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BIOMASS FOR ENERGY OR MATERIALS?

A Western European MARKAL MATTER1.0 model characterisation

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Abstract

This report discusses the structure and input data for the biomass module of the MATTER 1.0 model, a MARKAL energy and materials systems engineering model for Western Europe. This model is used for development of energy and materials strategies for greenhouse gas emission reduction in the framework of the MATTER study and the BRED study. Preliminary biomass results are presented in order to identify key processes and key parameters that deserve further analysis. The results show that the production of biomaterials is an attractive option for the reduction of greenhouse gas emissions. Biomaterials can substitute materials which require a lot of energy for production or which are derived from fossil fuels. Increased biomaterial production will result in increasing amounts of waste biomass which can be used for energy production. An increase of the use of biomaterials for the production of materials needs to get more attention.

CONTENT

SUMMARY

Biomass can be used to reduce greenhouse gas emissions. It can either be used as an energy source or it can be used to substitute materials. It can also be used in a sequence of both applications: first as a material, second as an energy source. This report discusses biomass applications in order to reduce greenhouse gas emission reduction.

This report first discusses the biomass module the MATTER 1.0 model, a MARKAL energy and materials systems engineering model for Western Europe. This model is used for the development of energy and materials strategies for greenhouse gas emission reduction in the framework of the MATTER study and the BRED study. Preliminary biomass results are presented for identification of key processes and key parameters which deserve further analysis.

Based on the MATTER model, scenario have been calculated with different CO_2 taxes. Modeling results show that Western European biomass availability is no constraint at emission penalty levels up to 50 ECU/t CO_2. As a consequence, no competition occurs between bioenergy and biomaterial applications. On the contrary: the production of biomaterials results in an increased availability of process waste and post consumer waste that can be used for energy recovery. Only at emission penalty levels from 100 ECU/t CO_2 upwards, a trade-off between both applications will occur. The crops that are applied are the high-yield crops: Eucalyptus, Sweet Sorghum, Miscanthus and Poplar. The crops are first introduced in the Southern region with high yields, followed by the Middle region. Forest wood recovery increases simultaneously in the Northern and Middle region.

At penalty levels up to 100 ECU/t, materials applications dominate energy applications. At higher penalty levels, energy applications dominate. This can be attributed to the combination of potentially higher energy market volumes and the features of competing emission abatement strategies in energy and material markets. The conclusion for biomass strategy analysis is that materials applications must also be considered for the future assessment of bioenergy.

The sensitivity analysis with generally more conservative technology estimates and higher cost estimates suggests that the results are fairly robust for bioenergy use. However these results are determined by the assumptions regarding the feasibility of ethylene production based on flash pyrolysis. Because this technology was excluded in the sensitivity analysis, biomaterials use was significantly affected. The sensitivity analysis for individual model parameters showed that flash pyrolysis for production of petrochemical feedstocks and bioethanol production from lignocellulose crops are key technologies in the analysis. The parameters for both technologies determine to a large extent how the biomass should be applied. However the total amount of biomass that is applied is relatively independent of these assumptions. Land availability is a key parameter that will determine the future of bioenergy. The use of biomaterials seems less sensitive for land availability constraints. As a consequence, biomaterials deserve special attention in a situation where future land availability is uncertain.

The combination of biomaterials and bioenergy strategies results in additional biomass use for energy production, as by-products from materials production, especially lignine

and by-products from pyrolysis processes can be used for energy recovery. Structural wood products with a long product life can only contribute to energy recovery after a product life of decades. Increased recycling and energy recovery of biomaterials poses an important option 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.

1. INTRODUCTION

This report describes the current energy and materials systems module in the MARKAL-MATTER1.0 model (status 1/7/1998) with special emphasis on biomass. This biomass module will be further detailed in the framework of the BRED project (Biomass for greenhouse gas emission REDuction) for the Environmental Technology unit (DG XII) of the European Commission. This report serves as starting document for the BRED project in order to facilitate review of the current model input and to show the kind of analyses that can be done with this model.

Chapter 2 focuses on the general MARKAL model structure. Chapter 3 discusses the improvement options on a general systems level. Chapter 4 discusses the biomass module input data in more detail. The MARKAL model has been used for a preliminary analysis of biomass strategies that is discussed in Chapter 5. Conclusions from these analysis regarding biomass policies and regarding further modeling within the BRED project are drawn in Chapter 6.

BRED: Biomass for GHG emission REDuction

Starting from the EU policy goal for GHG emission reduction, the objective of the BRED project is to 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 GHG emission reduction on the long term (period 2000-2050). Based on model calculations, 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 number of strategies have been proposed to reduce greenhouse gas emissions. One of the proposed strategies is based on the introduction of more plant biomass. Biomass can be used for energy purposes, or it can serve as feedstock for synthetic organic materials and for structural materials like timber. Biomass can also be used in a sequence of both applications: first as a material, second as an energy source. However, the availability of biomass (i.c. bioenergy and biomaterial crops) in Western Europe is limited by the land availability and the biomass yields per square kilometre. This limits the potential of the biomass strategy for CO_2 emission reduction. The BRED project focuses on the cost-effective allocation of limited biomass resources for GHG emission reduction in order to assess its attractiveness. Competition with other strategies for GHG emission reduction is taken into account.

The relation between biomass and the greenhouse gas balance

The ratio behind biomass strategies is the fact that biomass is produced by plants that fix CO_2 from the atmosphere. This CO_2 is released if the biomass is incinerated. Biomass is a CO_2-neutral resource. However apart from the neutral life cycle carbon balance of individual plants, the effects of changing biomass stocks must be considered. As a consequence of increasing stocks, biomass can even constitute a carbon sink.

This is for example the case in Western European where forest regrowth exceeds removals to a considerable extent. Apart from forests, other stages in the biomass life cycle (product use and waste disposal) can also constitute carbon sinks. These sinks can be further enhanced by policy measures.

The biomass stocks are decreasing in many regions outside Western Europe. Approximately 20% of the global CO_2 emissions can be attributed to deforestation and changes in land use. Especially tropical rainforests are still used in a non-sustainable manner, amongst other reasons for timber production: removals exceed regrowth. Part of this timber is exported to Western Europe. This deforestation results in a net CO_2 emission that can be attributed to the Western European consumption.

A final notion is that the relevance of biomass for the greenhouse gas balance extends beyond CO_2 emissions. Significant amounts of CH_4 are produced in landfills sites and during manure storage. This methane results from the anaerobic digestion of biomass by microorganisms. 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 arise in agriculture. Microorganicms in the soil convert both part of natural nitrogen fertilizers and synthetic nitrogen fertilizers into N_2O. CH_4 and N_2O are per weight unit 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. Table 1.1 shows the greenhouse gas balance of the biomass production and biomass use in Western Europe. All emissions within Western Europe and the emissions abroad for Western European materials consumption have been considered. These emissions can be compared to total Western European emissions of 4250 Mt CO_2 equivalents. The table shows that the use of biomass results in a significant net CO_2 emission reduction. However this effect is balanced by the net emissions of CH_4 and N_2O. CH_4 and N_2O emissions are nowadays largely related to food production and food use. The figures in Table 1.1 indicate that both greenhouse gases must be considered in a proper analysis of the potential of biomass strategies for greenhouse gas emission reduction.

Table 1.1: *The relevance of Western European biomass for greenhouse gas emissions (GWP 100 years) (based on [1,2,3])*

	CO_2 [Mt pa]	CH_4 [Mt CO_2 equiv. pa]	N_2O [Mt CO_2 equiv. pa]
Increasing forest stock[1]	-150 - -250	-	-
Fertilizer use	-	-	100-200
Imported wood products[2]	25-50	-	-
Increasing product stock	-75	-	-
Landfills	-23	100-200	-
Energy production/recovery[3]	-50 - -150	-	-
Total	*-248 - -473*	*100-200*	*100-200*

European biomass markets

The current role of biomass in Western Europe can be split into a number of markets:

- food and fodder
- paper and pulp
- building and construction materials
- biochemicals (e.g. surfactants, solvents, natural rubber)
- natural fibers for textiles
- energy

The first market segment is by far the most substantial one (expressed on mass flow units). Only cereal production amounts to 200 Mt per year. Assuming a fodder to meat ratio of 7:1, the Western European meat consumption implies a fodder consumption of 250 Mt per year. A preliminary analysis of paper and pulp and building and construction

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[1] This main uncertainty is related to the impact of forest fires (50% of the net regrowth according to Nabuurs et al.)

[2] The bulk of the emissions associated with wood products arises from deforestation abroad

[3] Compared to average European power production with 0.1 t CO_2/GJe, assuming 25% efficiency in conversion

material flows that serves as reference for the calculations has been discussed in [3] (see Figure 1.1). Paper consumption amounted in 1992 to 65 Mt per year. Wood consumption for building and construction materials amounted to 82 Mt. Biochemicals and natural fibers are of secondary importance (less than 10 Mt together). Biomass use for energy is detailed in Table 1.2 [4]. 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 suggests a total consumption of 68 Mt biomass for energy purposes. This is a lower estimate since estimates in [4] are based on IEA statistics. IEA states: “Data under this heading are often based on small sample surveys or other incomplete information. This 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”.

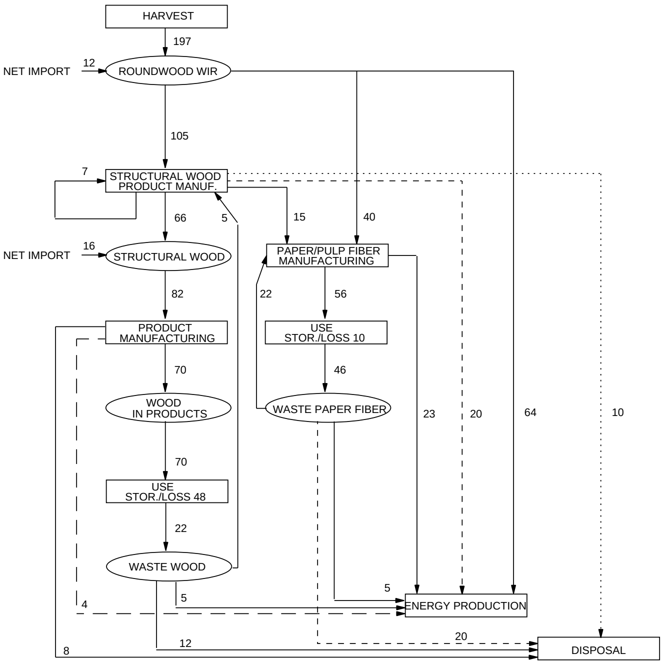

Figure 1.1: *Wood balance for Western Europe (figures indicate material flows in Mt pa; paper and pulp figures refer to the fiber content); 1992/1993; WIR= Wood In the Rough (all wood removed from forests and from trees outside the forests) [3]*

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 [3]. Peat production in Western Europe amounted to 17 Mt in 1995 (however the water content relating to this figure is not clear [5]). Some peat is used for heating, but a certain fraction is used for soil improvement (and is probably 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 [3]. One should add that the bioenergy use constitutes less than 2% of the total energy consumption in Western Europe. Its relative insignificance is probably the main reason for the high uncertainties.

Table 1.2: *Biofuel consumption in OECD Europe according to IEA statistics, 1993 [6]*

Country	Residential [PJ]	Industrial [PJ]	Total [PJ]
Solid bio	209	706	915
Biogas+liquids	0	0	0
Municipal waste	4	0	4
Industrial waste	14	83	97
Total	227	789	1016

Biomass and the Kyoto protocol

The definitions in the Kyoto protocol have consequences for the relevance of biomass strategies for GHG emission reduction. 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), banking of emission reductions is allowed beginning in the year 2000. 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” and can apply these reductions to achieving compliance with their reduction commitments. CDM will be further elaborated in at the next treaty meeting in Buenos Aires in November 1998. The current definitions suggest that certified emission reduction credits could be generated prevention of deforestation in tropical countries, a potential loophole in the protocol because the definition of the baseline is not clear [7]. However, this part of the biomass issues relating to the Kyoto protocol are not considered in this study. More important for this study is that stock changes related to products and waste disposal sites seems not to be accounted [8,9]. The significant net carbon storage due to the increasing Western European forest stock (see Table 1.1) cannot be accounted because these forests were planted before 1990.

These definitions are relevant for the carbon accounting and for biomass strategies. However, definitions are still not clear. Moreover, definitions may change in the period beyond 2012. For this reason, it is thought that some flexibility should be applied regarding the implications of the Kyoto negotiations for the current modeling study.

2. GENERAL MODEL STRUCTURE

2.1 An energy and materials model

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 [10,11]. MARKAL is an acronym for MARKet Allocation.
The model was originally developed for energy systems analysis. In recent years, the model has been extended for materials modeling. This resulted in a MARKAL Energy and Materials model. The model covers now the whole energy and materials life cycle ‘from cradle to grave’. Figure 2.1 shows the generic MARKAL energy and materials system model structure. Figure 2.2 focuses on the materials model structure.

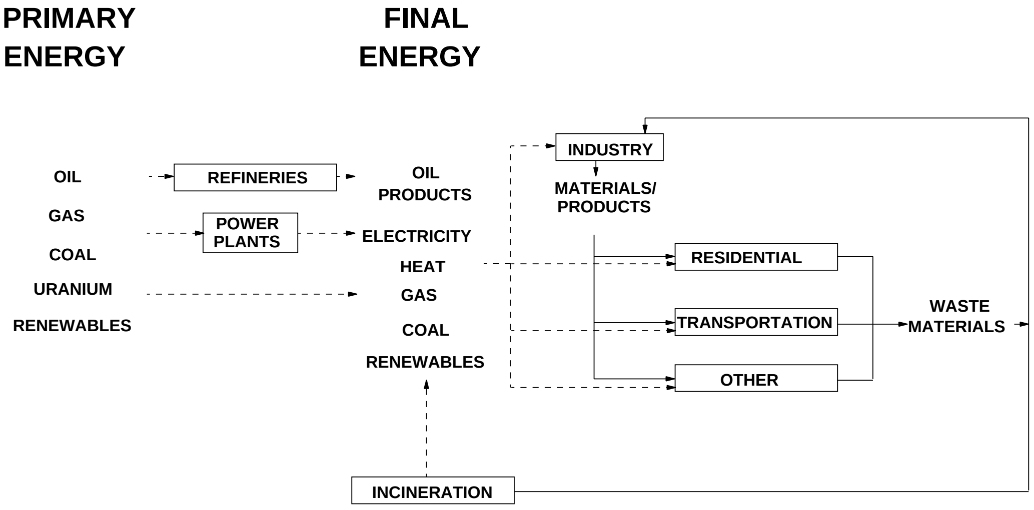

Figure 2.1: *Generic MARKAL energy and materials system structure*

A MARKAL energy and materials model is a representation of (part of) the economy of a region. The economy is modeled as a system, represented by processes and physical and monetary flows between these processes. These processes represent all activities that are necessary to satisfy a fixed demand for products and services. The database of processes and the constraints for individual processes and for the whole region are defined by the model user. Processes are characterised by their physical inputs and outputs of energy and material, by their costs, by operational specifications, by their environmental impacts and by constraints. Costs are both investments and operating and maintenance costs. Operational specifications are for instance availibility factors and lifetime. Constraints are determined by lower and upperbounds for the demand and supply for products and services, the maximum introduction rate of new processes, the availability of resources, environmental policy goals for energy use and for emissions etcetera. Constraints may concern the individual processes or groups of processes.
Many products and services are generated through a number of alternative (sets of) processes. A MARKAL energy and materials model easily contains a database of several

hundred processes, covering the whole life cycle for both energy and materials with GHG relevance.

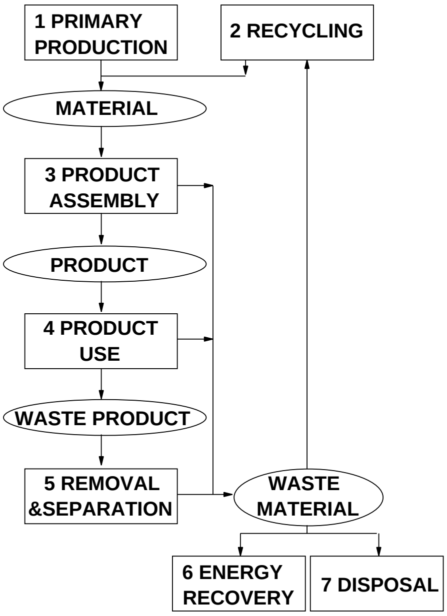

Figure 2.2: *Materials system model structure [12]*

A MARKAL energy and materials model calculates the least-cost system configuration which meets the fixed demand for products and services during this period and given a number of constraints. This system configuration is characterised by process activities and flows.

The model is a linear programming model based on perfect foresight, i.e. that the system configuration in year T is calculated taking into account technology development and energy demand after year T. Moreover, the model is dynamic, i.e. that not only the system configuration is described but also the transformation from one system configuration to another.

2.2 The Western European MARKAL MATTER 1.0 model

General

The extension of the MARKAL energy model for materials modeling resulted in the Western European MARKAL MATTER 1.0 model. The model covers the whole life cycle of energy and materials that are consumed in Western Europe. The model has been developed within the MATTER project (MATerials Technologies for GHG Emission Reduction) in order to study these strategies in more detail. MATTER is a joint project of 5 Dutch institutes in the framework of the National Research Programme on Global Air Pollution and Climate Change (NOP-MLK). The final model version was finished in the spring of 1998. The total development has required 20 man-years.

The model covers more than 25 energy carriers and 125 materials. More than 50 products represent the applications of these materials. 30 categories of waste materials are modeled. These materials are characterised by their physical characteristics and by their quality (e.g. steel scrap, demolition wood, polyethylene in municipal solid waste MSW).

Materials

The selection of materials is based on the analysis in [13]. Important (groups of) materials from a GHG emission point of view are disaggregated.

The level of detail for both materials and products is determined by their relevance from a greenhouse gas emission point of view. The general rule that has been applied is that all material flows with an upstream GHG emission that equals at least 0.1% of the total Western European GHG emission are separately modeled. (0.1% is equivalent to approximately 5 Mt CO2 equivalents per year.)

Both primary materials and waste materials are modeled. Most materials have waste material equivalents. However, some materials have not. Such materials are intermediates, materials which are consumed during their use phase (such as fertilizers) and waste materials which are irrelevant from a GHG emission point of view since they can neither be recycled (with significant GHG benefits) nor be used for energy recovery. Other materials have one or several waste material equivalents. Several waste materials have been modeled if the quality of the waste material limits the recycling potential. The waste quality depends on the product category where the product category is applied. For example, the bulk of the paper ends up in separately collected waste paper, while cardboard beverage packaging end up in MSW.

The waste material approach with different waste qualities allows easy modeling of waste cascades. It is generally no problem to use clean waste materials in processes that can handle mixed waste materials. However the other way around is only possible if expensive separation and upgrading processes are applied. An example of a cascade is a waste cascade for plastics (see figure 2.3). Three types of plastic waste are modeled: high quality waste (HQ), representing pure plastics that can be re-extruded to yield polymers. This type of waste arises from production residues and from e.g. industrial packaging. Mixed plastics, e.g. shredder residues, can only be recycled to high-grade polymers after separation.

They can however be downcycled (back-to-monomer recycling, i.c. pyrolysis and back-to-feedstock recycling, i.c. hydrogenation). Grate incineration and disposal are options for plastics in Municipal Solid Waste (MSW), e.g. food packaging. Upgrading of this waste type is possible, but requires extensive and expensive collection and separation.

Similar cascades are modeled for wood products. For steel and aluminium, scrap in MSW has been modeled separately. Recovery and upgrading costs for these scrap types are significantly higher than for other scrap types.

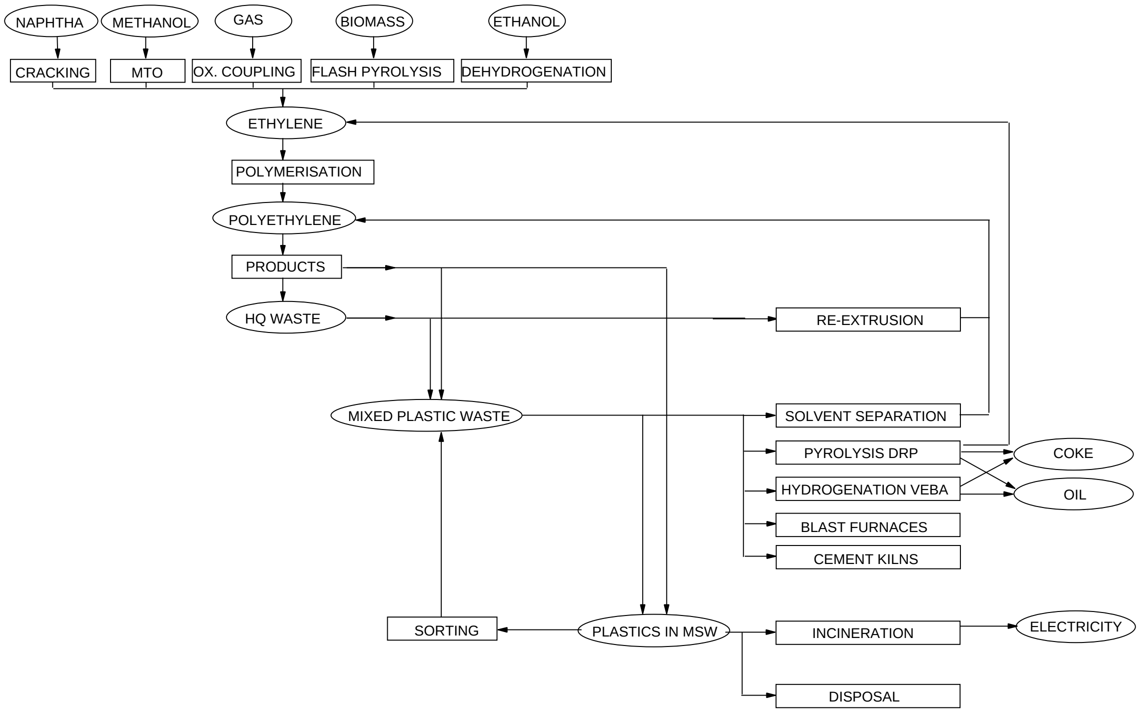

Figure 2.3: *Example of materials cycle modeling including a waste cascade for plastics (MTO = Methanol To Olefins process; ox. coupling=oxydative coupling; Deutsche Reifen Produktion; Veba = a company)*

Products

The list of product service categories has been developed from the aggregated list of 12 groups of product services that is discussed in [14]:

1. Residential buildings
2. Other buildings
3. Roads
4. Other infrastructure
5. Passenger cars
6. Other transportation equipment
7. Machinery and other production equipment
8. Furniture and interior decoration
9. Consumer durables
10. Packaging
11. Other non-durable products
12. Auxiliaries/residual demand

These product groups have been selected because the materials consumption - from a GHG emission point of view - is evenly distributed among these product groups. Moreover, the product life is significantly different, resulting in different system dynamics.

Greenhouse gas emissions

The Greenhouse gas (GHG) emissions under concern are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and perfluorocarbons (PFC). HFC emissions and CH4 emissions are not considered because they are of minor importance compared to the other GHG emissions. Other environmental impacts such as waste volumes or land requirements are also considered. All environmental impacts are endogenised in the process costs and the costs of energy and matter flows between processes. Therefore, environmental impacts are part of the optimising process.

Approximately one third of all GHG emissions can be attributed to the materials system []. Changes in material flows show significant impact on GHG emissions and GHG emission reduction costs.

The processes with the highest GHG emissions are generally the primary materials production (including upstream emissions in electricity production) and the waste management (recycling, energy recovery, and disposal). For this reason, these processes are modeled in more detail than the other ones. The other processes are relevant because they determine the materials production and waste management.

The GHG emissions related to imports into Western Europe and exports out of Western Europe are also accounted. Upstream emissions abroad ("rucksacks") are accounted for all net imports of energy and materials. For net exports of materials, emissions within Western Europe are deducted ("credits"). The GHG-value of net imports and exports has been based on the GHG impact of the current Western European production processes. With regard to the net imports and net exports, no changing emissions due to emission reduction policies are considered. Imports and exports are constrained by upper and lower bounds. A proper analysis will require a regionalized world model, beyond the scope of the current optimization.

Net imports and exports of finished products have not been considered. For net exports of waste products (such as trucks) and waste materials (such as steel scrap) to countries outside Western Europe, no GHG credits for foreign recycling are attributed to the system. It is difficult to estimate the GHG impact of waste handling, because it requires a detailed analysis of different materials chains. Moreover, MARKAL results where credits are attributed to waste exports result in export/accounting strategies to "solve" environmental problems. This effect is caused by the fact that emissions in primary materials production decline rapidly in a scenario with emission penalties. As a consequence, the emission benefits of recycling within the system decline. However the emission credits for exports remain the same. Consequently it becomes attractive to export waste to reduce the systems emissions. This is thought to be no sensible policy option. For this reason, no credits are accounted for waste exports.

Upstream emissions are in the MARKAL methodology transferred in the process chain through the increased shadow prices' of energy, materials and products.

System boundaries

System boundaries in this study are based on the end-use of energy and materials by Western European consumers in the period 1990-2070. Model results for the period beyond 2050 are not reported because of potential effects of the system boundary on the system configuration. Waste materials that are released beyond the time horizon may affect the modeling results in the last two decades.

Final demand for Product and Material Services

In order to find key demand parameters for sensitivity analyses, the impact of (groups) of demand categories on the total GHG emissions in 2030 has been analysed. This is not a straightforward calculation in MARKAL, because the model provides only a value for the emissions on a systems level. The model does not produce an emission value for individual products or demand categories. As a consequence, a method has been developed to estimate this emission. The result is shown in the last column of Table 2.1. These emission values have been obtained by calculation of the difference in GHG emissions between two runs without any GHG emission constraints (base-case runs). One run encompassed all demand categories as indicated in Table 2.1. In the other run, the end use of one (group of) demand categories was set to zero. The difference in GHG emission between both runs represents the contribution of this individual demand category to the total GHG emission.

One should add that this is a measure for the *marginal* impacts. The totals for all demand categories, treated in such a way, will not add up to the total emissions. For example, the marginal electricity production (the most costly option that is applied to satisfy total electricity demand) may be based on renewables with zero CO_2-emissions, while a significant fraction of the total electricity production is based on coal (with high CO_2 emissions). Each time one demand category is set to zero and electricity demand decreases, the same renewable energy based electricity production will be excluded in the cost minimisation approach (with limited GHG consequences). As a consequence, the total impact for all demand categories, calculated according to this method, can not equal the total emission for the whole system.

The results show the importance of the categories buildings (code C0..Rk) and transportation equipment (T0..T2). Their importance is so high because these end use parameters also determine the direct energy use (heating and cooling, and transportation fuel demand, respectively). Assuming that 15-20% of the CO_2 equivalents for buildings and for transportation can be allocated to materials, the total impact of materials is 1200-1300 Mt CO_2 equivalents. For some product groups such as infrastructure the net impact is very small due to the carbon storage effect (i.c. bitumen storage in asphalt). The results indicate that the transportation demand and the building demand are key parameters for sensitivity analyses.

Greenhouse gas emissions reduction strategies

An array of technological measures can be applied to reduce GHG emissions, ranging from fuel shifts in power generation and renewable energy sources to energy savings or shifts in materials use. Different reduction strategies influence each others efficiency. If for example the electricity production becomes less CO_2 intensive due to introduction of renewables, electricity production in waste incineration plants becomes less attractive for GHG emission reduction. As a consequence of such interactions, the assessment of the potential and the cost-effectiveness of reduction strategies requires an integrated approach that takes the whole energy and materials system into account. MARKAL MATTER is especially suited to study such interactions.
Chapter 3 discusses several energy and materials strategies to reduce greenhouse gas emissions.

Table 2.1: *Product service demand trends in the Western European MARKAL model (index)*

Code	Demand category	Unit	1990	2020	2050	Contribution 2030 [Mt CO_2 equiv.]
C0/1/2/3	Service sector buildings	[m2]	100	147	164	629
R1/5/6/8	Single family dwellings (2 types)	[m2]	100	122	128	
R2/4/7	Multi family dwellings	[m2]	100	160	228	
RJ	Industrial/agricultural buildings type 1	[m2]	100	109	119	
RK	Industrial/agricultural buildings type 2	[m2]	100	108	116	
P1	Beverages, carbonated	[10^9 litres]	100	117	131	127
P2	Beverages, non-carbonated	[10^9 litres]	100	120	139	
P3	Dairy products, no milk	[10^9 litres]	100	132	163	
P4	Wet food	[10^9 litres]	100	152	204	
P5	Dry food, non-susceptible	[10^9 litres]	100	112	125	
P6	Dry food, susceptible	[10^9 litres]	100	152	204	
P7	Non-food liquids	[10^9 litres]	100	151	203	
P8	Dry non-food	[10^9 litres]	100	111	123	
P9	Carrier bags	[10^9 bags]	100	115	130	
PA	Industrial bags	[Mt]	100	157	213	
PB	Transport packaging	[10^9 litres]	100	142	185	
PC	Pallet wrapping	[10^9 trip units]	100	175	250	
TU	Pallets	[10^9 pieces]	100	125	150	
T0	Passenger car (2 types)	[pieces]	100	144	193	1207
T1	Van	[pieces]	100	123	131	
T2	Truck	[pieces]	100	138	170	
IA	Residual aluminium	[Mt]	100	134	150	215
IB	Residual bricks	[Mt]	100	50	50	
IC	Residual chlorine	[Mt]	100	71	71	
ID	Residual glass	[Mt]	100	267	300	
IK	Residual sodium chloride	[Mt]	100	106	112	
IM	Machinery	[pieces]	100	110	119	
IS	Residual petrochemicals	[Mt]	100	155	175	
IZ	Capital equipment	[pieces]	100	115	130	
IR	Fertilizers	[Mt]	100	120	120	150
IV	Residual paper	[Mt]	100	186	200	53
N1	Non Energy Use: Lubricants+Bitumen	[PJ]	100	100	100	7
CG	Desks	[pieces]	100	134	175	33
JS	Pipes and ducts	[Mt PVC equiv.]	100	175	250	
JT	Window frames	[10^9 frames]	100	119	138	
JV	Cellars	[10^8 m2]	100	119	137	
RM	Outside wall cladding	[10^9 m2]	100	138	175	
RV	Floor cladding	[10^8 m2]	100	125	150	
RZ	Interior wall cladding	[10^9 m2]	100	125	150	
IU	Residual cement clinker	[Mt]	100	100	100	49
IX	Residual wood	[Mt]	100	138	144	
JR	Electr./telecomm. wire	[Mt copper wire equiv.]	100	121	143	203
KA	Industrial pressure vessels	[pieces]	100	100	100	
KB	Nuts, bolts, nails etc.	Mt steel equiv.]	100	119	138	
KC	Pipelines	[Mt steel equiv.]	100	138	175	
RP	Furniture (chests)	[pieces]	100	113	125	113
RQ	Appliance materials use dummy	[pieces]	100	125	150	
RU	Textiles	[Mt]	100	125	150	
RX	Compost	[Mt]	100	100	100	
TH	High volume roads	[m2]	100	137	175	20
TL	Low volume roads	[m2]	100	113	118	
TR	Railway tracks	[km]	100	121	143	
TS	Waterworks	[Mt THW equivalents]	100	100	100	

3. IMPROVEMENT OPTIONS

A large number of improvement options to reduce greenhouse gas emissions (GHG's) exist in the energy system and the materials system Significant greenhouse gas emissiion reduction will imply a significant CO_2 emission reduction. A number of strategies (groups of options with similar characteristics) have been suggested in order to mitigate CO_2 emissions. They are presented in Table 3.1. For reducing other greenhouse gases, the emphasis is on process improvements, end-of-pipe technology and on substitution [15].

Some characteristics of the emission reduction strategies for CO_2 are also summarised in Table 3.1. Cost estimates, and the potential contribution to the reduction of total Western European emissions is shown. The column 'strategy characterisation' indicates whether the strategy can be characterised as end-of-pipe, process integration, substitution or prevention.

Table 3.1: *Characteristics of CO_2 emission reduction strategies for Western Europe, 1st half 21st century, compared to autonomous development [16,17]*

	Cost [ECU/t CO_2]	Strategy characterisation	Potential [% of CO_2 emission]
Renewables	0-1000	Substitution/ prevention	10-25
Nuclear energy	0-100	Substitution	10-25
CO_2 capture and disposal	0-100	End-of-pipe	10-25
Fossil fuel switch	100-500	Substitution	10-20
Enhancing forestry	100-1000	End-of-pipe	5-10
Energy conservation/ increased efficiency	-100-100	Prevention	10-25
Waste heat utilisation	100-1000	Process integration	5-10
Materials recycling/reuse	?	Process integration	?
Dematerialisation/substitution	?	Prevention/process integration	?

Energy and materials strategies
The preliminary assessment in Table 3.1 indicates that a mix of strategies must be applied for emission reduction in order to achieve a significant reduction. The total for all strategies exceeds 100%. The interaction of options will reduce the potentials for emission reduction.

The characterisation prevention/process integration/substitution/end-of-pipe indicates the quality of the measure. Prevention is generally most attractive, because this type has generally positive environmental side-effects and shows often zero or negative costs. Process integration reduces the emissions, but increases the 'lock-in' of the technological pathway, which may not be sustainable. The side effects of both energy and materials substitution are unclear on forehand and require further analysis. The costs of substitution depend on the application. End-of-pipe finally reduces the environmental impact, but results often in a shift of environmental problems, e.g. from gaseous emissions to additional solid waste. This group of options is generally costly. End-of-pipe solutions may work for non-CO_2 GHGs which can be converted into less harmful compounds. CO_2 conversion seems no viable strategy. In fact, the substance is generated as a waste product of energy production. Conversion back into its original state will require the same amount or even a higher amount of energy. However underground CO_2 storage is a viable option (see Chapter 5). End-of pipe strategies are attractive because they are comparatively easily implemented because they do not affect the economic and technological system configuration.

Materials strategies

Regarding options that affect the materials system, there is still considerable uncertainty regarding their attractiveness, their potential and their long term consequences. Again, interactions complicate the analysis. The interactions are much more complicated than for energy strategies because of the recycling loop and because of the time lag between materials consumption and waste release beyond the product life.

Options to reduce greenhouse gas emissions in the materials system can be divided in four groups [**Error! Bookmark not defined.**].

Energy and materials efficiency
1 Increased energy efficiency: alternative materials production processes, based on new technology
2 Increased materials efficiency: increased materials quality
3 Increased materials efficiency: product redesign
Waste handling
4 New recycling technologies
5 Waste separation and product reuse
6 New energy recovery technologies
Substitution effects
7 Substitution of energy carriers
8 Substitution of raw materials for materials production
9 Substitution of materials
End-of-pipe solutions
10 End-of-pipe technology

Energy and materials efficiency

An increase in the energy and materials efficiency can be achieved by materials production processes which are more energy efficient, by an increase in materials quality and by product re-design. The meaning of re-design in the sense of the MARKAL energy and materials model is limited to re-design that is based on the same materials mix and design for disassembly. The re-design of products shows a strong relation with increased materials quality, product re-use and materials substitution. These strategies will generally result in product re-design.

Waste handling

Recycling rates are for most materials already fairly high, compared to the amount of waste material that is released. Existing recycling technologies are modeled for steel, aluminium, copper, paper, lubricants, asphalt and glass. Plastics are the only major materials group where new conversion processes can increase recycling rates and decrease GHG emissions.

Waste separation has been modeled for used cars (disassembly) and for plastics, paper, steel, and aluminium from MSW. Re-use has been modeled for a number of packagings and for one building type (see Table 2.4).

A number of new energy recovery technologies for waste materials are included in the model. They cover the whole spectrum from anaerobic digestion to gasification, pyrolysis, and conventional grate incineration. Co-combustion has been modeled for plastics in blast furnaces and for tyres, wood, and plastics in cement kilns. For wood waste, a number of dedicated and co-combustion options for electricity production have been included (see [18] for a data description).

Substitution effects

Substitution of energy carriers in primary materials production has already been included in the energy system model. Combined heat and power generation (CHP) for steam generation, substitution of coal and oil by natural gas, by renewable energy, and by nuclear energy are examples of such substitutions.

Substitution of raw materials for materials production can be split into substitution of fossil fuel feedstocks and substitution of inorganic resources. Substitution of materials has been modeled for a number of products. The types of materials that are competing depend on the product group. Materials substitution results generally in new product design.

From a modeling point of view, the substitution is characterised by discrete product alternatives. For example, a passenger car designed in steel competes with an “aluminium” passenger car and a .”plastic” passenger car. The latter two are designed for maximum steel substitution. The product alternatives represent extremes. For many products, data for competing product designs are derived from LCA studies.

This generic list of strategies serves as starting point for development of biomass strategies in Chapter 4.

4. THE MODEL STRUCTURE FOR BIOMASS

4.1 Introduction

Technologies which use biomass as input will be discussed in more detail in this chapter. First general biomass strategies for GHG emission reduction will be discussed in qualitative terms (Section 4.2). Next, the model input parameters will be discussed. The discussion is split into four sections according to different stages of the product/materials life cycle:

1. Biomass supply (Section 4.3)
2. Biomass conversion (Section 4.4)
3. Biomaterials use (Section 4.5)
4. Waste treatment (Section 4.6)

The model input parameters regarding the biomass supply, conversion and use options are presented in tables. The tables shown in the sections 4.3 till 4.6 inclusive should be interpreted taking into account the following guidelines and definitions:

Inputs:	relate to the defined inputs or outputs
Costs:	relate to the defined inputs or outputs can be divided in investments costs and O&M (operating and maintenance) costs
Investment costs	are the total costs of 1 unit of installed capacity include all costs during construction as well as the interest charges include all costs except the costs of the input products
O&M costs	can be split in fixed and variable operating and maintenance (O&M) costs variable O&M costs are annual operating and maintenance costs which are proportional to the production activity. fixed O&M costs are annual operating and maintenance costs associated with the installed capacity and charged regardless of utilization include all costs except the costs of the input products
Bounds	relate to the installed capacity may be lower or upperbounds
Life	is the time period capacity is utilized.
Availibility	The total annual availibility of a process. It should account for both forced and scheduled outages during the entire year.

4.2 Biomass strategies

The interaction of bioenergy and biomaterial applications is shown in Figure 4.1. Due to the interactions, a split of energy and materials is difficult and can potentially result in double counting of biomass flows. In order to prevent double counting, the flows across the system boundary are accounted (biomass removals and biomass imports). In the following discussion, the term “bioenergy” includes all biomass which is directly used for energy production. Residues and cascade use of biomass is allocated to the category “biomaterials”. Biomaterials include the traditional applications like pulp and paper, building materials, and natural fibers. New applications like biomass feedstocks are also included in the category biomaterials. The terms ‘bioenergy” and “biomaterials” refer to the biomass input into the system (grown/collected within the system).

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

- substitution of fossil fuels for energy and feedstocks
- substitution of CO_2-intensive materials by biomaterials
- substitution of non-renewable timber by renewable timber
- carbon storage in forests, products, and disposal sites
- increased recycling/reuse of biomaterials
- increased energy recovery from waste biomass

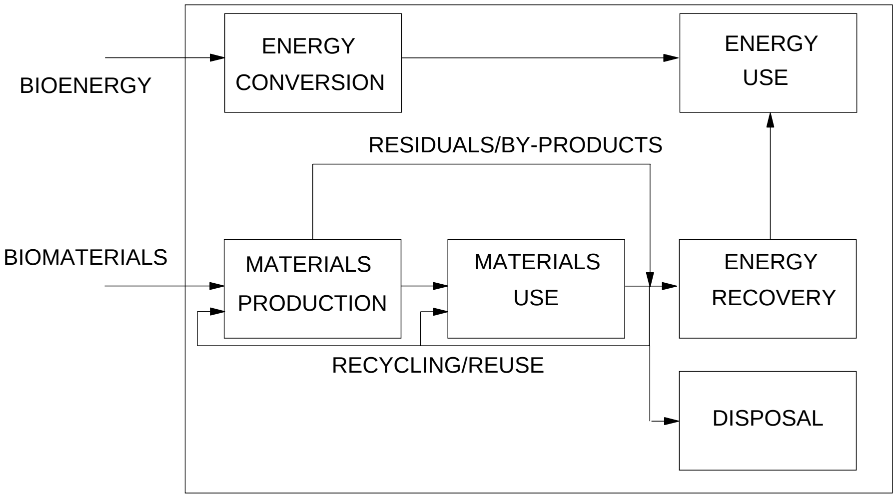

Figure 4.1: *Definition of bioenergy and biomaterials*

4.3 Biomass supply

Biomass can be obtained from a number of sources:

- Residual biomass from wood production
- Residues from agricultural crops
- Residual biomass in MSW, sewage sludge, manure
- Biomass crops on agricultural land
- Biomass from forests
- Biomass imports from other regions

Residues constitute momentarily already an important biomass resource. Black liquor is a by-product from chemical pulping that is used for energy recovery. Important amounts of logging residues, forest thinnings, and sawing mill residues, are used for energy recovery by small industries and by households. Agricultural residues like straw are in some countries applied for energy recovery. Apart from the processing residues, post-consumer waste contains significant amounts of biomass. Paper and wood constitute an important part of the energy content of municipal solid waste (MSW). One quarter of the MSW is combusted with energy recovery. Biogas is recovered from waste disposal sites and in special kitchen waste digesting installations. Sewage sludge and manure are nowadays mainly used as fertilizer, but regional surpluses can be used for other purposes. Energy recovery from waste biomass can be further increased, but the costs of such a strategy are generally high because of the high biomass collection costs [19].

Apart from residues, dedicated production from forests and on agricultural land are two other biomass sources. Forests are already widely used for biomass production, but a considerable potential exists for additional recovery. Agricultural bioenergy and biomaterials crops are currently of limited relevance. However the potential is much higher than the potential for additional residue recycling [20]. Additional biomass use will result in additional waste that can be used for energy recovery. The following analysis will especially focus on the use of dedicated biomass crops. Biomass imports from other regions have not been considered in the calculations because of the speculative nature of import potentials in a world that focuses on greenhouse gas emission reduction. Moreover, imports are prone to result in new environmental problems abroad, if additional land is taken into production.

Forestry as biomass source

Approximately 200 Mt wood is annually harvested in Western Europe. The latest European Timber Trend scenario study concludes that until the year 2020, wood harvests in Western Europe will remain below 70% of the annual regrowth [21]. This implies a surplus of 100 Mt wood per year. Apart from additional wood harvesting, the wood cascade can be further improved. In a cascade, the waste material of one process (of lower quality than the original material) can be used as input material for other processes.

Cascading is currently already widely practiced in the biomass industry. The production of sawn wood and pulp from roundwood results in considerable amounts of wood waste. A significant amount of this waste is used for production of particle board. Significant amounts of wood residues are used for pulp production. Both wood processing residues and pulping residues are used for energy production (see Figure 1.1).

Agriculture as biomass source

In the next decades, a significant fraction of the Western European agricultural land area will become available due to the decreasing food production subsidies and the increasing product yields. However, the extent of land that will become available for energy production will depend on future imports of food, on the future diet, and on the extent of other land claims like protected areas and construction. Scenario studies for Western Europe suggest a land availablity for energy crops of 200 to 250 thousand km^2 [22]. This land area is for 16% located in the Northern region (Denmark, Finland, Norway and Sweden), for 56% in the Middle region (Austria, Belgium, France, Germany, Ireland, Luxembourg, the Netherlands, Switzerland and the UK), and for 28% in the Southern region (Greece, Italy, Portugal and Spain).

Biomass yields differ in these regions because the climate differs: the amount of daylight, the rainfall and the temperature influence the growth. Table 4.1 lists the estimated attainable yields for important agricultural crops in the two largest regions. Because of similar biomass yields and relative insignificance, the Northern agricultural land is aggregated with the Middle region in the following analysis. The data in Table 4.1 refer to the whole aboveground plant mass and represent averages: e.g. in Sweden, biomass yields in forests range from 10 t dm/ha/year for willow plantations in the Southern part to 1.5 t dm/ha/year in the forests of the North. For the Southern region, the yields are averages that consider the limited water availability. In case the water supply poses no problem, the yields can be up to 100% higher. However, it is assumed that such prime land is primarily destined for food production. Coupling of the land availability and the yields in Table 4.1, 500 Mt biomass can be produced per year on the surplus agricultural land. The potential may significantly increase in future decades due to the increasing product yields, based on bioengineering and improved land management. However the relevance of such improvements is unclear (see e.g. [23]). Increasing GHG concentrations can also influence future biomass production potentials. CO_2 concentrations and increasing temperatures can also increase biomass yields by 10-20% [24]. However yields may regionally decrease by 5-10% due to a decreased precipitation due to climate change. The net effect of climate change is thought to be less relevant than the changes in productivity due to improved technology. As a consequence, these changes have not been considered in the calculations. However, these figures can serve as illustration for the accuracy of yield figures.

Surplus agricultural land is probably the least productive land, and the impact of pests on dedicated large-scale crops may be substantial. As a consequence, high growth rates for biomass yields from literature (e.g. [25]) have not been considered in the calculations.

Table 4.1: *Attainable biomass yields on agricultural land (fibre+seeds) [26]*

	Middle [t dmha/year]	South [t dm/ha/year]
Sugar beet	18	10.4
Rape seed	7.5	-
Sweet sorghum	-	10.9
Eucalyptus	-	22.9
Miscanthus	10.0	10.9
Wheat	11.5	9.6
Poplar	9.0	-

In conclusion, the total biomass potential for Western Europe (primary biomass input) is at most 800 Mt dry matter per year. The energy content of biomass (lower heating value LHV) ranges from 15 GJ/t for straw to 28 GJ/t for rape seed [27]. Because water must be evaporated, the energy content is to some extent influenced by the water content. The energy content of fresh biomass may be up to 20% lower than for dried harvested biomass (expressed per tonne oven dry matter). The total biomass potential represents an energy equivalent of approximately 15 EJ per year, compared to an actual Western European primary energy consumption of 55 EJ per year, i.e. 27% of the primary energy consumption [28].

Model inputs for biomass supply

Residues

A number of categories of residues are considered in the calculations that are listed in Table 4.2.

Table 4.2: *Model input parameters regarding residue availability*

	Availability 2030 [PJ/year]	Cost [ECU/GJ]
Straw	375	1
Forest thinnings low cost	250	5
Forest thinnings medium cost	250	7
Forest thinnings high cost	250	16

Forests

Wood availability from forests is split into roundwood from the Northern region (maximum 150 Mt/year) and roundwood from the middle region (maximum 150 Mt per year). Production costs are in both cases assumed to be 100 ECU/t roundwood (including hauling to the road side). No further split has been applied, e.g. for hardwood and softwood. This is a modeling issue for BRED.

Agricultural land

Agricultural land availability is in the current model split into a Southern European region and a Middle and Northern European region. Land availability is modeled in a two-step supply curve. The first 15 million hectares is available at a price of 250 ECU/ha/year. More land is available at a price of 750 ECU/ha/year. Concerning land use, total land availability increases from 5 million hectares in 1990 to 22 million hectares in 2010 and stabilizes afterwards. This land availability is split into 10 million hectares in the Southern region and 12 million hectares in the Middle and Northern region.

Imports

Imports have been considered for sawn timber (500 ECU/t) and tropical timber (250 ECU/t).

Agricultural crops

Agricultural land can be used in several ways:

- production of sugar/starch crops;
- production of lignocellulose crops;
- production of lipids;
- production of oil crops;
- production of chemical precursors;
- production of timber;
- carbon storage in new forests.

The selection of crops focused on high yield crops in all categories (see table 4.3). 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. [29]).

Table 4.3: *List of biomass production processes in MARKAL*

BP1	Biomass growing rapeseed Middle
BP2	Biomass growing wheat Middle
BP3	Biomass growing sugarbeet Middle
BP4	Biomass growing miscanthus Middle
BP5	Biomass growing poplar Middle
BP6	Biomass growing algae Middle
BP7	Timber quality wood production Middle
BP8	Marigold flower Middle
BP9	Timber quality wood Middle ex. forests
BPA	Biomass/growing sorghum South
BPB	Biomass/growing wheat South
BPC	Biomass/growing sugarbeet South
BPD	Biomass/growing miscanthus South
BPE	Biomass/growing eucalyptus South
BPM	Timber quality wood production North
BPN	Carbon storage new forest areas

The model inputs for the biomass supply production processes are shown in the tables 4.4 till 4.18 inclusive. The tables should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Table 4.4: *Biomass growing rapeseed Middle region BP1*

	Units	1990	2030	2050
Input				
- Diesel	[GJ]	0.04	0.04	0.025
- N-fertilizer	[t NH_3-equiv.]	0.002	0.002	0.002
- Agricultural land	[0.001 km^2]	0.1	0.1	0.1
Output				
- Rapeseed (excl. straw)	[GJ]	1.0	1.0	1.0
- Straw	[GJ]	1.0	1.0	1.0
- Fixed costs	[ECU 95/GJ rapeseed]	7.5	7.5	7.5
- Variable	[ECU 95/GJ rapeseed]	7.5	7.5	7.5
Availability	[-]	1	1	1
Life	[years]	10		
Bound Low	[PJ rapeseed]	0.01	0.05	0.07
Bound Up	[PJ rapeseed]	100	1000	1500

Table 4.5: *Biomass growing wheat Middle region BP2*

	Units	1990	2030	2050
Input				
- Diesel	[GJ]	0.06	0.06	0.06
- N-fertilizer	[t NH_3-equiv]	0.0017	0.0017	0.0017
- Agricultural land	[0.001 km^2]	0.09	0.09	0.09
Output				
- Wheat	[GJ]	1.0	1.0	1.0
- Straw	[GJ]	0.52	0.5	0.48
- Fixed costs	[ECU 95/GJ wheat]	5	5	5
- Variable costs	[ECU 95/GJ wheat]	20	20	20
Availability	[-]	1	1	1
Life	[years]	10		
Bound Low	[PJ wheat]	0.01	0.05	0.07
Bound Up	[PJ wheat]	100	500	750

Table 4.6: *Biomass growing sugarbeet Middle region BP3*

	Units	1990	2010	2050
Input				
- Diesel	[GJ]	0.06	0.06	0.06
- N-fertilizer	[t NH_3-equiv.]	0.0044	0.0044	0.0044
- Agricultural land	[0.001 km^2]	0.35	0.3	0.3
Output				
- Sugarbeet	[GJ]	1.0	1.0	1.0
- Fixed costs	[ECU 95/GJ sugarbeet]	4	4	4
- Variable costs	[ECU 95/GJ sugarbeet]	4	4	4
Availability	[-]	1	1	1
Life	[years]	10		
Bound Low	[PJ sugarbeet]	0.01	0.03	0.07
Bound Up	[PJ sugarbeet]	100	500	1500

Table 4.7: *Biomass growing miscanthus Middle region BP4*

	Units	1990	2010	2020	2050
Input					
- Diesel	[GJ]	0.03	0.03	0.03	0.03
- N-fertilizer	[t NH_3-equiv.]	0.0003	0.0003	0.0003	0.0003
- Agricultural land	[0.001 km^2]	0.058	0.04	0.035	0.035
Output					
- Straw	[GJ]	1.0	1.0	1.0	1.0
- Variable costs	[ECU 95/GJ straw]	2.5	2.5	2.5	2.5
Availability	[-]	1	1	1	1
Life	[years]	10			
Bound Low	[PJ straw]	0.01	0.03	0.04	0.07
Bound Up	[PJ straw]	100	2500	3500	8500

Table 4.8: *Biomass growing poplar Middle region BP5*

	Units	1990	2010	2030	2050
Input					
- Diesel	[GJ]	0.04	0.04	0.04	0.04
- N-fertilizer	[t NH_3-equiv.]	0.00074	0.00074	0.00074	0.00074
- Agricultural land	[0.001 km^2]	0.058	0.045	0.045	0.045
Output					
- Energy wood (< 5 cm)	[GJ]	1.0	1.0	1.0	1.0
- Variable costs	[ECU 95/GJ]	2.5	2.5	2.5	2.5
Availability	[-]	1	1	1	1
Life	[years]	10			
Bound Low	[PJ output]	0.01	0.03	0.04	0.07
Bound Up	[PJ output]	100	2500	3500	8500

Table 4.9: *Biomass growing algae Middle region (available in 2000) BP6*

	Units	2000	2010	2030	2050
Input					
- N-fertilizer	[t NH_3-equiv.]	0.00015	0.00015	0.00015	0.00015
- Electricity	[GJ]	0.20	0.20	0.20	0.20
- Agricultural land	[0.001 km^2]	0.024	0.012	0.012	0.012
Output					
- Lipids from algae	[GJ]	1.0	1.0	1.0	1.0
- Natural gas	[GJ]	0.48	0.48	0.48	0.48
Investment costs	[ECU 95/GJ lipids]	250	250	250	250
- Fixed costs	[ECU 95/GJ lipids]	13	13	13	13
- Variable costs	[ECU 95/GJ lipids]	0.5	0.5	0.5	0.5
Availability	[-]	1	1	1	1
Life	[years]	25			
Bound Low	[PJ lipids]	0.01	0.03	0.04	0.07
Bound Up	[PJ lipids]	100	400	750	1450

Table 4.10: *Timber quality wood Middle region BP7*

	Units	1990	2050
Input			
- Diesel	[GJ]	0.2	0.2
- Agricultural land	[0.001 km^2]	2.0	2.0
Output			
- Timber quality roundwood (15 % H_2O)	[ton]	1.0	1.0
- Variable costs	[ECU 95/ton output]	100	100
Availability	[-]	1	1
Bound Low	[Mton output]	0.01	0.07
Bound Up	[Mton output]	150	150

Table 4.11: *Marigold flower Middle region (available in 2000) BP8*

	Units	2000	2050
Input			
- Diesel	[GJ]	8.0	8.0
- Agricultural land	[0.001 km^2]	20	20
- Electricity	[GJ]	1.0	1.0
- N-fertilizer	[t NH_3-equiv.]	0.2	0.2
Output			
- Marigold flower oil	[t]	1.0	1.0
- Straw	[GJ]	105	105
Investment costs	[ECU 95/t oil]	1000	1000
- Fixed costs	[ECU 95/t oil]	100	100
- Variable costs	[ECU 95/t oil]	150	150
Availability	[-]	1	1

Table 4.12: *Timber quality wood Middle region existing forests BP9*

	Units	2000	2050
Input			
- Diesel	[GJ]	0.2	0.2
Output			
- Timber quality roundwood (15 % H_2O)	[t]	1.0	1.0
- Variable costs	[ECU 95/t rwd]	100	100
Availability	[-]	1	1
Bound low	[Mt roundwood]	0.05	0.05
Bound up	[Mt roundwood]	150	150

Table 4.13*: Biomass/growing sweet sorghum Southern region BPA*

	Units	1990	2010	2050
Input				
- Diesel	[GJ]	0.04	0.04	0.04
- Agricultural land	[0.001 km^2]	0.03	0.025	0.025
- N-fertilizer	[t NH_3-equiv.]	0.0005	0.0005	0.0005
Output				
- Sweet sorghum (whole plant)	[GJ]	1.0	1.0	1.0
- Variable costs	[ECU 95/GJ sorghum]	2	2	2
Availability	[-]	1	1	1
Life	years	10		
Bound low	[PJ sorghum]	0.01	0.03	0.07
Bound up	[PJ sorghum]	100	550	1600

Table 4.14: *Biomass/growing wheat Southern region BPB*

	Units	1990	2010	2030	2050
Input					
- Diesel	[GJ]	0.06	0.06	0.06	0.06
- Agricultural land	[0.001 km^2]	0.06	0.053	0.053	0.053
- N-fertilizer	[t NH_3-equiv.]	0.0017	0.0017	0.0017	0.0017
Output					
- Wheat (excl. straw)	[GJ]	1.0	1.0		1.0
- Straw	[GJ]	0.52	0.48	0.45	0.45
- Fixed costs	[ECU 95/GJ wheat]	5	5	5	5
- Variable costs	[ECU 95/ GJ wheat]	10	10	10	10
Availability	[-]	1	1	1	1
Life	[years]	30			
Bound low	[PJ wheat]	0.01	0.03	0.05	0.07
Bound up	[PJ] wheat]	100	300	550	800

Table 4.15: *Biomass/growing sugarbeet Southern region BPC*

	Units	1990	2010	2030	2050
Input					
- Diesel	[GJ]	0.05	0.05	0.05	0.05
- Agricultural land	[0.001 km^2]	0.058	0.05	0.05	0.05
- N-fertilizer	[t NH_3-equiv.]	0.0044	0.0044	0.0044	0.0044
Output					
- Sugar beet (whole plant)	[GJ]	1.0	1.0	1.0	1.0
- Fixed costs	[ECU 95/GJ wheat]	4	4	4	4
- Variable costs	[ECU 95/ GJ wheat]	4	4	4	4
Availability	[-]	1	1	1	1
Life	[years]	10			
Bound low	[PJ sugarbeet]	0.01	0.03	0.05	0.07
Bound up	[PJ sugarbeet]	100	550	1100	1600

Table 4.16: *Biomass growing miscanthus Southern region BPD*

	Units	1990	2010	2030	2050
Input					
- Diesel	[GJ]	0.03	0.03	0.03	0.03
- N-fertilizer	[t NH_3-equiv.]	0.0003	0.0003	0.0003	0.0003
- Agricultural land	[0.001 km^2]	0.058	0.035	0.033	0.030
Output					
- Straw	[GJ]	1.0	1.0	1.0	1.0
- Variable costs	[ECU 95/GJ straw]	2.5	2.5	2.5	2.5
Availability	[-]	1	1	1	1
Life	[years]	10			
Bound Low	[PJ output]	0.01	0.03	0.05	0.07
Bound Up	[PJ output]	100	2500	4500	8500

Table 4.17: *Biomass growing Eucalyptus Southern region BPE*

	Units	1990	2030	2050
Input				
- Diesel	[GJ]	0.04	0.04	0.04
- N-fertilizer	[t NH_3-equiv.]	0.001	0.001	0.001
- Agricultural land	[0.001 km^2]	0.027	0.027	0.027
Output				
- Energy Wood (>5 cm)	[GJ]	1.0	1.0	1.0
- Fixed costs	[ECU 95/GJ]	2	2	2
- Variable costs	[ECU 95/GJ]	1	1	1
Availability	[-]	1	1	1
Life	[years]	10		
Bound Low	[PJ output]	0.01	0.04	0.07
Bound Up	[PJ output]	100	3500	8500

Table 4.18: *Timber quality wood Northern region BPM*

	Units	1990	2050
Input			
- Diesel	[GJ]	0.2	0.2
Output			
- Timber quality round wood (15 % H_2O)	[ton]	1.0	1.0
- Variable costs	[ECU 95/ton]	100	100
Availability	[-]	1	1
Life	[years]	10	
Bound Low	[Mt output]	0.01	0.07
Bound Up	[Mt output]	150	150

Land use change

Land use change refers to the carbon storage is soils and trees due to conversion of agricultural land into forested land. The costs are accounted for by land costs, plantation costs, and carbon storage potentials. Costs and potentials will depend on the future land use (production forests or carbon storage sec). The carbon storage option seems more likely, if the surplus wood situation in Europe is considered. Assuming 50 years of carbon storage, 5-10 t CO_2 storage per ha per year, 1000 ECU/ha/year, costs are 100-200 ECU/t CO_2. This measure is not cost-effective within the framework of the Kyoto agreement. One must however emphasize that new forests can provide major secondary benefits. For example wood production, recreation, and erosion control are examples of secondary benefits. The distribution of forest management costs among these categories can reduce emission reduction costs. In this study, the costs are completely allocated to carbon storage because really large scale development of new forests will reduce the value of secondary benefits.

Table 4.19: *Carbon storage new forest areas BPN*

	Units	TID	1990	2050
Input				
- Agricultural land	[0.001 km^2]		10	10
Output				
- CO_2 storage	[t/year]		8.0	8.0
Investment costs	[ECU 95]		2000	2000
- Fixed costs	[ECU 95]		20	20
Availability	[-]		1	1
Life	[years]	80		

4.4 Biomass conversion

Data for reference processes (the competing fossil fuel based process chains for biomass alternatives) are based on [30,31]. A list of biomass technologies that has been considered and the data sources that have been used to characterize the technologies is shown in Table 4.20. The following sections 4.4.1-4.4.5 provide an overview of the model input parameters. The processes are split into five types of biomass conversion technologies, based on the product characteristics:

- production of liquid fuels/petrochemical feedstocks
- production of petrochemical intermediates
- production of solid fuels
- production of electricity
- production of building and construction materials

Data sources are indicated in Table 4.20 for processes that are not discussed in detail.

Table 4.20: *Biomass conversion technologies and data sources*

1 Production of liquid fuels/petrochemical feedstocks	*Data sources*
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	
2 Production of petrochemicals	
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	[32]
BK1 Synthetic lubricants from rapeseed oil	
IO3 Viscose for substitution of polyamide/PET	
IOU Carbon black from wood	
3 Production of solid fuels	
BB1 Straw briquetting	
BC1 Wood chips from poplar/eucalyptus	
Straw from crop residuals/miscanthus/sweet sorghum	[33]
IHA/IHC Charcoal from wood for iron production	
4 Production of electricity	
BD1 Lignine boiler/large indutrial cogeneration	[34]
BD2 Lignine gasifier/large industrial cogeneration	[34]
BE1 Industrial CHP unit (Total Energy (TE) 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	

Figures 4.3 and 4.4 show the biomass model structure that has been used for this study. The two figures represent the use of wood and the use of other biomass crops, respectively. This split focuses on the supply side; the following discussion focuses on the biomass use, split into bioenergy and biomaterials. 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 [35].

Bioenergy

Biomass can be used for electricity production, for heating and for liquid transportation fuels. Electricity production has been split into co-combustion in large scale plants and separate dedicated biomass fired power plants. Pressurised gasification has been considered for co-combustion in gas fired power plants (STAG Steam and Gas power plants). Moreover, a smaller size stand-alone power plant has been considered. For industrial use, a small scale cogeneration plant (Total Energy TE-unit) has also been modeled, based on the Stirling engine concept. In the heating market, a number of ovens and heating systems for industry, for agriculture and for residential heating have been considered.

Biodiesel can be produced from Rapeseed (i.c. Rapeseed Methyl Ester). Biodiesel can also be derived from wood through a process called HydroThermal Upgrading (HTU) and from algae. Ethanol and methanol can be used as gasoline substitute [41]. Both alcohols can also be used for production of petrochemicals like ethylene (see below).

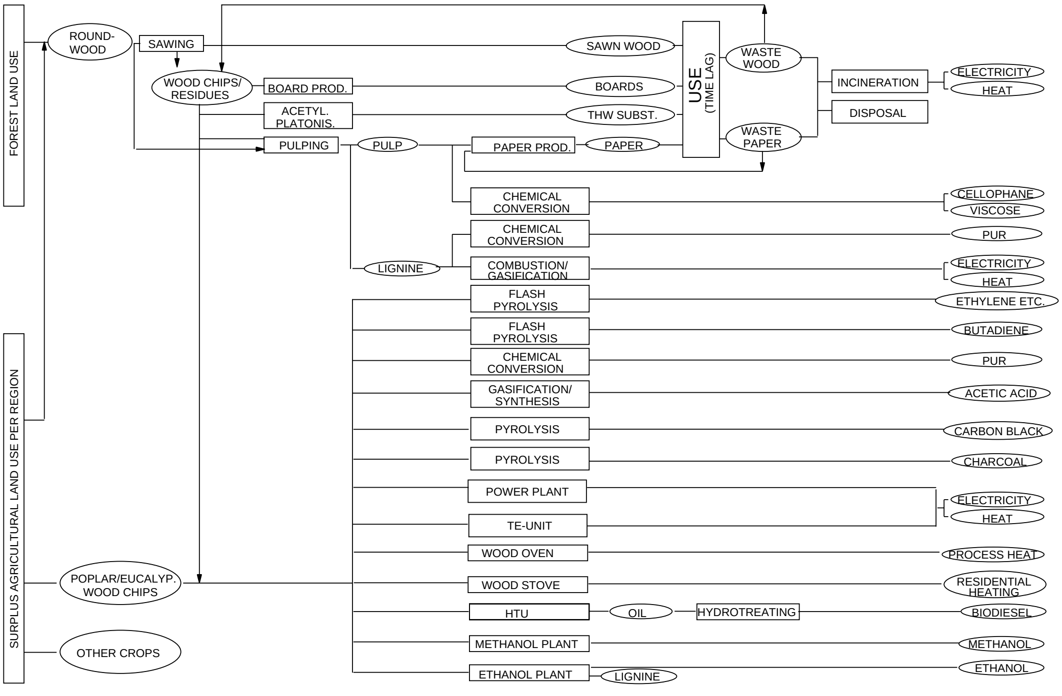

Figure 4.3: *Model structure for wood*

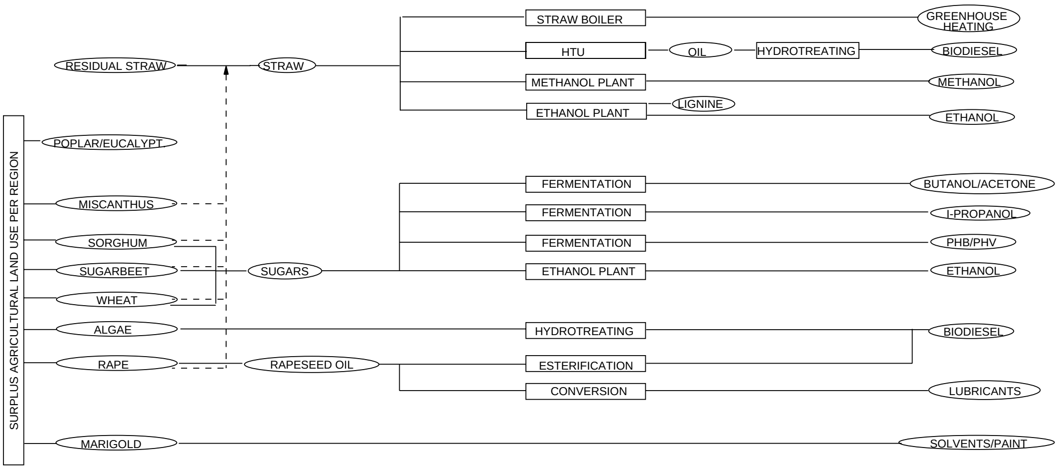

Figure 4.4: M*odel structure for agricultural crops*

Biomaterials

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 products. A number of other materials like particle board, fiber 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, fibers, solvents, resins, and a number of applications of lesser relevance. Plastics and fibers constitute the largest market segment (together approximately 30 Mt per year, see Chapter 2, [36]). 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 lignine. 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 and polyhydroxyvalerate PHB/PHV) has been considered in the model calculations.

4.4.1 Production of liquid fuels/petrochemical feedstocks

The tables shown in this section should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Table 4.21: *Biomass/methanol from straw/wood chips BF1/BF2 [37]*

	Units	1990	2030	2050
Input				
- Electricity	[GJ]	0.1	0.1	0.1
- Straw/wood chips	[GJ]	1.6	1.6	1.6
Output				
- Methanol	[GJ]	1.0	1.0	1.0
Investment costs	[ECU 95/GJ methanol]	30	30	30
- Fixed costs	[ECU 95/GJ methanol]	0.7	0.7	0.7
- Variable costs	[ECU 95/GJ methanol]	2	2	2
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ output]	0.001	0.002	0.003
Bound High	[PJ output]	1	1000	1000

Table 4.22: *Biomass/RME from rapeseed BG1 [38]*

	Units	1990	2030	2050
Input				
- Electricity	[GJ]	0.025	0.025	0.025
- Low Temperature heat	[GJ]	0.2	0.2	0.2
- Diesel	[GJ]	0.025	0.025	0.025
- Methanol	[GJ]	0.03	0.03	0.03
- Rapeseed (excl. straw)	[GJ]	1.8	1.8	1.8
Output				
- RME	[GJ]	1.0	1.0	1.0
- Glycerol +fodder	[GJ]	0.83	0.83	0.83
Investment costs	[ECU 95/GJ wood]	15	15	15
- Fixed costs	[ECU 95/GJ wood]	5	5	5
- Variable costs	[ECU 95/GJ wood]	1	1	1
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		20
Bounds Up	[PJ output]	100	2000	2000

Table 4.23: *Biomass/ethanol from cellulose BH1 [41, 18 ,39]*

	Units	1990	2030	2050
Input				
- Electricity	[GJ]	0.05	0.05	0.05
- Low Temperature Heat	[GJ]	0.45	0.4	0.3
- Cellulose	[GJ]	1.75	1.35	1.35
Output				
- Ethanol (95%)	[GJ]	1.0	1.0	1.0
Investment costs	[ECU 95/GJ ethanol]	25	25	25
- Fixed costs	[ECU 95/GJ ethanol]	1	1	1
- Variable costs	[ECU 95/GJ ethanol]	1	1	1
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ ethanol]	0.001	0.002	0.002
Bound Up	[PJ ethanol]	5	2000	2000

Table 4.24: *Biomass/ethanol from hemicellulose (available in 2010) BH2*

	Units	2010	2030	2050
Input				
- Electricity	[GJ]	0.05	0.05	0.05
- Low temperature heat	[GJ]	0.4	0.035	0.3
- Hemicellulose	[GJ]	1.49	1.49	1.49
Output				
- Ethanol (95%)	[GJ]	1.0	1.0	1.0
Investment costs	[ECU 95/GJ ethanol]	25	25	25
- Fixed costs	[ECU 95/GJ ethanol]	1	1	2
- Variable costs	[ECU 95/GJ ethanol]	1	1	2
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ ethanol]	0.001	0.002	0.002
Bound Up	[PJ ethanol]	5	2000	2000

Table 4.25: *Biomass/ethanol from sugar/starch BH3 [40,41]*

	Units	1990	2000	2050
Input				
- Electricity	[GJ]	0.05	0.05	0.05
- Low Temperature Heat	[GJ]	0.35	0.2	0.2
- Sugar/Starch	[GJ]	1.35	1.35	1.35
Output				
- Ethanol (95%)	[GJ]	1.0	1.0	1.0
Investment costs	[ECU 95/GJ ethanol]	25	25	25
- Fixed costs	[ECU 95/GJ ethanol]	1	1	1
- Variable costs	[ECU 95/GJ ethanol]	1	1	1
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ ethanol]	0.001	0.002	0.002
Bound Up	[PJ ethanol]	5	2000	2000

Table 4.26: *Biomass/ethanol purification 95% to 99% BH4 [30]*

	Units	2000	2050
Input			
- Electricity	[GJ]	0.09	0.03
- Low Temperature Heat	[GJ]	0.09	0.03
- Ethanol (95%)	[GJ]	1.0	1.0
Output			
- Ethanol (99%)	[GJ]	1.0	1.0
Investment costs	[ECU 95/GJ ethanol]	2.2	2.2
- Fixed costs	[ECU 95/GJ ethanol]	0.1	0.1
- Variable costs	[ECU 95/GJ ethanol]	0.25	0.25
Life	[years]	20	

Table 4.27: *Biomass/HTU oil production from wood (available in 2010) BI1 [38]*

	Units	2010	2030	2050
Input				
- Electricity	[GJ]	0.027	0.027	0.027
- Wood chips	[GJ]	1.32	1.32	1.32
Output				
- HTU oil	[GJ]	1.0	1.0	1.0
Investment costs	[ECU 95/GJ output]	15	15	15
- Fixed costs	[ECU 95/GJ output]	0.5	0.5	0.5
- Variable costs	[ECU 95/GJ output]	0.25	0.25	0.25
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ output]	0.001	0.002	0.002
Bound Up	[PJ output]	1000	2000	2000

Table 4.28: *Biomass/HTU oil production from lignine (available in 2010) BI2 [38]*

	Units	2010	2030	2050
Input				
- Electricity	[GJ]	0.027	0.027	0.027
- Lignin + other residuals	[GJ]	1.32	1.32	1.32
Output				
- HTU oil	[GJ]	0.5	0.5	0.5
- Residual fuel oil	[GJ]	0.5	0.5	0.5
Investment costs	[ECU 95/GJ output]	15	15	15
- Fixed costs	[ECU 95/GJ output]	0.5	0.5	0.5
- Variable costs	[ECU 95/GJ output]	0.25	0.25	0.25
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ output]	0.001	0.002	0.002
Bound Up	[PJ output]	1000	2000	2000

Table 4.29*: Biomass/HTU oil conversion to diesel (available in 2010) BI3 [42,43]*

	Units	2010	2030	2050
Input				
- Electricity	[GJ]	0.05	0.027	0.027
- Hydrogen	[GJ]	0.15	0.15	0.15
- HTU-oil	[GJ]	0.9	0.9	0.9
Output				
- Diesel	[GJ]	1.0	1.0	1.0
Investment costs	[ECU 95/GJ diesel]	50	50	50
- Fixed costs	[ECU 95/GJ diesel]	1	1	1
- Variable costs	[ECU 95/GJ diesel]	1	1	1
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ diesel]	0.001	0.002	0.002
Bound Up	[PJ diesel]	1000	2000	2000

Table 4.30: *Biomass/biodiesel from algae lipids BJ1 [44]*

	Units	1990	2030	2050
Input				
- Electricity	[GJ]	0.025	0.025	0.025
- Low Temperature Heat	[GJ]	0.2	0.2	0.2
- Diesel	[GJ]	0.025	0.025	0.025
- Methanol	[GJ]	0.03	0.03	0.03
- Lipids from algae	[GJ]	1.8	1.8	1.8
Output				
- Diesel	[GJ]	1.0	1.0	1.0
- Glycerol + fodder	[GJ]	0.83	0.83	0.83
Investment costs	[ECU 95/GJ diesel]	15	15	15
- Fixed costs	[ECU 95/GJ diesel]	5	5	5
- Variable costs	[ECU 95/GJ diesel]	1	1	1
Availability	[-]	0.9	0.9	0.9
Life	[years]	25		
Bound Low	[PJ diesel]	0.001	0.002	0.002
Bound Up	[PJ diesel]	100	2000	2000

Table 4.31: *Wheat to constituents (available in 2000) BO1 [27]*

	Units	2010	2030	2050
Input				
- Wheat	[GJ]	1.0	1.0	1.0
Output				
- Cellulose	[GJ]	0.1	0.1	0.1
- Lignine + other residuals	[GJ]	0.1	0.1	0.1
- Hemicellulose	[GJ]	0.1	0.1	0.1
- Sugar and Starch	[GJ]	0.7	0.7	0.7

Table 4.32: *Sugarbeet to constituents (available in 2000) BO2*

	Units	2010	2030	2050
Input				
- Sugarbeet	[GJ]	1.0	1.0	1.0
Output				
- Cellulose	[GJ]	0.25	0.25	0.25
- Lignine + other residuals	[GJ]	0.15	0.15	0.15
- Hemicellulose	[GJ]	0.25	0.25	0.25
- Sugar and Starch	[GJ]	0.20	0.20	0.20

Table 4.33: *Straw to constituents (available in 2000) BO3*

	Units	2010	2030	2050
Input				
- Straw	[GJ]	1.0	1.0	1.0
Output				
- Cellulose	[GJ]	0.45	0.45	0.45
- Lignine + other residuals	[GJ]	0.3	0.30	0.30
- Hemicellulose	[GJ]	0.2	0.20	0.20

Table 4.34: *Wood to constituents (available in 2000) BO4*

	Units	2010	2030	2050
Input				
- Wood chips	[GJ]	1.0	1.0	1.0
Output				
- Cellulose	[GJ]	0.5	0.5	0.5
- Lignine + other residuals	[GJ]	0.25	0.25	0.25
- Hemicellulose	[GJ]	0.25	0.25	0.25

Table 4.35: *Sweet sorghum to constituents (available in 2000) BO5*

	Units	2010	2030	2050
Input				
- Sorghum	[GJ]	1.0	1.0	1.0
Output				
- Straw	[GJ]	0.5	0.5	0.5
- Sugar and Starch	[GJ]	0.5	0.5	0.5

4.4.2 Production of petrochemicals

The tables shown in this section should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Table 4.36: *Lubricants production from rapeseed oil BK1 [45]*

	Units	2010	2050
Input			
- Rapeseed (excl. straw)	[GJ]	100	100
- Low Temperature Heat	[GJ]	2	2
- Hydrogen	[GJ]	1	1
Output			
- Lubricants	[t]	1.0	1.0
- Glycerol + fodder	[GJ]	50	50
Investment costs	[ECU 95/ t lubricants]	5000	5000
- Fixed costs	[ECU 95/ t lubricants]	250	250
- Variable costs	[ECU 95/ t lubricants]	100	100
Availability factor	[-]	0.9	0.9
Life	[years]	20	

Table 4.37: *Ethanol dehydrogenation ING [47,46]*

	Units	1990	2050
Input			
- Electricity	[GJ]	0.76	0.76
- Ethanol (95%)	[GJ}	50	40
- Gas	[GJ]	1.8	1.8
- High temperature steam	[GJ]	3.4	3.4
Output			
- Ethylene	[t]	1	1
-Investment costs	[ECU 95/t]	400	400
- Fixed costs	[ECU 95/t]	20	20
-Variable costs	[ECU 95/t]	10	10
Life	[years]	25	
Availability	-	0.95	0.95

Table 4.38: *Ethylene/BTX from wood flash pyrolysis (available in 2010) INH [47]*

	Units	2010	2050
Input			
- Electricity	[GJ]	1.2	1.2
- Wood chips	[GJ]	122	122
Output			
- Ethylene	[t]	1	1
- BTX	[t]	0.77	0.77
- Gas for industry	[GJ]	28.3	28.3
- Investment costs	[ECU 95/t]	1000	1000
- Fixed costs	[ECU 95/t]	20	20
-Variable costs	[ECU 95/t]	10	10
Life	[years]	25	
Availability	-	0.95	0.95

Table 4.39: *Ethylene/BTX from methanol pyrolysis INE [48,49]*

	Units	2010	2050
Input			
- Electricity	[GJ]	0.2	0.2
- Methanol	[GJ]	96.5	96.5
Output			
- Ethylene	[t]	1	1
- Propylene	[t]	0.51	0.51
- C4	[t]	0.10	0.10
- BTX	[t]	0.14	0.14
- Pyrolysis gasoline	[GJ]	3.5	3.5
- Residual gas	[GJ]	4.0	4.0
Investment costs	[ECU 95/t]	760	760
- Fixed costs	[ECU 95/t]	25	25
-Variable costs	[ECU 95/t]	13	13
Life	[years]	25	
Availability	-	0.95	0.95

Table 4.40: *Viscose production IO3 [50]*

	Units	1990	2050
Input			
- Chemical pulp	[t]	0.98	0.98
- NaOH	[t]	0.75	0.75
- Coal	[GJ]	4.0	4.0
- Electricity	[GJ]	3.1	3.1
Output			
- Viscose/Rayon	[t]	1	1
Investment costs	[ECU 95/t]	1625	1625
- Fixed costs	[ECU 95/t]	80	80
- Variable costs	[ECU 95/t]	114	114
Life	[years]	25	
Availability	-	0.95	0.95

Table 4.41: *Cellophane production IO4 [50]*

	Units	1990	2050
Input			
- Chemical pulp	[t]	1.0	1.0
- NaOH	[t]	0.75	0.75
- Coal for industry	[GJ]	4.0	4.0
- Glycerol + fodder	[GJ]	6.0	6.0
- Electricity	[GJ]	3.1	3.1
Output			
- Cellophane	[t]	1	1
Investment costs	[ECU 95/t]	1750	1750
- Fixed costs	[ECU 95/t]	88	88
-Variable costs	[ECU 95/t]	500	500
Life	[years]	25	
Availability	-	0.95	0.95

Table 4.42: *Acetic acid production from biomass IOP [51]*

	Units	1990	2050
Input			
- Methanol	[GJ]	10.5	10.5
- Wood Chips	[GJ]	8.0	8.0
- High temperature steam	[GJ]	5.4	5.4
- Electricity	[GJ]	0.85	0.85
Output			
- Acetic acid	[t]	1	1
Investment costs	[ECU 95/t]	350	350
- Fixed costs	[ECU 95/t]	15	15
-Variable costs	[ECU 95/t]	25	25
Life	[years]	20	
Availability	-	0.95	0.95

Table 4.43: *Butanol/acetone production from biomass fermentation IOQ [51]*

	Units	1990	2050
Input			
- Electricity	[GJ]	0.5	0.5
- Sugar and Starch	[GJ]	75	75
- Low temperature steam	[GJ]	10	10
Output			
- Butanol	[t]	1	1
- Ethanol (95%)	[GJ]	2	2
- Acetone	[t]	0.39	0.39
Investment costs	[ECU 95/t]	890	890
- Fixed costs	[ECU 95/t]	100	100
-Variable costs	[ECU 95/t]	50	50
Availability	-	0.95	0.95
Life	[years]	25	

Table 4.44: *I-propanol from biomass IOR [52]*

	Units	1990	2050
Input			
- Sugar and Starch	[GJ]	55	55
- Low temperature steam	[GJ]	10	10
- Electricity	[GJ]	0.5	0.5
Output			
- I-propanol	[t]	1	1
Investment costs	[ECU 95/t]	890	890
- Fixed costs	[ECU 95/t]	100	100
-Variable costs	[ECU 95/t]	50	50
Availability	-	0.95	0.95
Life	[years]	25	

Table 4.45: *Butadiene through flash pyrolysis [51]*

	Units	1990	2050
Input			
- Electricity	[GJ]	1.2	1.2
- Wood chips	[GJ]	122	122
Output			
- BTX	[t]	1.0	1.0
- Butadiene	[t]	0.77	0.77
- Gas	[GJ]	28.3	28.3
Investment costs	[ECU 95/t]	1000	1000
- Fixed costs	[ECU 95/t]	20	20
-Variable costs	[ECU 95/t]	10	10
Availability	-	0.95	0.95
Bound low	[t]	10	100
Life	[years]	25	

Table 4.46: *PUR from lignine IPC [53]*

	Units	2010	2050
Input			
- Electricity	[GJ]	1.0	1.0
- Lignine	[GJ]	4.0	4.0
- Toluenediisocyanate	[t]	0.87	0.87
- Ethylene oxide	[t]	0.05	0.05
Output			
- PUR	[t]	1.0	1.0
Investment costs	[ECU 95/t]	1200	1200
- Fixed costs	[ECU 95/t]	60	60
-Variable costs	[ECU 95/t]	30	30
Availability	-	0.95	0.95
Life	[years]	25	

Table 4.47: *Phenol through lignine hydrotreatment (available in 2010) IOT [51]*

	Units	2010	2050
Input			
- Electricity	[GJ]	1.2	1.2
- Lignine	[GJ]	70	70
- Hydrogen	[GJ]	5	5
Output			
- Phenol	[t]	1.0	1.0
Investment costs	[ECU 95/t]	500	500
- Fixed costs	[ECU 95/t]	20	20
-Variable costs	[ECU 95/t]	10	10
Availability	-	0.95	0.95
Life	[years]	25	

Table 4.48: *Carbon black production from wood IOU [54]*

	Units	1990	2050
Input			
- Wood chips	[GJ]	70	70
Output			
- Carbon black	[t]	1.0	1.0
Investment costs	[ECU 95/t]	1500	1500
- Fixed costs	[ECU 95/t]	75	75
- Variable costs	[ECU 95/t]	50	50
Availability	-	0.95	0.95
Life	[years]	20	

Table 4.49: *Surfactant production(AES) from palm oil IOV [55]*

	Units	1990	2050
Input			
- Ethylene oxide	[t]	0.35	0.35
- Palm kernel oil[4]	[t]	0.491	0.491
- Methanol	[GJ]	0.2	0.2
- Low temperature heat	[GJ]	5.0	5.0
- Electricity	[GJ]	0.5	0.5
Output			
- Surfactant (AES)	[t]	1.0	1.0
Investment costs	[ECU 95/t]	500	500
- Fixed costs	[ECU 95/t]	25	25
- Variable costs	[ECU 95/t]	50	50
Availability	-	0.95	0.95
Life	[years]	20	

Table 4.50: *Paint production from Marigold oil IOX [56]*

	Units	1990	2050
Input			
- Marigold flower oil	[t]	0.4	0.4
- Electricity	[GJ]	1.0	1.0
Output			
- Paint	[t paint equivalents]	1.0	1.0
Investment costs	[ECU 95/t]	10.000	10.000
- Fixed costs	[ECU 95/t]	500	500
- Variable costs	[ECU 95/t]	500	500
Availability	-	0.95	0.95
Life	[years]	20	

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[4] Modeled as an import option

Table 4.51: *Biopol (PHB/PHV) production IOY [57]*

	Units	1990	2050
Input			
- Sugar and Starch	[t]	60	60
- Low temperature steam	[GJ]	5.0	5.0
- Electricity	[GJ]	1.0	1.0
Output			
- PHB/PHV (Biopol)	[t]	1.0	1.0
Investment costs	[ECU 95/t]	10.000	10.000
- Fixed costs	[ECU 95/t]	200	200
- Variable costs	[ECU 95/t]	200	200
Availability	-	0.95	0.95
Life	[years]	20	

4.4.3 Production of solid fuels

The tables shown in this section should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Straw briquetting data in Table 4.52 refer to two different installations. The high costs in 1990 refer to a so-called “brendorfer” installation with a low availability factor (1000 hours per year) and high labour costs. The data for 2010 and beyond refer to a automatic pelletising installation with a high availability factor (3000 hours per year).

Table 4.52: *Biomass straw briquetting plant [58]*

	Units	1990	2010	2030	2050
Input					
- Electricity	[GJ]	0.53	0.35	0.35	0.35
- Straw	[GJ]	1.0	1.0	1.0	1.0
Output					
- Energy Wood (size > 5 cm)	[GJ]	1.0	1.0	1.0	1.0
Investment	[ECU 95/GJ wood]	14.3	7.1	7.1	7.1
- Fixed	[ECU 95/GJ wood]	3.1	0.3	0.3	0.3
- Variable	[ECU 95/GJ wood]	0.2	0.02	0.02	0.02
Availability factor	[-]	1	1	1	1
Life	[years]	30			
Bounds Low	[PJ output]	0.001		0.002	0.002

Table 4.53: *Biomass/wood chipping BC1 [27]*

	Units	1990	2010	2030	2050
Input					
- Wood	[GJ]	1.0	1.0	1.0	1.0
Output					
- Wood Chips	[GJ]	1.0	1.0	1.0	1.0
- Variable costs	[ECU 95/GJ wood chips]	0.5	0.5	0.02	0.02
Availability factor	[-]	1	1	1	1

Table 4.54: *Charcoal production for steel industry (available in 2010) IHA [59,60]*

	Units	2010	2020	2050
Input				
- Wood for industry	[GJ]	1.8	1.8	1.8
Output				
- Naphta	[GJ]	0.10	0.10	0.10
- Residual gas for steel industry	[GJ]	0.15	0.15	0.15
- Wood for steel industry	[GJ]	1	1	1
Investment costs	[ECU 95/GJ]	15	15	15
- Fixed costs	[ECU 95/GJ]	0.5	0.5	0.5
-Variable costs	[ECU 95/GJ]	1.5	1.5	1.5
Life	[years]	35		
Availability	-	0.9	0.9	0.9
Bound Up	[PJ]	300	400	400

Table 4.55: *Dummy wood to coal/iron production with CO_2 removal (available in 2010) IHC*

	Units	2010	2050
Input			
- Charcoal	[GJ]	1.0	1.0
- Low Temperature steam	[GJ]	0.1	0.1
- High temperature steam	[GJ]	0.05	0.05
Output			
- Coal substitute	[GJ]	1	1
Investment costs	[ECU 95/GJ]	15	10
- Fixed costs	[ECU 95/GJ]	1.5	1.5
Life	[years]	20	
Availability	-	0.9	0.9

4.4.4 Production of electricity

Abstract based on [38]

The tables shown in this section should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Biomass Gasification Combined Cycle (BIG-CC)

Demonstration projects

One of the most promising options for power generation from biomass is ‘Biomass Gasification Combined Cycle' (BIG-CC). BIG-CC is limited to larger capacities (generally 30+ MW). Demonstration BIG-CCs are due to be built in a number of countries, with electrical efficiencies of 32-41% and total efficiencies up to 83% (based on the lower heating value of biomass). The efficiency strongly depends on the moisture content of the fuel and the corresponding energy needed for pre-drying. *Here it is assumed that clean wood with a moisture content of 10% by weight is used as fuel. Generally, wood as received (a.r.) has a higher moisture content (up to 50% by weight); therefore some predrying is assumed.* Figure 4.5 shows the investment cost and the electrical efficiency of a few demonstration projects [61], [62], [63], [64].

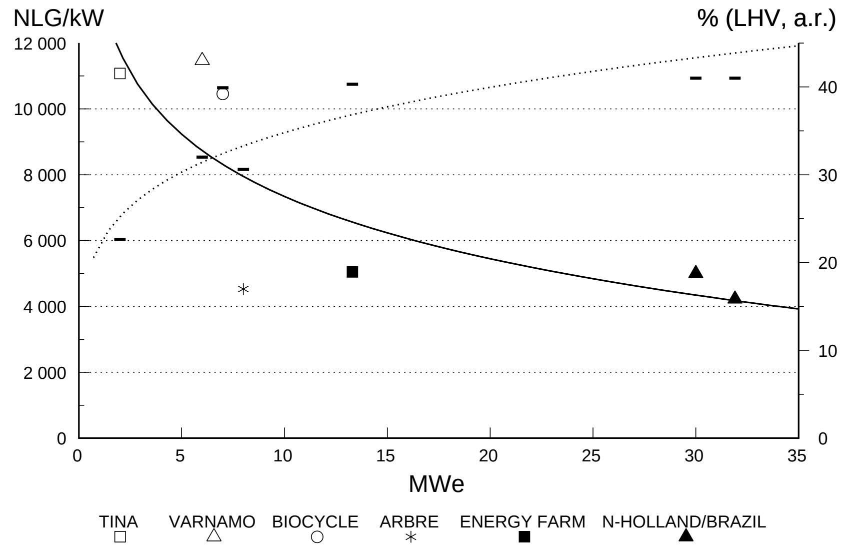

Figure 4.5 *Investment cost and efficiency of demo biomass gasification projects for power production or combined heat and power (1 ECU=2.1 NLG)*

[1] LHV, a.r. = Lower Heating Value, as received.

[2] - corresponding with efficiency (right axis).

Relatively small biomass gasification projects are characterised by high specific capital cost, at least in the demonstration stage. For larger demonstration projects, investment cost is presumably of the order of magnitude of NLG 4000-5000/kW$_e$. Net generating efficiency increases from about 22% for really small projects (2 MW$_e$) till 40% for relatively large projects (30 MW$_e$). The main options for intermediate scale biomass gasification (30+ MW$_e$) are:

- Atmospheric Circulating Fluidised Bed (ACFB) gasification.
- Pressurised Circulating Fluidised Bed (PCFB) gasification.
- Indirect gasification (Battelle process).

Intermediate scale biomass gasification projects are mostly based on air gasification, unlike oxygen gasification in case of coal fired Integrated Gasification Combined Cycle, IGCC. Use of air as gasifying agent requires bulky gas cleaning equipment compared to oxygen gasification. More experience is needed in order to determine the optimum scale of biomass gasification. The same holds for optimal gasification pressure - near-atmospheric or pressurised - and optimal gasifying agent (air or oxygen).

For projects with hot-air turbines, gas cleaning can be rather straightforward. In case of biomass gasification production of tars in the gasification process can cause plugging of downstream equipment. Therefore, catalytic or thermal decomposition of tars is needed. Residual tars are removed by 'water scrubbing', high-temperature gas cleaning (in case of pressurised gasification), etc. Furthermore, several types of scrubbers, ceramic filters, etc. are applied to reduce the dust load. The technology applied depends on the pressure of the gasification process.

Commercial projects

In case of relatively large scale BIG-CCs (60+ MW$_e$) very efficient gas turbines can be applied, enabling net generating efficiencies of about 47% [65]. Using projects as

'ARBRE' and World Bank/Brazil[5], both based on the TPS process, as a reference, investment cost of a commercial 60 MW_e BIG-CC could be as low as NLG 3000/kW_e. Such a level of investment cost - about ECU 1500/kW_e - is also reported in [66] for a 30 MW_e BIG-CC (the 'Noord-Holland' project). For larger 120 MW_e BIG-CCs investment cost is estimated at ECU 1200/kW_e in 2020. This level of investment cost is comparable with a cost estimation of US$ 1500/kW_e for a commercial 52 MW_e BIG-CC [39]. Operation and maintenance costs are estimated at 12 ECU/MWh in 2000, decreasing to 9.5 ECU/MWh in 2020 (which is within the range suggested in [42]).

For the unit size of 120 MW_e generating efficiency could amount to some 54% (Figure 4.6). The generating efficiency is assumed to increase from 41% in 2000 to 52% in 2020. This is within the range of the highest efficiencies achievable with future, so-called 'advanced' BIG-CC systems, presented in [67].

Based on the data of Figure 4.6, parameters of a BIG-CC system for district heating are estimated in Table 4.56. Although both investment cost and operation and maintenance cost have to be decreased to a large extent, and the net generating efficiency has to be boosted considerably compared to current standards, such dramatic improvements seem to be achievable.

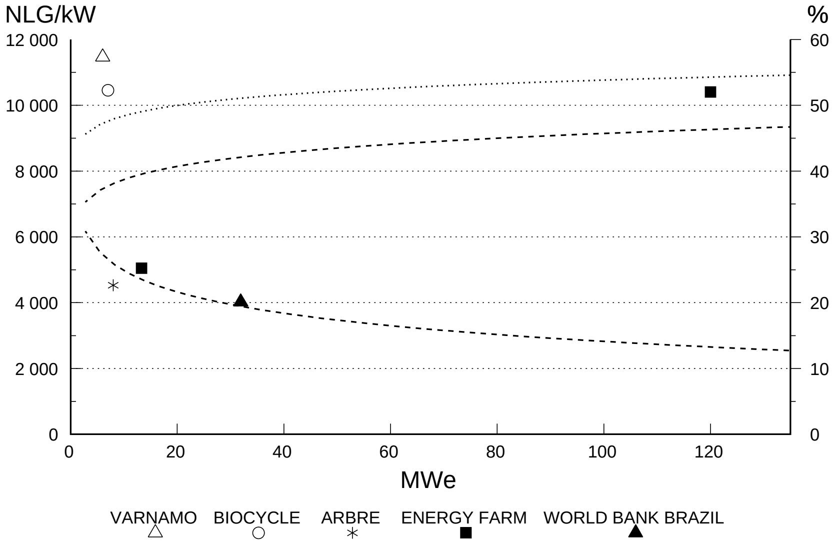

Figure 4.6 *Commercial BIG-CC; investment cost compared to those of some demonstration plants; efficiency compared to 'state-of-the-art' (dashed) and 'advanced' (dotted) BIG-CCs [43] (1 ECU=2.1 NLG)*

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[5] This Brazilian biomass gasification project has about the same installed power and the same investment cost as the so-called `Noord-Holland' project.

Table 4.56: *Costs and efficiencies of BIG-CC system for district heating BE3 [38]*

	2000	2010	2020
Year average net efficiency[1] [%]	41.0	47.0	52.0
District heating efficiency - Electrical [%]	35.0	41.0	46.0
- Thermal [%]	36.5	36.5	36.5
Investment costs [ECU_{1995}/kW_e]	2000[2]	1425	1200
O&M costs [$ECU_{1995}/kW_e/yr$]	79	70	62
Life [yr]	25	25	25
Upper bound [GW_e]	0.1	0.5	0.5

[1] Sole power production.

[2] Second BIG-CC project after Noord-Holland project.

Co-combustion in gas fired power plants 250 MW

Input data for gasification and subsequent co-combustion in large scale 250 MW gas fired power plants are shown in Table 4.57. The data refer to a plant where biomass (wood chips) constitutes 25% of the heating value of the fuel input.

Table 4.57 *Co-combustion in gas fired power plants*

	2000	2010	2030
Electrical net efficiency [%]	50.0	53.0	55.5
Investment costs [ECU_{1993}/kW_e]	950	890	880
O&M costs [$ECU_{1995}/kW_e/yr$]	45	45	45
Life [yr]	25	25	25
Upper bound [GW_e]	0.5	1	25

Biomass Gasification SOFC (BIG-SOFC)

VTT Energy (Finland) [*68*] investigated a system consisting of a pressurised biomass gasifier and a Solid Oxide Fuel Cell (SOFC) coupled to a combined cycle. Researchers at ECN analysed other high-temperature fuel cell systems [69]. A biomass gasifier and a (high-temperature) fuel cell system, integrated with a combined cycle or gas turbine, offers the perspective of very high efficiencies. The highest efficiencies are attainable with a system, consisting of a pressurised gasifier, high-temperature gas cleaning, high-temperature fuel cells and a combined cycle. Such a system can be applied to district heating, offering an additional efficiency gain. This most advanced system, which has been analysed by VTT Energy, is the reference biomass gasification fuel cell system. Investment cost and operation and maintenance costs are estimated tentatively (Table 4.58).

Table 4.58 *Costs and efficiencies of BIG-SOFC system for district heating BE4*

	2000	2010	2020	2030
Year average net efficiency[1] [%]		56.5	57.0	57.0
District heating efficiency				
- Electrical [%]		54.5	56.5	56.5
- Thermal [%]		36.5	36.5	36.5
Investment costs [ECU_{1995}/kW_e]		2400	1650	1425
O&M costs [$ECU_{1995}/kW_e/yr$]		110	100	100
Life [yr]		25	25	25
Upper bound [GW_e]				

[1] Sole power production.

Biomass Integrated Combustor - Stirling Engine

In addition to relatively large scale options like BIG-CC and PFBC gasification or combustion on a small scale could be used for small district heating or Total Energy schemes (local distribution of heat for e.g. residential heating). Here the focus is on the combination of biomass combustion and a Stirling engine. Stirling engines, based on external combustion, have a long history. Practical applications have been rather limited until now. One of the future applications could be conversion of biomass (chips) into heat and power. Small scale biogas combustion coupled with Stirling engines with capacities of 30-300 kW_e are in the development and demonstration stage.

Parameters for a `Biomass Integrated Combustor - Stirling Engine' (BIC-SE) have been derived from literature by van Ree [70] (Table 4.59).

Table 4.59 *Biomass Integrated Combustor - Stirling Engine for small scale district heating or Total Energy schemes BE1*

	2000	2010	2020
Total Energy mode			
- Electrical efficiency [%]	25	27	28
- Thermal efficiency [%]	50	50	50
Investment costs [ECU_{1995}/kW_e]	1900	1650	1575
O&M costs [$ECU_{1995}/kW_e/yr$]	115	105	100
Life [yr]	20	20	20

4.4.5 Production of building and construction materials

The tables shown in this section should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Table 4.60: *Sawn wood production IXA [34]*

	Units	1990	2010	2050
Input				
- Roundwood (15% H_2O)	[t]	1.82	1.82	1.82
- Low Temperature heat	[GJ]	3.6	3.0	2.0
- Truck service	[t.km]	1000	1000	1000
- Electricity	[GJ]	1.2	1.0	0.8
Output				
- Sawn Wood	[t]	1	1	1
- Wood process waste (15% H_2O)	[t]	0.82	0.82	0.82
Investment costs	[ECU 95/t]	20	20	20
- Fixed costs	[ECU 95/t]	2	2	2
Residual capacity	[Mt/year]	25	0	0
Availability	-	0.9	0.9	0.9
Life	[years]	25		

Table 4.61: *Chipboard production IXB [34]*

	Units	1990	2010	2050
Input				
-Wood process waste (15% H_2O)	[t]	0.90	0.90	0.90
- Low Temperature heat	[GJ]	5.0	5.0	5.0
- Truck service	[t.km]	100	100	100
- UF-resins	[t]	0.10	0.10	0.10
Output				
-Chipboard	[t]	1	1	1
Investment costs	[ECU 95/t]	100	100	100
- Fixed costs	[ECU 95/t]	10	10	10
Residual capacity	[Mt/year]	10	0	0
Availability	-	0.9	0.9	0.9
Life	[years]	25		

Table 4.62: *Acetylated wood production IXC [71]*

	Units	1990	2050
Input			
- Acetic anhydride	[t]	0.65	0.65
- Sawn timber (15 % H_2O)	[t]	0.9	0.9
- Low temperature heat	[GJ]	2.5	2.5
- Truck service	[t.km]	100	100
Output			
- Acetic acid	[t]	0.65	0.65
- Acetylated sawn timber (15 % H_2O)	[t]	1	1
Investment costs	[ECU 95/t]	66	66
- Fixed costs	[ECU 95/t]	3	3
- Variable costs	[ECU 95/t]	8	8
Availability	-	0.9	0.9
Life	[years]	25	

Table 4.63: *PLATO-wood production IXD [72]*

	Units	1990	2050
Input			
- Energy wood (size > 5 cm)	[GJ]	18	18
- Low Temperature heat	[GJ]	5.0	5.0
- Electricity	[GJ]	1.0	1.0
- Truck service	[t.km]	100	100
Output			
- Platonised sawn timber (15% H_2O)	[t]	1	1
Investment costs	[ECU 95/t]	5000	5000
- Fixed costs	[ECU 95/t]	200	200
- Variable costs	[ECU 95/t]	200	200
Availability	-	0.9	0.9
Life	[years]	25	

4.5 Biomaterials use

Biomass is used in products. A list of the important products in the MATTER1.0 model in where biomaterials are applied is shown in Table 4.64. For each product, one assembly/construction process has been modeled and one demolition process has been modeled. The data for these processes are presented in this section. It is not possible to provide a similar list for bioenergy, because the difference between electricity from biomass and electricity from fossil fuels cannot be made. As a consequence, all electricity use must be described, which extends beyond the scope of this report. For a characterization of the energy model, one is referred to the background reports (e.g. [73]).

Table 4.64: *Biomass use in products, process list*

JE2	Wooden frame office building construction
JE5	Wooden frame office building demolition
JF2	Wooden frame industrial/agricultural building construction
JF5	Wooden frame industrial/agricultural building demolition
JH2	Solid wood residence construction type 2
JH3	Wood frame residence construction type 2
JH5	Used solid wood residence demolition type 2
JH6	Used wood frame residence demolition type 2
JQ1	Plywood desk construction

JQ2 MDF desk construction
JQ4 Plywood desk demolition
JQ5 MDF desk demolition
JT6 Wood window frame assembly
JT7 Tropical wood window frame assembly
JTB Wood window frame disassembly
JTC Tropical wood window frame disassembly
JU1 Wood parquet production
JU5 Wood parquet demolition
JW2 Wood railway track construction
JW4 Wood railway track demolition
JX1 THW waterworks construction
JX5 THW waterworks demolition
JY1 Wooden pallet production
JY3 Wooden pallet disassembly

The model inputs for the biomaterials use processes are shown in the tables 4.65 till 4.88 inclusive. The tables should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Table 4.65: *Wooden frame office building construction JE2 [74]*

	Units	1990	2050
Input			
- Reinforcement steel	[t]	0.1	0.1
- Tropical hardwoods (15 % H_2O)	[t]	0.75	0.75
- Sawn wimber (15 % H_2O)	[t]	10.0	10.0
- Chipboard	[t]	0.6	0.6
- Ready mix concrete	[t]	10	10
- Gypsum	[t]	2.1	2.1
- Bldg Weight including load	[t/100 m^2]	50	50
Output			
- Wooden frame office building	[100 m^2]	1	1
- Demolition wood	[t]	2.0	2.0
Investment costs	[ECU1995/100 m^2]	300000	300000
O&M costs			
- Fixed	[ECU1995/100 m^2.yr]		
- Variable	[ECU1995/100 m^2]	17500	17500
Life	[years]	20	20

Table 4.66: *Wooden frame office building demolition JE5*

	Units	1990	2050
Input			
- Wooden frame office building	[100 m^2]	1	1
- Diesel	[GJ]	5	5
Output			
- Steel Scrap	[t]	0.1	0.1
- Disposable Waste	[t]	10	10
- Demolition wood	[t]	8.0	8.0
Investment costs	[ECU1995/100 m^2]	1100	1100
O&M costs			
- Fixed	[ECU1995/100 m^2.yr]	300	300
- Variable	[ECU1995/100 m^2]	400	400

Table 4.67: *Wood frame industrial/agricultural building construction JF2 [74]*

	Units	1990	2050
Input			
- Reinforcement steel	[t]	2.0	2.0
- Sawn wood (15 % H_2O)	[t]	5.0	5.0
- Chipboard	[t]	0.6	0.6
- Ready mix concrete	[t]	45	45
- Bldg Weight including load	[t/100 m^2]	200	200
Output			
- Wooden frame industr./agricult. building	[100 m^2]	1	1
- Demolition wood	[t]	0.2	0.2
Investment costs	[ECU1995/100 m^2]	150000	150000
O&M costs			
- Fixed	[ECU1995/100 m^2.yr]		
- Variable	[ECU1995/100 m^2]	10000	10000
Life	[years]	20	20

Table 4.68: *Wooden frame industrial/agricultural building demolition JF5*

	Units	1990	2050
Input			
- Wooden frame industr./agricult. building	[100 m^2]	1	1
- Disposible Waste	[t]	45	45
- Diesel	[GJ]	10	10
Output			
- Steel Scrap	[t]	1.8	1.8
- Demolition wood	[t]	3.5	3.5
Investment costs	[ECU1995/100 m^2]	1100	1100
O&M costs			
- Fixed	[ECU1995/100 m^2. yr]	300	300
- Variable	[ECU1995/100 m^2]	400	400

Table 4.69: *Solid wood frame residence construction type 2 JH2 [75]*

	Units	1990	2050
Input			
- Reinforcement steel	[t]	0.35	0.35
- Sawn wood (15 % H_2O)	[t]	30	30
- Chipboard	[t]	0.78	0.78
- Ready mix concrete	[t]	4	4
- Gypsum	[t]	3.1	3.1
- Polystyrene	[t]	0.13	0.13
- Building weight including load	[t/100 m^2]	65	65
Output			
- Wooden frame indust/agri building	[100 m^2]	1	1
- Steel Scrap	[t]	0.03	0.03
- Demolition wood	[t]	3.2	3.2
Investment costs	[ECU1995/100 m^2]	300000	300000
O&M costs			
- Fixed	[ECU1995/100 m^2.yr]		
- Variable	[ECU1995/100 m^2]	15000	15000
Life	[years]	30	30

Table 4.70: *Used solid wood residence demolition JH5*

	Units	1990	2050

Input			
- Wood frame residence building	[100 m^2]	1	1
- Diesel for Transport	[GJ/100 m^2]	5	5
Output			
- Polystyrene waste clean	[t]	0.13	0.13
- Demolition wood	[t]	25	25
- Disposable Waste	[t]	4	4
Investment costs	[ECU1995/100 m^2]	700	700
O&M costs			
- Fixed	[ECU1995/100 m^2.yr]	150	150
- Variable	[ECU1995/100 m^2.yr]	300	300

Table 4.71: *Wood frame residence construction type 2 JH3 [75]*

	Units	1990	2050
Input			
- Reinforcement steel	[t]	0.45	0.45
- Sawn wood (15 % H_2O)	[t]	11	11
- Chipboard	[t]	0.87	0.87
- Ready mix concrete	[t]	4.5	4.5
- Gypsum	[t]	10	10
- Polystyrene	[t]	0.25	0.25
- Building weight including load	[t/100 m^2}	50	50
Output			
- Wooden frame residence building	[100 m^2]	1	1
- Steel Scrap	[t]	0.05	0.05
- Demolition wood	[t]	1.6	1.6
Investment costs	[ECU1995/100 m^2]	300000	300000
O&M costs			
- Fixed	[ECU1995/100 m^2. yr]		
- Variable	[ECU1995/100 m^2]	15000	15000
Life	[years]	30	30

Table 4.72: *Used wood frame residence demolition type 2 JH6*

	Units	1990	2050
Input			
- Wood frame residence building	[100 m^2]	1	1
- Diesel	[GJ/100 m^2]	5	5
Output			
- Polystyrene waste clean	[t]	0.25	0.25
- Demolition wood	[t]	9	9
- Disposable Waste	[t]	15	15
Investment costs	[ECU1995/100 m^2]	700	700
O&M costs			
- Fixed	[ECU1995/100 m^2. yr]	150	150
- Variable	[ECU1995/100 m^2]	300	300

Table 4.73: *Plywood desk construction JQ1 [76]*

	Units	1990	2050
Input			
- Cold rolled coal f&p steel	[t]	25	25
- UF-Resins	[t]	5.5	5.5
- Tropical hardwood (15%H_20)	[t]	25	25
- Natural gas	[GJ/1000 pcs]	1	1
- Electricity	[GJ/1000 pcs]	1	1
Output			
- Plywood desk	[1000 pcs]	1	1
- PET mixed	[t]	0.35	0.35
- Demolition wood	[t]	5.4	5.4
Investment costs	[ECU1995/1000 pcs]		
O&M costs			
- Fixed	[ECU1995/ 1000 pcs	50	50
- Variable	[ECU1995/ 1000 pcs]	50	50
Life	[years]	30	30
Bound Low	[10^6 pieces]	30	0

Table 4.74: *Plywood desk demolition JQ4*

	Units	1990	2050
Input			
- Plywood desk	[1000 pcs]	1	1
- Truck service	[t. km]	50	50
- Electricity	[GJ/1000 pcs]	0.1	0.1
Output			
- Steel scrap	[t]	22.6	22.6
- PET mixed	[t]	5.2	5.2
- Demolition wood	[t]	19.6	19.6
- Variable costs	[ECU1995/1000 pcs]	25	25

Table 4.75: *MDF desk construction JQ2 [76]*

	Units	1990	2050
Input			
- Cold rolled coal f&p steel	[t]	30	30
- Aluminium	[t]	4	4
- PVC	[t]	0.4	0.4
- UF Resins	[t]	4	4
- MDF	[t]	20	20
- Gas for industry	[GJ/1000 pcs]	1	1
- Electricity	[GJ1000 pcs]	1	1
Output			
- MDF desk	[1000 pcs]	1	1
- Steal scrap	[t]	5.92	5.92
- Aluminium Scrap	[t]	0.2	0.2
- PET mixed	[t]	0.4	0.4
- Demolition Wood	[t]	3.8	3.8
Investment costs	[ECU1995/1000 pcs]		
O&M costs			
- Fixed	[ECU1995/ 1000 pcs	50	50
- Variable	[ECU1995/ 1000 pcs]	50	50
Life	[years]	30	30

Table 4.76: *MDF desk demolition JQ5*

	Units	1990	2050
Input			
- MDF desk	[1000 pcs]	1	1
- Truck service	[t. km]	50	50
- Electricity	[GJ/1000 pcs]	0.1	0.1
Output			
- Steel scrap	[t]	24.1	24.1
- Aluminium scrap	[t]	3.8	3.8
- PET mixed	[t]	3.6	3.6
- Demolition wood	[t]	16.2	16.2
- Variable costs	[ECU1995/1000 pcs]	25	25

Table 4.77: *Wood window frame assembly JT6 [77,78]*

	Units	1990	2050
Input			
- Renewable sawn timber (15% H2O)	[t]	120	120
- PVC	[t]	1.2	1.2
- Paint	[t paint equivalents]	2.0	2.0
- Aluminium	[t]	1.0	1.0
- Glass	[t]	165	250
- Electricity	[GJ/1000 pcs]	50	50
- Labour	[man.hours]	2000	2000
Output			
- Wooden window frame	[1000 pcs]	1	1
- Wood process waste	[t]	35	35
Investment costs	[ECU1995/ 1000 pcs]	4 * 10^6	4 * 10^6
- Variable	[ECU1995/ 1000 pcs]	600.000	600.000
Life	[years]	25	25
Bound low	[10^6 pieces]	10	0

Table 4.78: *Wood window frame disassembly JTB*

	Units	1990	2050
Input			
- Used wooden window frame	[1000 pcs]	1	1
- Truck service	[t. km]	8500	8500
- Labour	[man.hours]	500	500
Output			
- PVC waste clean	[t]	1	1
- Waste Glass	[t]	100	200
- Demolition Wood	[t]	60	60
- Aluminium Scrap	[t]	1	1
- Variable	[ECU1995/1000 pcs]	-	-(kan dit ??)

Table 4.79: *Tropical wood window frame assembly JT7 [77]*

	Units	1990	2050
Input			
- Non renewable sawn timber (15% H2O)	[t]	150	150
- PVC	[t]	1.2	1.2
- Paint	[t paint equivalents]	3.0	3.0
- Aluminium	[t]	0.5	0.5
- Glass	[t]	165	250
- Electricity	[GJ/1000 pcs]	50	50
- Labour	[man.hours]	2000	2000
Output			
- Hardwood window frame	[1000 pcs]	1	1
- Wood proces waste	[t]	48	48
Investment	[ECU1995/ 1000 pcs]	$4 * 10^6$	$4 * 10^6$
- Variable	[ECU1995/ 1000 pcs]	600.000	600.000
Availability factor	[-]		
Life	[years]	25	25
Bound low	[10^6 pieces]	10	0

Table 4.80: *Tropical wood window frame disassembly JTC*

	Units	1990	2050
Input			
- Used hardwood window frame	[1000 pcs]	1	1
- Truck service	[t. km]	12.000	12.000
- Labour	[man.hours]	500	500
Output			
- PVC waste clean	[t]	1	1
- Waste Glass	[t]	100	200
- Demolition Wood	[t]	80	80
- Aluminium Scrap	[t]	1	1
- Variable costs	[ECU1995/1000 pcs]	-	-(kan dit ??)

Table 4.81: *Wood parquet production JU1 [79,80]*

	Units	1990	2050
Input			
- Renewable sawn timber (15% H2O)	[t]	10	10
- UF resins	[t]	0.5	0.5
- Labour	[man.hours]	1000	1000
Output			
- Cladding wood parquet	[1000 m^2]	1	1
- Demolition wood	[t]	20	20
- Variable costs	[ECU1995/ 1000 m^2]	25.000	25.000
Life	[years]	50	50

Table 4.82: *Wood parquet demolition JU5*

	Units	1990	2050
Input			
- Cladding wood parquet	[1000 m^2]	1	1
- Labour	[man.hours]	500	500
Output			
- Demolition Wood	[t]	60	60

Table 4.83: *Wood railway track construction JW2 [81]*

	Units	1990	2050
Input			
- Renewable sawn timber (15% H2O)	[t]	0.091	0.091
- Residual fuel oil	[GJ]	0.0045	0.0045
- Cold rolled f&p steel	[t]	0.0089	0.0089
- Hot rolled section steel	[t]	0.03	0.03
- Cast Iron	[t]	0.0166	0.0166
- Truck service	[ton km]	12	12
- Labour	[man.hours]	1	1
Output			
- Wood railway tracks	[pcs]	1	1
- Variable costs	[ECU1995/ pcs]	50	50
Bound low	[10^6 pcs]	5	5

Table 4.84: *Wood railway track demolition JW4*

	Units	1990	2050
Input			
- Wood railway track	[pcs]	1	1
- Truck service	[t.km]	10	10
- Labour	[man.hours]	0.1	0.1
Output			
- Demolition Wood	[t]	0.091	0.091
-Steel scrap	[t]	0.02	0.02
- Variable costs	[ECU1995/pcs]	10	10

Table 4.85: *THW waterworks construction JX1 [82]*

	Units	1990	2050
Input			
- Tropical wood (15% H_2O)	[t]	1	1
- Hot rolled section steel	[t]	0.01	0.01
- Truck service	[t.km]	100	100
Output			
- THW waterworks	[t THW-equiv.]	1	1
- Variable costs	[ECU1995/ t THW-equiv.]	250	250

Table 4.86*: Waterworks demolition JW4*

	Units	1990	2050
Input			
- THW waterworks	[t THW-equiv.]	1	1
Output			
- Demolition Wood	[t]	0.5	0.5
- Variable costs	[ECU1995/t THW-equiv.]	25	25

Table 4.87: *Wooden pallet production JY1 [83]*

	Units	1990	2050
Input			
- Sawn timber (15% H_2O)	[t]	27	27
- Wire rod steel	[t]	0.5	0.5
- Electricity	[GJ/1000 pcs]	7.2	7.2
Output			

- Wooden pallet	[1000 pcs]	1	1
- Variable costs	[ECU1995/ 1000 pcs.]	7500	7500

Table 4.88: *Wooden pallet disassembly JY3*

	Units	1990	2050
Input			
- Wooden pallets	[1000 pcs]	1	1
Output			
-Steel scrap	[t]	0.4	0.4
- Wood process waste	[t]	20	20
- Variable costs	[ECU1995/ 1000 pcs.]	100	100

4.6 Waste Treatment

Table 4.89 provides an overview of processes that are modeled for biomass waste treatment. The list excludes the use of waste wood in dedicated wood combustion plants and co-combustion in coal fired power plants (both are modeled). Methane emissions are modeled for disposal of natural organic materials. Methane recovery from landfill sites has been considered as an end-of-pipe technology for reduction of landfill gas emissions. Apart from landfill gas recovery, a switch from disposal to energy recovery, digestion, or recycling pose strategies for CH_4 emission mitigation.

4.89: *Biomass waste treatment, process list (MSW = Municipal Solid Waste)*

DAA Methane recovery from disposal sites
DND Disposal demolition wood
DNF Disposal waste fiber
DNK Disposal kitchen waste
DNP Disposal waste paper
DPX Disposal bioplastics
UA5 Incineration waste paper in MSW
UA6 Incineration waste elastomeres in MSW
UA7 Incineration wood waste in MSW
UA8 Incineration kitchen waste in MSW
DXA Aerobic digestion kitchen waste
DXK Anaerobic digestion kitchen waste

The model inputs for the waste treatment options are shown in the tables 4.89 till 4.93 inclusive. The tables should be interpreted taking into account the guidelines and definitions as discussed in section 4.1.

Table 4.90: *Methane emissions from disposal without landfill gas recovery [84]*

	[kg CH_4/t]	[t CO_2 equiv./t waste]
Demolition wood	65	1.4
Waste fiber	65	1.4
Kitchen waste	100	2.1
Waste paper	100	2.1
Bioplastics	50	1.1

Costs for methane recovery from waste disposal sites range from 0.12 to 0.49 ECU per kg methane (i.e. 6-23 ECU/t CO_2 equivalents). The maximum recovery efficiency for the whole landfill life cycle is 55% [85]. The closer the drainage pipes, the higher the efficiency, and the higher the costs. Total potential in the EU: 150 PJ (70 Mt CO_2 equivalents) (based on [86]).

Table 4.91 and Table 4.92 show the model input parameters for aerobic digestion and anaerobic digestion, respectively. The data refer to large-scale plants (>100 kt per year). One must add that recent measurements at a VALORGA installation for anaerobic digestion did not meet the expectations that are expressed in Table 4.92 [87]. Quality standards for compost were not (yet) met.

Table 4.91: *Aerobic digestion kitchen waste [88]*

	Units	1990	2050
Input			
- Kitchen waste (30 % H_2O)	[t]	1	1
Output			
- Compost (15 % H_2O)	[t]	0.45	0.45
-Investment costs	[ECU 95/t]	200	200
- Fixed costs	[ECU 95/t]	25	25
Life	[years]	25	
Availability	-	0.95	0.95

Table 4.92: *Anaerobic digestion kitchen waste [88]*

	Units	1990	2000	2010	2050
Input					
- Kitchen waste (30 % H_2O)	[t]	1	1	1	1
Output					
- Natural Gas	[GJ]	1.5	1.5	1.5	1.5
- Compost (15 % H_2O)	[t]	0.6	0.6	0.6	0.6
-Investment costs	[ECU 95/t]	250	250	250	250
- Fixed costs	[ECU 95/t]	50	50	50	50
Life	[years]	25			
Availability	-	0.95	0.95	0.95	0.95
Bound Low	[Mt input]	0.9	5.0	5.0	5.0
Bound Up	[Mt input]	1.0	7.0	30.0	30.0

Table 4.93 shows the model input parameters for incineration of a number of materials. Current grate firing systems achieve an efficiency of 20-22%. Higher efficiencies are possible if the incineration plant is coupled to combined cycle power plants. LT steam from the incinerator is further heated in the power plant and subsequently used in a steam turbine. Such combined plants can achieve a 28% efficiency for the incineration section. One such plant has been built in the Netherlands and is currently operating [89]. This efficiency increase is considered in the model calculations.

Table 4.93: *Lower heating values and specific CO_2 emissions during incineration [90]*

	[GJ/t]	[t CO_2 equiv./t]
Polyolefines	43	3.14
Polystyrene	40	3.35
PVC	16	1.30
Other plastics	30	3.30
Elastomeres	35	3.30
Paper	15	-
Wood	16	-
Kitchen waste	10	-

5. Biomass Results

The MARKAL model has been used for a base case calculation without greenhouse gas emission penalties (BC) and for a set of calculations including emission penalties. Three sets of scenarios have been evaluated, where the emission penalty increases lineary between 2000 and 2020 to 50 ECU/t, 100 ECU/t and 200 ECU/t CO_2 equivalent, respectively. The penalty stabilizes afterwards. Both lower penalty scenarios are within the range that is currently discussed. The 200 ECU/t case represents an unlikely case from a practical point of view. It should be considered as reference value, representing a system that is truly dedicated to greenhouse gas emission reduction.

Greenhouse gas emissions

In the year 2030, the total amount of GHG emissions in a base case without penalties is about 4600 MT of CO_2 equivalents. In case of emission penalties of 50 ECU/t, 100 ECU/t and 200 ECU/t, the total GHG emissions reduce by about 35%, 50% and 65% respectively. The emission reductions per ton of biomass are about 5.3 in the 50 ECU/t case. The emission reductions are about 4.8 and 3.7 kg of GHG emissions per kg of biomass in the 100 and 200 ECU/t cases.

Biomass production

The land use for dedicated biomass crops is shown in Figure 5.1. The results show little use of biomass crops in the base case. In the case without tax, limited amounts of sweet sorghum and eucalyptus are introduced in the base case. In the 50 ECU/t case, significant amounts of biomass are introduced. In the 200 ECU/t case, the full area of 220 thousand km^2 is used. Eucalyptus in the Southern region is first introduced, followed by sweet sorghum in the Southern region. This selection can be attributed to their high yields. At the 100 ECU/t penalty level, miscanthus is introduced in the Middle region. Wheat, sugar beet, rapeseed, Marigold and algae are not introduced in any of the cases. Timber production on agricultural land or conversion of agricultural land to forest for carbon storage are options that are not introduced in any of the cases.

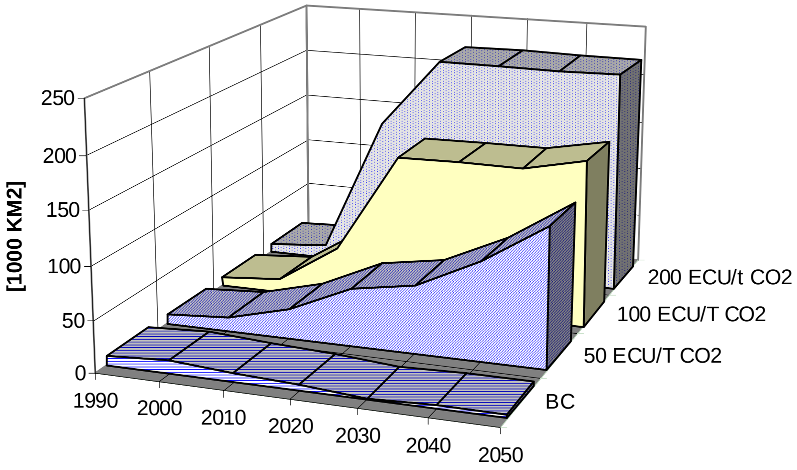

Figure 5.1: *Land use in scenarios with increasing emission penalties*

The production of wood from forests increases in 2030 from 137 Mt in the base case to 152 Mt in the 100 ECU/t case and to 300 Mt in the 200 ECU/t case. The comparison of the growth figures for biomass from forests and biomass from agricultural land (Figure 5.1) shows that most growth occurs for the agricultural production.

The use of biomass for energy and for materials is detailed in Figure 5.2. The figure shows that biomaterial applications dominate in the base case and in the emission penalty cases up to a penalty of 100 ECU/t CO_2. Only in the case with a 200 ECU/t penalty, the energy applications dominate.

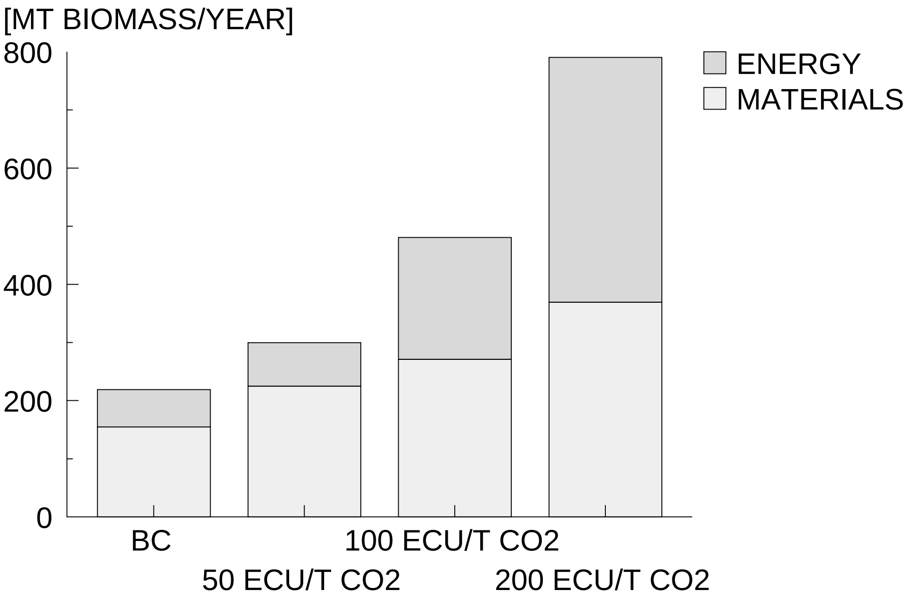

Figure 5.2: *Biomass use with increasing GHG emission penalties*

The use of bioenergy is detailed in Figure 5.3. In the base case, only heat is produced. In the 50 ECU/t case, some ethanol production emerges. Ethanol production shows a particularly strong growth at higher emission penalties. In the 100 ECU/t case, biomass is introduced for power production. Methanol is introduced on a large scale in the transportation market at a penalty level of 200 ECU/t. The HTU process is not applied in this case, but emerges on a large scale at penalty levels above 200 ECU/t CO_2.

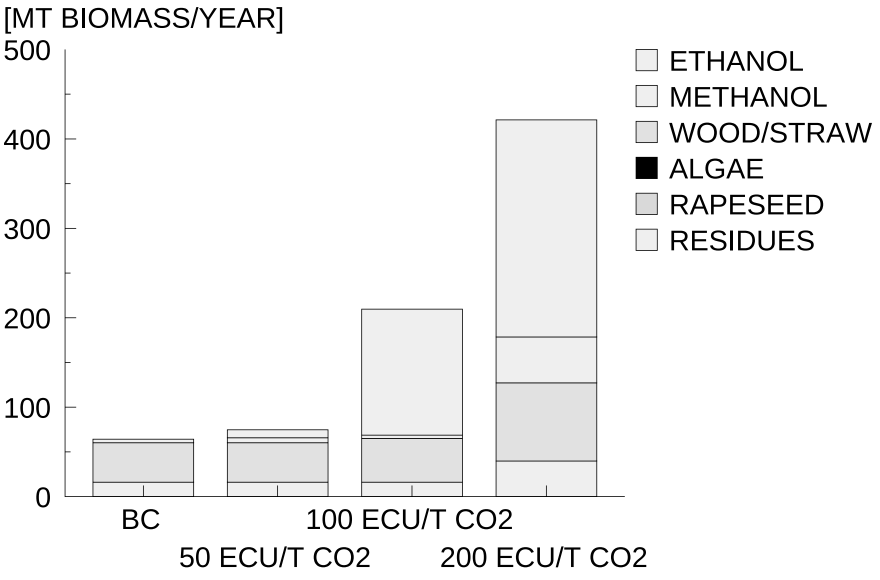

Figure 5.3: *Bioenergy use, split into applications, 2030*

The use of biomaterials is detailed in Figure 5.4. Biomass is introduced for production of petrochemical intermediates at a penalty level of 50 ECU/t CO_2. Flash pyrolysis of biomass for ethylene and butadiene production are introduced. The fermentation of I-propanol, phenol production from lignine, lignine for PUR production, carbon black and acetic acid (via synthesis gas) for petrochemicals are additionally introduced. Palm kernel oil is introduced at a penalty level of 200 ECU/t CO_2. Butadiene, natural rubber, the fermentation of butanol and acetone, Marigold flower resins and synthetic lubricants are not introduced on a large scale. Ethanol dehydrogenation for ethylene production is not introduced in any case.

Regarding fiber applications, viscose for substitution of synthetic fibers is not introduced. Acetylated wood and PLATOnised wood are introduced from 50 ECU/t upward. Biopol and cellophane are not introduced in any of the emission reduction cases.

At the 200 ECU/t penalty level, charcoal is introduced for iron production. The use of structural wood products for the building and construction market increases also at this high penalty level. However, its growth is comparatively small.

One must add that a significant fraction of the biomass that is used for materials end up in materials applications. A fraction (e.g. in flash pyrolysis) is converted into liquid and gaseus fuels during the production process. Residuals from wood swing are applied for energy purposes. The bulk of the petrochemical products, waste paper and used wood products are ultimately used for energy recovery. Note the increasing pulp production in the 200 ECU/t CO_2 case: waste paper is increasingly used for energy recovery instead of being recycled.

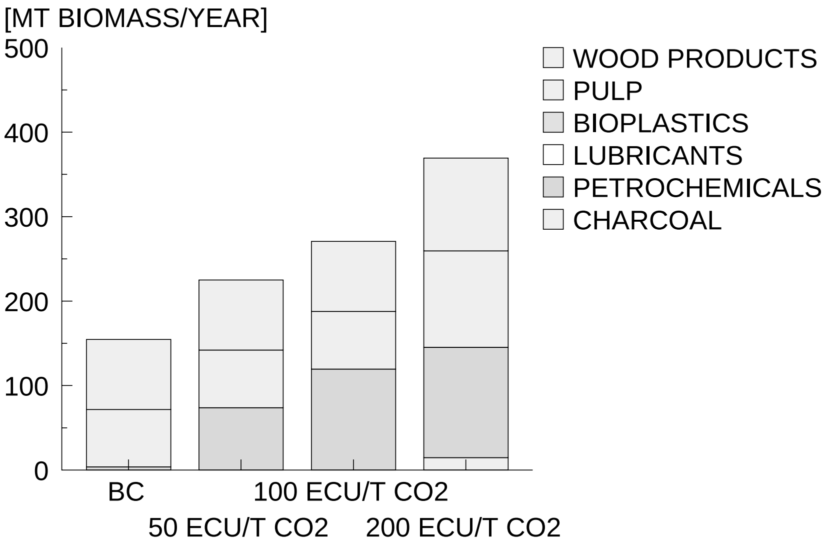

Figure 5.4: *Biomaterial use, split into applications, 2030*

Figures 5.5 and 5.6 show the results for a sensitivity analysis, characterized by more conservative assumptions regarding technology and resource availability [91]. The land availability is in this sensitivity analysis limited to 150 thousand km^2. This land is fully utilized from a penalty level of 100 ECU/t CO_2 upwards. Figure 5.5 shows comparatively little differences compared to Figure 5.3. The ethanol consumption is higher in the 100 ECU/t CO_2 case due to the higher demand for transportation fuels.

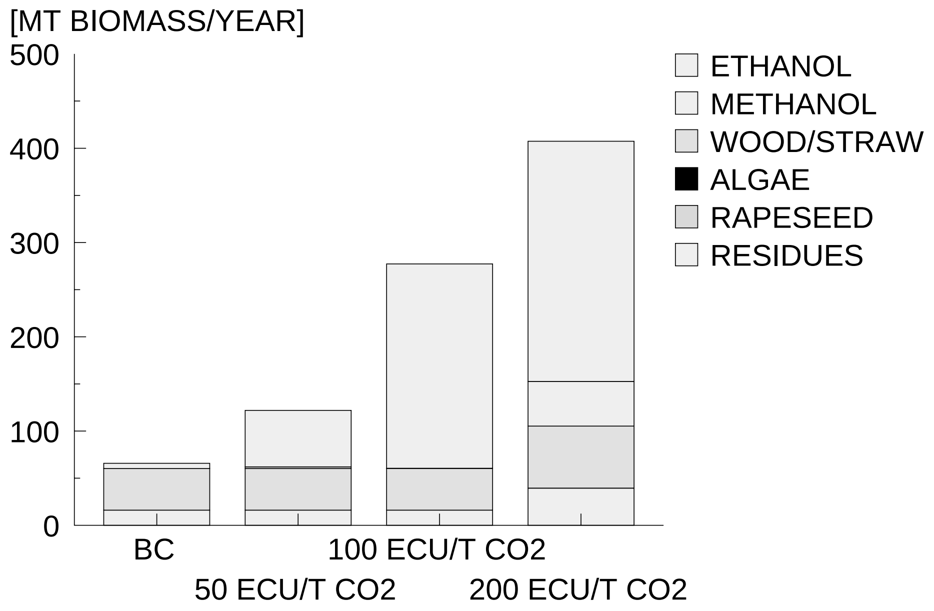

Figure 5.5: *Bioenergy use, split into applications, 2030, sensitivity analysis*

Figure 5.6 shows for the sensitivity analysis significant differences for the biomass use for materials production compared to the reference scenario. Especially the biomass use for petrochemical feedstocks is reduced. The bulk of the reduction is accounted for by the reduced flash pyrolysis. (Flash pyrolysis for ethylene production is not included in this scenario).

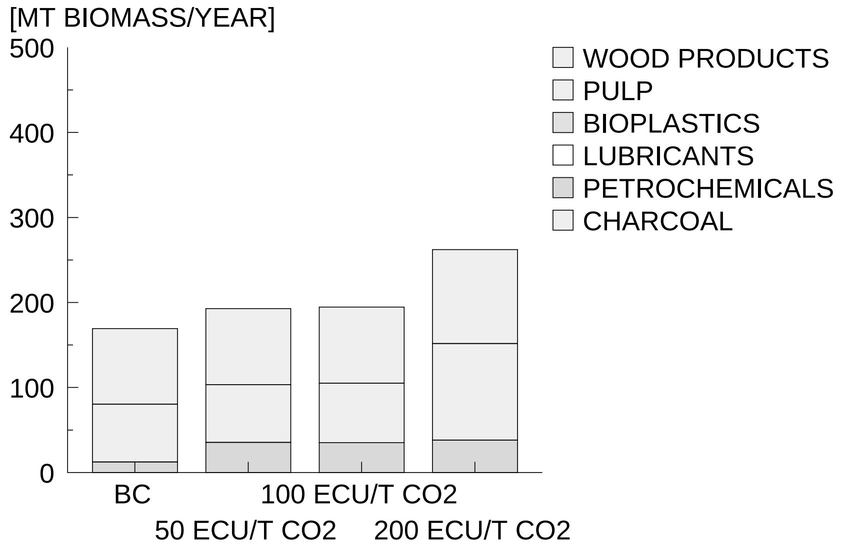

Figure 5.6: *Biomaterial use, split into applications, 2030*

Three key sets of parameters have been evaluated individually in order to analyse the sensitivity of the modelling results for input data. These parameters are land availability, ethanol production from lignocellulose crops, and ethylene production based on flash pyrolysis of wood. The latter two processes represent the bulk biomass application for bioenergy and biomaterials, respectively, in the cases with emission penalties.

Sensitivity analysis for land availability

The availability of surplus agricultural land in Western Europe in the next three decades is highly uncertain. It depends on many interacting parameters. A scenario analysis of future trends can be found in [92]. This analysis has resulted in three scenarios: 0 hectares, 22 hectares and 26 million hectares in 2050, depending on the scenario parameters. Below, two land availibility scenarios are worked out: one with a low land and one with a high land availibility.

In modeling terms, the scenarios are translated into a land availability of 2 million hectares and 22 million hectares, respectively. This level is reached in 2010. The 22 million hectare scenario has been used in the reference scenario model calculations, the 2 million hectare represents the sensitivity analysis. Higher land availability has not been analysed because the results for the 22 million hectare case show that land availability poses no constraint at penalty levels that are currently considered to be reasonable (up to 100 ECU/t CO_2). The maximum land availability level is in both scenarios reached in the year 2010. This implies a drastic change of European agricultural policies, especially for the 22 Mha case.

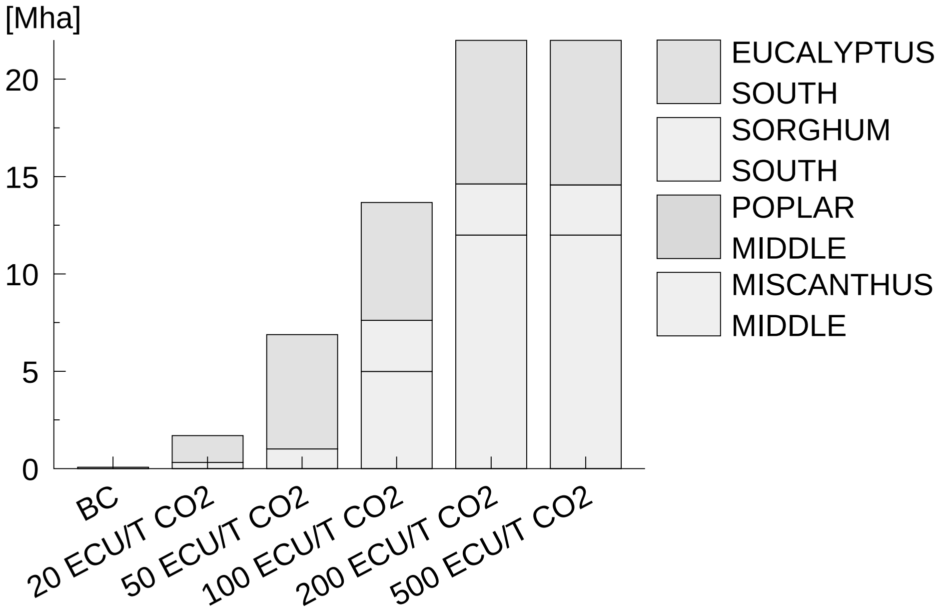

Figure 5.7: *Land use in the 22 Mha scenario, increasing GHG penalties, 2030*

The land use in the 22 Mha scenario is shown in Figure 5.7. The figure shows that the land use for biomass production is negligible in the base case. At a penalty level of 20 ECU/t CO_2, Eucalyptus and sweet sorghum production emerges in the South region. At the 100 ECU/t CO_2 penalty level, miscanthus production is introduced in the middle European region. At the 200 ECU/t CO_2 level, the full land area of 22 Mha is utilised. The land use in the 2 Mha scenario is shown in Figure 5.8. Again, the land use is negligible in the base case. At the 20 ECU/t CO_2 level, Eucalyptus and sweet sorghum are introduced in the Southern region. Moreover, poplar is introduced in the middle region. At 50 ECU/t CO_2, the full land area is utilised. Poplar is replaced by miscanthus at 100 ECU/t CO_2 because of the higher biomass yields. At the 200 ECU/t CO_2 level, Eucalyptus is substituted by sweet sorghum (again because of the higher yields). The result is in accordance with common sense: if land availability becomes a serious constraint for biomass production, the high yield crops are selected.

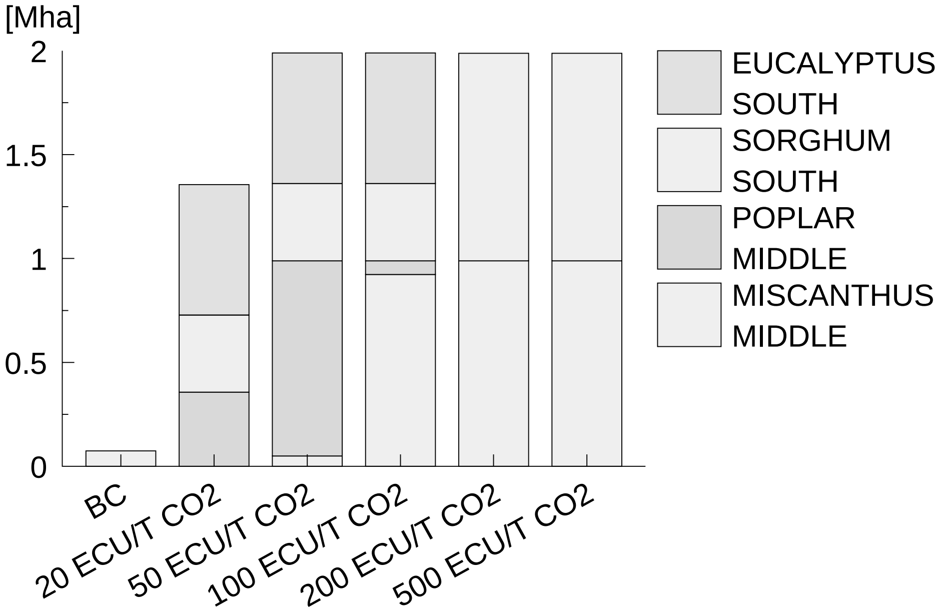

Figure 5.8: *Land use in the 2 Mha scenario, increasing GHG penalties, 2030*

Figure 5.9 shows the impact of land availability on the use of biomass for enery purposes. The impact proves to be very significant at penalty levels of more than 20 ECU/t CO_2. At lower penalty levels, around 100 Mt biomass from wood residues and agricultural residues is used for energy purposes. The gap between both scenarios increases to around 250 Mt biomass at penalty levels of 200 ECU/t upward. The main part of difference between the 2 Mha and 22 Mha case can be attributed to the production of ethanol from lignocellulose crops.

Figure 5.10 shows the impact of land availability on the use of biomass for materials production. The impact is not as pronounced as for energy production. The difference between both land availability cases is approximately 50-75 Mt biomass. The difference can mainly be attributed to the biomass use for production of petrochemical products such as ethylene.

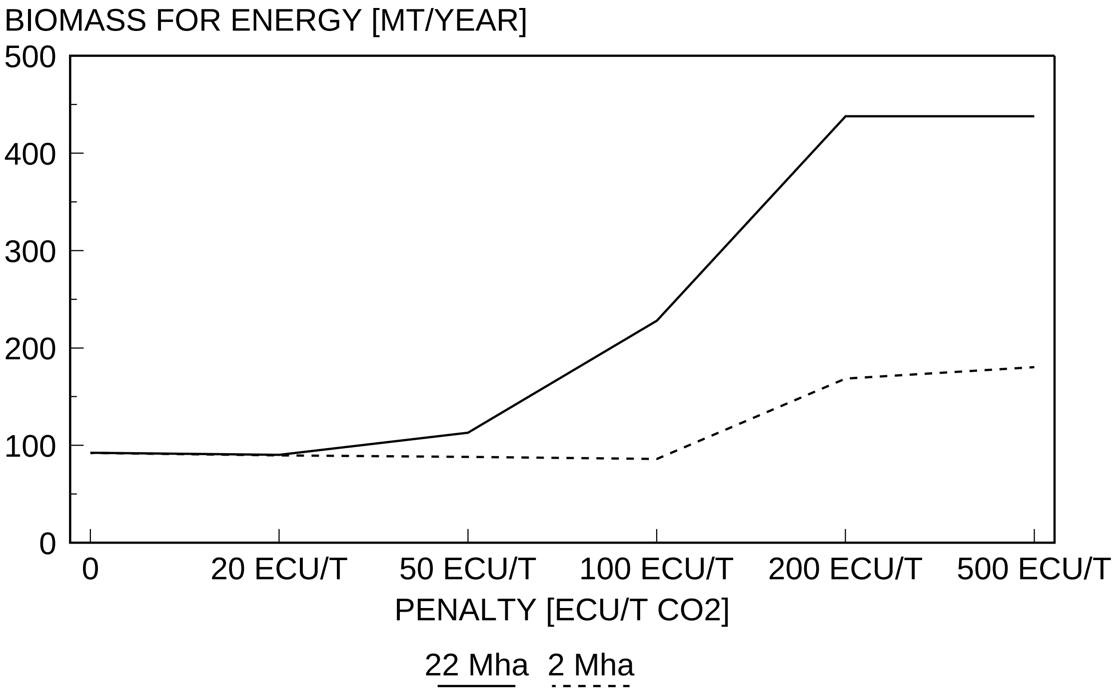

Figure 5.9: *Biomass use for energy, depending on land availability, increasing GHG penalties, 2030*

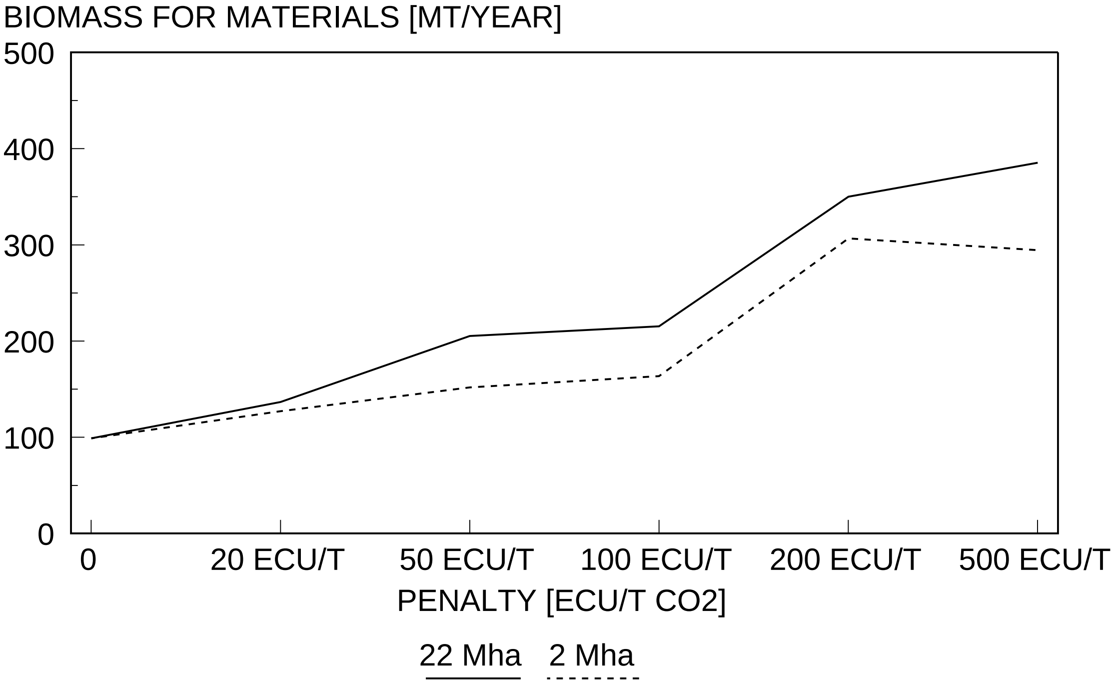

Figure 5.10: *Biomass use for materials, depending on land availability, increasing GHG penalties, 2030*

Figure 5.11 shows the impact of the reduced land availability on total GHG emissions. The difference between both scenarios increases to approximately 225 MT CO_2

equivalents at higher emission penalties (from 100 ECU/t CO_2 upward). This difference represents 5-10% of the total GHG emissions at these penalty levels or approximately 3% of the GHG emissions in the base case.

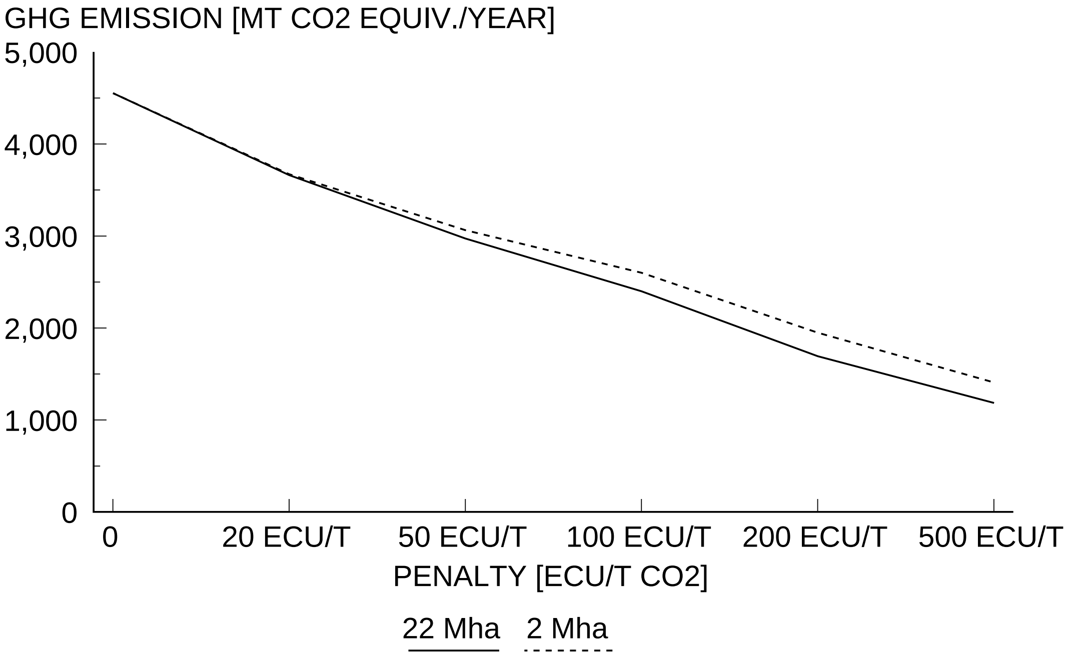

Figure 5.11: *The sensitivity of GHG emissions for land availability, 2030*

The results show that land availability is of key importance for bioenergy production, but to a much lower extent relevant for biomaterials production. Whether or not large amount of bioethanol are produced depends to a high extent on the availability of large areas of surplus land. The selection of crops remains largely the same for the high and low land availability cases, with a dominance of high yield crops.

Sensitivity analysis for ethanol production efficiency

The results for the reference case show that the ethanol production represents a very significant part of bioenergy production if GHG emission penalties are introduced. In a second sensitivity analysis, the efficiency of ethanol production has been analysed in more detail.

This parameter has been selected because the model assumptions regarding conversion efficiencies are thought to be fairly optimistic [18]. The reference case assumes an energy efficiency (carbon in biomass to ethanol, excluding additional steam inputs for distillation etc. and excluding consideration of lignine inputs and by-products) of 74% for sugar and starch, 74% for cellulose and 67% for hemicellulose. This includes pretreatment, hydrolysis, and fermentation, and is quite close to the theoretical maximum yield of 79%. Other sources indicate lower efficiencies (e.g. approximately 55% for ethanol from wood in the advanced simultaneous saccharification and fermentation with xylose fermentation case in [93]). Given that the process is not yet proven on a commercial scale and given the complex process route, efficiencies are uncertain.

The results in Figure 5.12 show that total biomass use for energy production is not affected by the lower ethanol production efficiency. However,the fraction of biomass use for ethanol production is significantly reduced. Instead, methanol production increases and the use of biomass for electricity production increases. This result shows that the production of biofuels (both quantity and fuel type) critically depends on the efficiency of the production processes. Therefore, the parameters of this process should be evaluated critically.

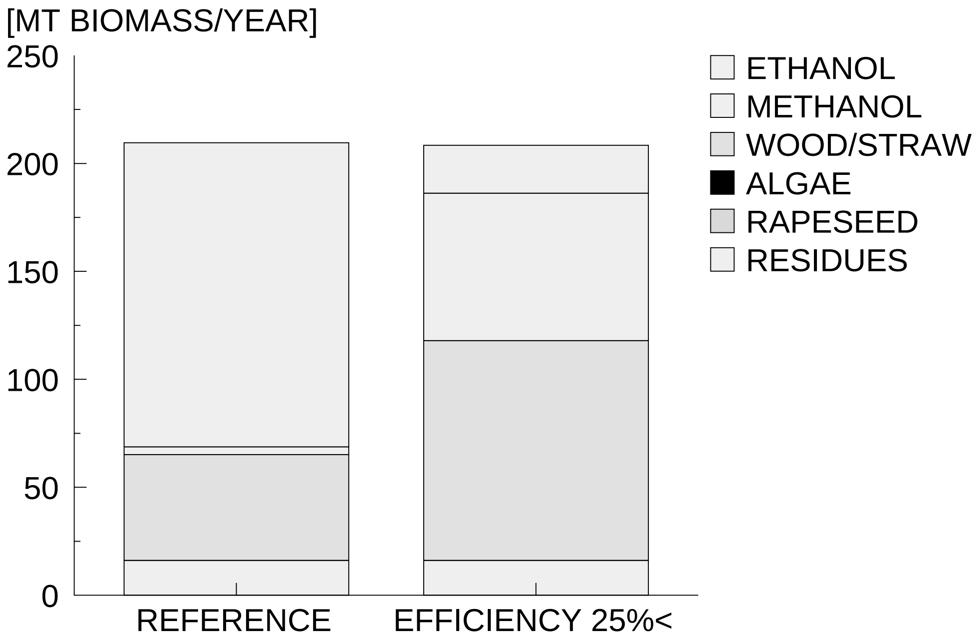

Figure 5.12: *The sensitivity of bioethanol production for the conversion efficiency of crops to ethanol, 2030*

Sensitivity analysis for wood flash pyrolysis

Regarding biomaterials production, the results show that the use of biomass for feedstock applications becomes significant in the cases with emission penalties. The main feedstock application is the flash pyrolysis of wood for production of ethylene and propylene. This is a technology which is not yet applied on a commercial scale and whose process characteristics are highly uncertain. One sensitivity run focuses on the efficiency towards the main products (ethylene and propylene). Another sensitivity run includes a generally worse conversion efficiency (both for the main products and for the by-products) and investment costs that are twice as high as for the reference case. The assumptions are shown in Table 5.1.

Table 5.1: *Parameters for wood flash pyrolysis in the sensitivity analysis*

	Unit	Reference case REF	Low ethylene yield case LE	Low yield/high cost case LY/HC
Ethylene yield	[t/unit]	1.00	0.50	0.50
BTX yield	[t/unit	0.75	0.37	0.37
Residual gas yield	[GJ/unit]	28.3	75	35
Investment costs	[ECU/unit]	1000	1000	2000

Figure 5.13 shows the ethylene production in 2030 in the base case and in the case with a 100 ECU/t CO_2 penalty. Wood pyrolysis is introduced at the 100 ECU/t CO2 penalty level and is indifferent from the assumptions regarding technology characteristics. However, the total amount of ethylene that is produced differs considerably (7 Mt ethylene less in the case with low yields and high costs). The difference is completely accounted for by the contribution of the wood flash pyrolysis process. The difference in production is related to a reduced consumption of polyethylene and reduced exports of ethylene oxide and ethylene glycol.

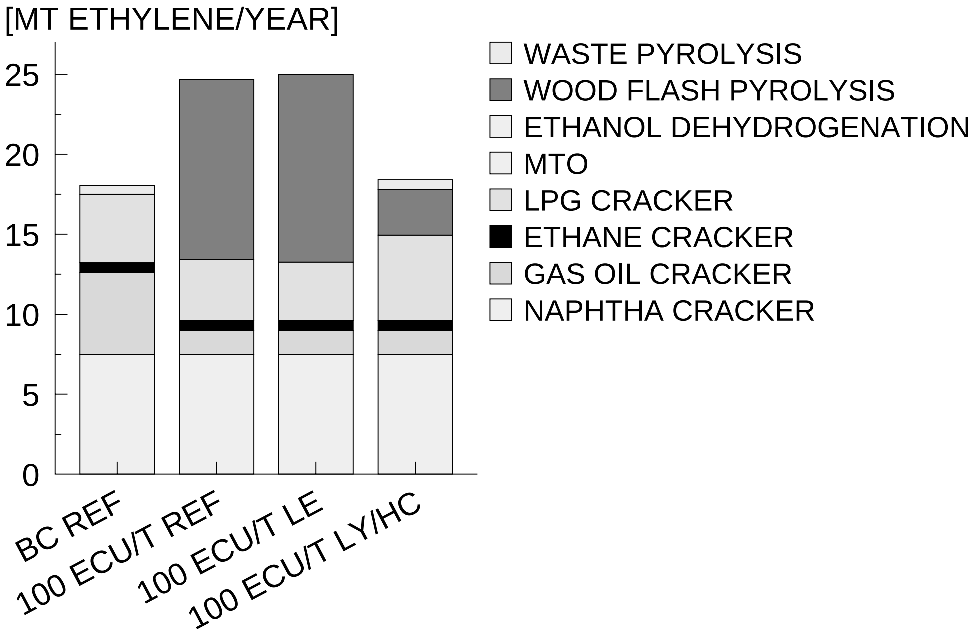

Figure 5.13: *The sensitivity of ethylene production for the flash pyrolysis parameters*

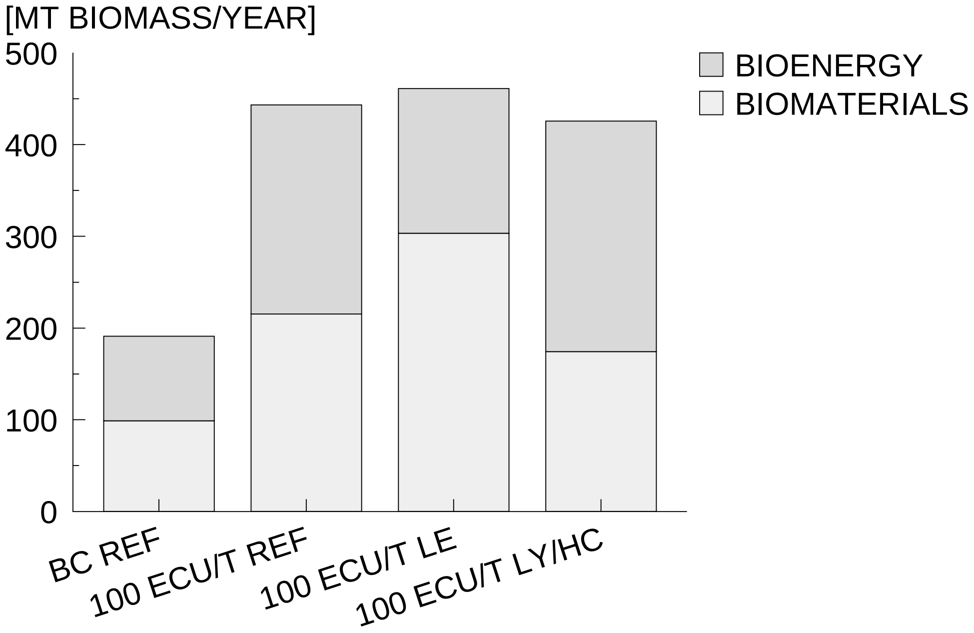

Figure 5.14: *The sensitivity of biomass use for the flash pyrolysis parameters*

Figure 5.14 shows the sensitivity of total biomass use for the wood flash pyrolysis parameters. Total biomass use is not significantly affected. However, the distribution over bioenergy and biomaterials differs significantly. In the case with low ethylene yield, twice as much biomass must be applied for flash pyrolysis in order to achieve the same ethylene yields (see figure 5.13). It is apparently not cost-effective to increase the total biomass production, hence less biomass is used for energy production.

From a Western European GHG emission reduction point of view, the difference hardly matters. For the year 2030, the GHG emission in the 100 ECU/t penalty case ranges from 2387 Mt in the case of low ethylene yields to 2426 Mt in the case of low total yield and high investment costs. The difference is only 1.6%.

6. CONCLUSIONS

MARKAL modeling results show that Western European biomass availability is no constraint at emission penalty levels up to 50 ECU/t CO_2. As a consequence, no competition occurs between bioenergy and biomaterial applications. On the contrary: the production of biomaterials results in an increased availability of process waste and post consumer waste that can be used for energy recovery. Only at emission penalty levels from 100 ECU/t CO_2 upwards, a trade-off between both applications will occur. The crops that are applied are the high-yield crops: Eucalyptus, Sweet Sorghum, Miscanthus and Poplar. The crops are first introduced in the Southern region with high yields, followed by the Middle region. Forest wood recovery increases simultaneously in the Northern and Middle region.

At penalty levels up to 100 ECU/t, materials applications dominate energy applications. At higher emission levels, energy applications dominate. This can be attributed to the combination of higher energy market volumes and the features of competing emission abatement strategies in energy and material markets. The conclusion for biomass strategy analysis is that materials applications must also be considered for the future assessment of bioenergy.

The sensitivity analysis with more conservative estimates suggests that the results are fairly robust for bioenergy use. However these results are determined by the assumptions regarding the feasibility of ethylene production based on flash pyrolysis. Because this technology was excluded in the sensitivity analysis, biomaterials use was significantly affected. The sensitivity analysis for individual model parameters showed that flash pyrolysis for production of petrochemical feedstocks and bioethanol production from lignocellulose crops are key technologies in the analysis. The parameters for both technologies determine to a large extent how the biomass should be applied. However the total amount of biomass that is applied is relatively independent of these assumptions. Land availability is a key parameter that will determine the future of bioenergy. The use of biomaterials seems less sensitive for land availability constraints. As a consequence, biomaterials deserve special attention in a situation where future land availability is uncertain.

The combination of biomaterials and bioenergy strategies results in additional biomass use for energy production, as by-products from materials production, especially lignine and by-products from pyrolysis processes can be used for energy recovery. Structural wood products with a long product life can only contribute to energy recovery after a product life of decades. Increased recycling and energy recovery of biomaterials poses an important option 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.

Regarding BRED, the following recommendations can be made:
- The data situation for bioenergy is considerably better than for biomaterials. It is recommended to focus further data acquisition on biomaterials.
- The current model database should be evaluated in by independent experts. Data quality criteria should be developed according to LCA and IAM guidelines. These indicators should be applied during the BRED data acquisition.

- More attention should be paid to food production in order to analyse future land availability.
- The emissions related to imported biomass should be analysed in more detail.
- CH_4 and N_2O emissions in the biomass life cycle deserve more attention.
- All biomass flows should be expressed in dry matter in order to facilitate comparison and ensure consistency.
- Treatment of labour inputs is not consistent in the current model version and should be adjusted.
- Data acquisition should be linked to the IEA bioenergy programme and related EU programmes (Euroflux etc.).

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Page 1

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