKAL analysis of the long-term impact of energy and CO_2 policies.* ECN-C-97-103. Petten, The Netherlands, February 1998.

Gielen, D.J., T. Gerlagh, A.J.M. Bos (1998a): *Biomass for Energy or Materials? A Western European MARKAL MATTER 1.0 model characterisation*. ECN-C--98-066. Petten, The Netherlands, December 1998.

Gielen, D.J., T. Gerlagh, A.J.M. Bos (1998b): *MATTER 1.0. A MARKAL Energy and Materials System Model Characterisation.* ECN-C--98-065, Petten, September 1998.

Gielen, D.J (1999a): *Western European Materials as Sources and Sinks of CO_2. A Materials Flow Analysis Perspective.* Journal of Industrial Ecology vol. 2, no. 2, 1998, pp. 43-62.

Gielen, D.J. (ed.) (1999b): *Factor 2/Factor 10 workshop proceedings 2 April 1998.* Dutch national research programme on global air pollution and climate change, Bilthoven, report no. 410200019, The Netherlands, 1999.

Gielen, D.J. (1999c): *Materialising dematerialisation. Integrated energy and materials systems engineering for greenhouse gas emission mitigation.* PhD Thesis. Design for Sustainability Program, Technical University Delft, April 1999.

Gielen, D.J. (1999d): *Building materials and CO_2. Analysis of Western European Emission Reduction Potentials.* In D.J. Gielen (ed.): Factor 2/Factor 10 workshop proceedings. NOP-MLK, The Netherlands, 1999

Gielen, D.J., A.J.M. Bos, M.A.P.C. de Feber, T. Gerlagh (1999): *Greenhouse gas emission reduction in agriculture and forestry. A Western European systems engineering perspective.* Paper presented at the colloquium 'Bilan et gestion des gaz a effet de serre dans l'espace rural'. Paris, France, 18 and 19 May 1999.

Gielen, D.J., T. Kram, J.C. Brezet (1999): *Integrated energy and materials scenarios for Greenhouse Gas emission mitigation.* Paper presented at IEA international workshop on technologies to reduce GHG emissions: engineering-economic analyses of conserved energy and carbon, 5-7 May 1999, Washington DC, USA, http://www.iea.org/workshop/engecon/.

Gielen, D.J., Pieters, J.: forthcoming: Instruments and Technologies for Climate Change Policy. Main volume and 3 annexes. OECD, Paris.

Granger Morgan, M., M. Henrion (1990): *Uncertainty. A guide to dealing with uncertainty in quantitative risk and policy analysis.* Cambridge University Press, Cambridge, UK, 1990.

Hall, D. (1994): *Biomass energy options in Western Europe (OECD) to 2050.* In: Energy technologies to reduce CO_2 emissions in Europe: Prospects, Competition, Synergy. IEA/OECD, 1994, pp. 159-193.

Hall, D.O., J. Woods, J. House (1992): *Biological systems for uptake of carbon dioxide.* Energy Conversion Management Vol. 33, 1992, pp. 721-728.

Hamilton, L.D., G. Goldstein, J.C. Lee, A. Manne, W. Marcuse, S.C. Morris, C.-O. Wene (1992): *MARKAL-MACRO: An overview.* Brookhaven National Laboratories #48377, November 1992.

Hekkert, M.P., L.A.J. Joosten, E. Worrell, forthcoming: Reduction of CO_2 emissions by improved management of material and product use, the case of primary packaging, *Resources, Conservation and Recycling*.

Hanisch, C. (1999): *Powering tomorrow's cars.* Environmental Science & Technology, pp. 458a-462a, November 1, 1999.

Houghton, J.T., L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskel (eds.)(1996): *Climate Change 1995. The Science of Climate Change.* Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, 1996.

IEA (1997): *Climate Technology Initiative.* Workshop proceedings, Jülich, Germany, October 1997.

International Energy Agency (1994): *Biofuels.* Paris, 1994.

Internet: *http://www.ecn.nl/unit_bs/markal/matter.*

IPCC emission accounting guidelines (1997): GHG emission accounting guidelines. WG1 technical support unit, Hadley Centre, Bracknell, UK, 1997.

IPCC SRES scenarios: forthcoming.

Jacoby, H.D., R.G. Prinn, R. Schmalensee (1998): *Kyoto's unfinished business.* Foreign Affairs July/August 1998, vol. 77, no. 4.

Kohlmaier, G.H. et al. (1998): *Future development of the carbon cycle: the role of the biota/forests within the IPCC stabilization scenarios.* In: G.H. Kohlmaier et al.: Carbon dioxide mitigation in forestry and wood industry, Springer Verlag, Heidelberg, 1998, pp. 269-291.

Körbitz, W. (1997): *The biodiesel market today and its future potential.* Paper presented at the conference 'Use of biofuels for transportation', 29 September-1 October 1997, Stockholm, Sweden

Koukios, E.G., N.D. Diamantidis (1998): *Biomass for greenhouse gas emission REDuction (BRED). Agriculture as a source of biomass in Western Europe.* NTUA, Bioresource technology unit, Athens, Greece.

L'Academie d'Agriculture de France (1999)*: Bilan et Gestion des Gaz a effet de serre dans l'espace rural.* 18-19 May 1999, Paris, France.

Loulou, R., D. Lavigne (1996): *MARKAL model with Elastic Demands: Application to Greenhouse Gas Emission Control.* In: C. Carraro, A. Haurie (eds.): Operations research and environmental management. Kluwers Academic Publishers, pp. 201-220, The Netherlands, 1996.

Lysen, E.H., C. Daey Ouwens, M.J.G. van Onna, K. Blok, P.A. Okken, J. Goudriaan (1992): *The Feasibility of Biomass Production for the Netherlands Energy Economy.* Report no. 71.140/0130. Novem, Utrecht, The Netherlands, 1992.

Marland, G., S. Marland (1992): *Should we store carbon in trees?* Water, Air and Soil Pollution 94, 1992, pp. 181-195.

Marland, G., B. Schlamadinger (1998): *Does the Kyoto Protocol make a difference for the optimal forest-based C mitigation strategy? Some results from GORCAM.* In: B. Schlamadinger, R. Madlener (eds): IEA bioenergy workshop proceedings', Effects of the Kyoto Protocol on forestry and bioenergy projects for mitigation of net carbon emissions', 9-13 March 1998, Rotorua, New Zealand, pp. 43-60.

Marland, G., B. Schlamadinger: forthcoming.

Nabuurs, G.J. (1996): *Significance of wood products in forest sector carbon balances.* M.J. Apps, D.T. Price (eds.): Forest ecosystems, Forest Management and the Carbon Balance. NATO ASI Series Vol. I 40, pp. 245-256.

Nabuurs, G.J., P. Päivinen, R. Sikkema, G.M.J. Mohren (1997): *The role of European forests in the global carbon cycle - a review.* Biomass and bioenergy vol. 13, no. 6, pp. 345-358, 1997.

Nabuurs, G.J. et al.(1999): *Resolving issues on terrestrial biospheric sinks in the Kyoto Protocol.* NOP-MLK report no. 410200030. IBN-DLO, Wageningen, 1999.

Nilsson S., W. Schopfhauser (1995)*: The Carbon-Sequestration Potential of a Global Afforestation Program.* Climatic Change 1995, 30, pp. 267-293.

Okken, P.A. et al.(1993): *Drastische CO_2-reductie. Hoe is het mogelijk*. ECN-C-92--066, Petten, The Netherlands, January 1993.

Okkerse, C., H. van Bekkum (1996): *Vernieuwende grondstoffen voor de chemische industrie. Innovative feedstocks for the chemical industry*. In: Interdepartmental research programme sustainable technology: Duurzaamheid en chemie. DTO, Delft,, pp. 11-43, The Netherlands, 1996.

Olivier, J. et al. (1996): *Description of EDGAR version 2.0.* RIVM report no. 771060002, Bilthoven, December 1996.

Paasen, S. van (1999): *Fischer Tropsch Process.* Process engineering project, Eindhoven University of Technology, The Netherlands, 1999.

Patel, M., J. Korell, N. Kopf, A. Theiss (1998): *Use of renewable materials in chemical industry.* Workshop proceedings, 15 May 1998, FhG-ISI, Karlsruhe.

Radetzki, M. (1997): *The economics of biomass in industrialized countries*: *an overview*. Energy Policy, vol. 25, no. 6, 1997, pp. 545-554.

Ree, R. van, R. Moonen, P. Lako, M. Mozaffarian (1999): *Technical and economic data biomass based energy conversion systems for the production of gaseous and liquid energy carriers.* ECN-C--99-059, Petten. The Netherlands, draft 26 October 1999.

Scharai-Rad, M., J. Welling, V. Sasse (1999): *Biomass for greenhouse gas emission reduction. Internal report on Forestry and Forest Products use in Western Europe.* Federal Institute for Forestry and Forest Products BFH, Hamburg, Germany.

Scharai-Rad, M., J. Welling (1999): *Biomass for greenhouse gas emission reduction. Task 4-6: Wood product technology characterisation.* BFH, Hamburg, Germany.

Schlamadinger, B., G. Marland (1998): *Some technical issues regarding land-use change and forestry in the Kyoto Protocol.* In: B. Schlamadinger, R. Madlener (eds): IEA bioenergy workshop proceedings', Effects of the Kyoto Protocol on forestry and bioenergy projects for mitigation of net carbon emissions', 9-13 March 1998, Rotorua, New Zealand, pp. 7-26.

Schmidt, K. (1998): *Coming to grips with the world's greenhouse gases.* Science vol. 281, 24 July 1998, pp. 504-506.

Schwager, J. (1995): *Les tendances de l'incineration en Europe*. Paper presented at the Seminar 'The Future of European Thermal Waste Treatment', 7-8 September 1995, Paris, France.

Sikkema, R., G. Nabuurs (1994): *Bossen en hout op de koolstofbalans.* Novem report. no. 9416. SBH, Wageningen, The Netherlands.

Sikkema, R., G.J. Nabuurs (1995): *Forest and forest products: the challenge for a better carbon balance.* In: A. Frühwald, B. Solberg (eds.): Life cycle analysis - a challenge for forestry and forest products. EFI proceedings no.8.

Sluijs, J.P. v/d (1997): *Anchoring amid uncertainty. On the management of uncertainties in risk assessment of anthropogenic climate change.* PhD Thesis, Utrecht University, The Netherlands.

Tol, R.S.J., P. Vellinga (1996): *Approaches to Integrated Assessment.* In A. Sors et al.: Prospects for Integrated Assessment: Lessons Learnt from the Case of Climate Change. Symposium Proceedings, October 24-26, 1996, Toulouse. EUR 17639. European Commission DG XII, Brussels, Belgium.

UN-ECE (1997): *Iron and Steel Scrap.* ECE Steel series. Geneva, Switzerland.

UN FCCC (1997a): *National Communications - Communications from parties included in Annex 1 to the convention.* FCCC SBI 1997 INF 4, 14 October 1997. Via Internet: http://www.unfccc/de.

UNFCCC (1997b): *Kyoto Protocol to the United Nations Framework Convention on Climate Change.* December 1997. Via Internet: http://www.unfccc.de.

UNFCCC (1997c): *National Communications. Communications from Parties included in Annex I to the Convention.* FCCC/SBI/1997/19/Add. 1, 1997. Via Internet.

United Nations Economic Commission for Europe/Food and Agriculture Organisation of the United Nations (1996): *European Timber Trends and Prospects: Into the 21st Century.* Geneva, Switzerland.

US Bureau of Mines (1997): *Mineral Industries of the World.* CD-ROM.

Vigon, B. (1997): *Life-cycle inventory: data quality issues.* In: Proceedings of the 1997 Total Life Cycle Conference - Life Cycle Management and Assessment (Part 1), pp. 47-54. Society of Automotive Engineers, Warrendale PA, USA.

Voss, A. (1997): *Erfahrungen, Grenzen und Nutzen von Energiemodellen*. (Experiences regarding the applicability of energy models). In: S. Molt, U. Fahl (eds.): Energiemodelle in der Bundesrepublik Deutschland - Stand der Entwicklung. Forschungszentrum Jülich, Germany.

Warmer Bulletin February 1994, no. 40.

Watson, R., M. C. Zinyowera, R.H. Moss, D.J. Dokken (eds.) (1996a): *Climate change 1995: Impacts, adaptions and mitigation of climate change: Scientific-technical analyses.* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. pp. 750. Cambridge University Press, Cambridge, UK, 1996.

Watson, R., M. C. Zinyowera, R.H. Moss, D.J. Dokken (eds.) (1996b): *Climate change 1995: Impacts, adaptions and mitigation of climate change: Scientific-technical analyses.* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. pp. 753. Cambridge University Press, Cambridge, UK 1996.

Watson, R., M. C. Zinyowera, R.H. Moss, D.J. Dokken (eds.) (1996c): *Climate change 1995: Impacts, adaptions and mitigation of climate change: Scientific-technical analyses.* Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. pp. 777. Cambridge University Press, Cambridge, UK 1996.

Waupotitsch, M., B. Schlamadinger, R. Madlener (1999): *A bibliography on greenhouse gas balances of bioenergy, forestry, wood products, land use and land use change.* IEA bioenergy implementing agreement task 25/Joanneum Graz, Austria.

Weterings, R., J. Kuijper, E. Smeets (1997): *81 mogelijkheden. Technologie voor duurzame ontwikkeling.* TNO-STB, The Netherlands.

Wynne, B. (1992): *Uncertainty and Environmental Learning - Reconceiving Science and Policy in the Preventative Paradigm.* Global Environmental Change 2 (2), June 1992, pp. 111-127.

Ybema, J.R. et al. (1995): *Prospects for energy technologies in the Netherlands.* Volume 1-2. ECN-C--95-039. Petten, The Netherlands.

Ybema, J.R., T. Kram (1996): *'Hedging' for CO_2 reduction. Including climate change characteristics in decisions on energy investments.* ECN-RX--96-055. Petten, the Netherlands.

Ybema, J.R. et al. (1999): *De bijdrage van duurzame energie in Nederland tot 2020.* Contribution of renewable energy in The Netherlands until 2020. ECN-C--99-053. Petten, The Netherlands.