

JANUARY 2000

ECN-C--99-078

**BIOMASS FOR GREENHOUSE GAS
EMISSION REDUCTION**

Task 7: Energy Technology Characterisation

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Abstract

This report gives the input data for the biomass module of the MATTER 4.2 model, a MARKAL energy and materials systems engineering model for Western Europe. This model is used within the BRED study to determine the optimal use of biomass for energy and materials 'from cradle to grave'. This report is the result of Task 7 in the project 'Techno-economic characterisation of energy recovery and disposal options'. The separate sections cover electricity production from biomass, biomass heat, biofuels and gaseous fuels. The results will be presented in the final report of the project.

Acknowledgement

This study has been performed as part of the BRED project (Biomass for Greenhouse Gas Emission REDuction, ECN projectnumber 7.7125). This study deals with the techno-economic characterisation of energy recovery and disposal options.

A lot of people within and outside ECN have contributed to this report. They are:

F. Goudriaan (from Biofuel),
H.A. Zanting (from Gibros PEC).

And the following colleagues from the Biomass unit of ECN:

L. Dinkelbach,
J. van Doorn,
D. Jansen,
J.P.A. Neeft,
A.B.J. Oudhuis,
R. van Ree,
J.H. Reith,
H. den Uil.

Here, we would like to thank everyone for their input.

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GLOSSARY

ACFB	Atmospheric Circulating Fluidised Bed
AOO	Dutch acronym for Waste Consultation Organisation
A.r.	As received
BIC-SE	Biomass Integrated Combustor - Stirling Engine
BIG-CC	Biomass Gasification Combined Cycle
BIG-GT	Biomass Integrated Gasifier-Gas Turbine
BRED	Biomass for Greenhouse Gas Emission REDuction
CBP	Consolidated BioProcessing
CEST	Condensing Extraction Steam Turbine
CFB	Circulating Fluidised Bed
CH ₄	Methane
CHP	Combined Heat and Power production
CO	Carbonmonoxide
CO ₂	Carbondioxide, the most important greenhouse gas
Df	Dutch guilders (Df 1 ≈ 0,45 EUR)
DME	DiMethyl Ether
ECN	Netherlands Energy Research Foundation
EFTA	European Free Trade Association (i.e. Western non-EU countries)
ETBE	Ethyl Tertiary Butyl Ether
EU	European Union
EUR	EURO, European Monetary Union Currency Unit (1 EUR ≈ 1 USD)
FT	Fischer Tropsch
GHG	GreenHouse Gas
GJ	Gigajoule (10 ⁹ Joule)
H ₂	Hydrogen
HT	High Temperature
HTU	HydroThermal Upgrading
IEA	International Energy Agency
IGCC	Integrated Gasification Combined Cycle
kW _e	Kilowatt electric (1 kW _e = 31,536 GJ)
LFG	LandFill gas
LHV	Lower Heating Value
LPG	Low Temperature
LT	Liquefied Petroleum Gas
MARKAL	MARKet Allocation
MATTER	MATerials Technologies for greenhouse gas Emission Reduction
MEA	MonoEthanol Amine
MSC	Multi-Stage Combustion
MSW	Municipal Solid Waste
MTBE	Methyl Tertiary Butyl Ether
NGCC	Natural Gas Combined Cycle
Nm ³	m ³ gas at normal conditions (T = 0 °C and p = 1 bar)
Novem	Netherlands Organisation for Energy and Environment

O&M	Operating & Maintenance
PCFB	Pressurised Circulating Fluidised Bed
PEC	Dutch acronym for Product and Energy Plant
RD&D	Research, Development & Demonstration
RME	Rapeseed Methyl Ester
RTP	Rapid Thermal Processing
SFIX	Simultaneous Fermentation and Isomerization of Xylose
SHF	Separate Hydrolysis and Fermentation
SNG	Synthetic Natural Gas
SOFC	Solid Oxide Fuel Cell
SSCF	Simultaneous Saccharification and Co-Fermentation
SSF	Simultaneous Saccharification and Fermentation
TE	Total Energy
w%	Weight percent

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 and second as an energy source. This report focuses on biomass *energy* applications in order to reduce greenhouse gas emissions.

This report gives the input data for the biomass module of the MATTER 4.2 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 within the framework of the BRED study (Biomass for greenhouse gas emission REDuction). The structure of the biomass module is comprehensively described in a separate report (Gielen et al., 1998d).

The processes dealt with in this report are bio-energy conversion technologies and agricultural and domestic waste disposal options. The separate sections cover electricity production from biomass, biomass heat, biofuels and gaseous fuels (e.g. from anaerobic digestion). The most important differences, when comparing these data with former ones, are:

- the improvement of electrical efficiency,
- the addition of CO₂ removal option in biomass electricity production,
- the inclusion of new processes such as:
 - Dimethyl ether (DME),
 - Pyrolysis to oil ('fast' pyrolysis),
 - Fischer Tropsch,
 - ETBE production from bio-ethanol,
 - Hydrogasification.

The model results will be presented in the final report of the project (Gielen et al., 2000).

1. INTRODUCTION

BRED is an acronym for Biomass for Greenhouse Gas Emission Reduction. The Environment and Climate research programme of the European Union funds this project, which started in January 1998 and will last until December 1999.

A number of strategies have been proposed to reduce greenhouse gas (GHG) emissions. One important strategy is based on the introduction of more biomass as a substitute for fossil energy carriers and for materials. Biomass can be used to produce energy, e.g. heat, electricity or transportation fuels (called 'bio-energy'), or it can serve as a feedstock for synthetic organic materials and for structural materials such as timber (called 'biomaterials'). Biomass can also be used in a sequence of both applications, i.e. first as a material, second as an energy source. The availability of biomass (i.e. bio-energy 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 GHG 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.

Starting from the European Union policy goal of GHG emission reduction, the objective of this project is to determine the optimal use of biomass for energy and materials 'from cradle to grave'. In this way, we aim to achieve cost-effective GHG emission reduction on the long term (period 2000-2050) in the Western European (i.e. EU + EFTA) economy. The ultimate 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.

The following problems will be analysed:

1. Which prospective crops and prospective markets can be discerned for biomass in Western Europe for the period 2000-2050?
2. Which combination of bio-energy and biomaterials crops should European agriculture focus upon from the point of view of cost-effective GHG emission reduction policies?
3. Which conversion technologies, which markets and which biomass waste processing technologies must be developed?
4. How do the emission reduction potentials and the costs of bio-energy and biomaterials options for GHG emission reduction compare to other technological improvement options that compete in the same product and service markets?
5. Should a biomass-for-carbon-storage or a biomass-for-energy-and-materials strategy be applied to the limited European land resources?
6. What is the impact of a changing energy and materials system configuration and different scenarios (e.g. with regard to energy prices, CO₂ storage, energy conservation, renewables) on the future cost-effectiveness of biomaterial and bio-energy options for GHG emission reduction?

A system modelling approach will be applied in the study. The economic system is characterised by the energy and materials flows and by the 'technologies' which represent the conversion processes of one material flow to another. Technologies are modelled as 'black boxes', characterised by a linear relation between their physical inputs and outputs and by their costs. The analysis will be based on calculations with an extended version of a Western European integrated energy and materials system model. The biomass technology database of the Western European MARKAL MATTER 1.0 system engineering model (Gielen et al., 1998c) will be extended and improved, based on detailed information regarding energy and material flows and potential future biomass applications.

The BRED project research tasks are:

1. Quantification of current biomass production and use in Europe.
2. Assessment of land availability.
3. Assessment of biomass yield and production costs for different regions.
4. Identification of options for substituting materials.
5. Techno-economic characterisation of material production and recycling options.
6. Techno-economic characterisation of product assembly, utilisation and separation.
7. Techno-economic characterisation of energy recovery and disposal options.
8. Analysis of the information from tasks 5-7 in the MARKAL modelling framework.

This report is the result of task 7 and focuses on the energy technology characterisation. The processes dealt with in this report are bio-energy conversion technologies and agricultural and domestic waste disposal options (see Figure 1.1).

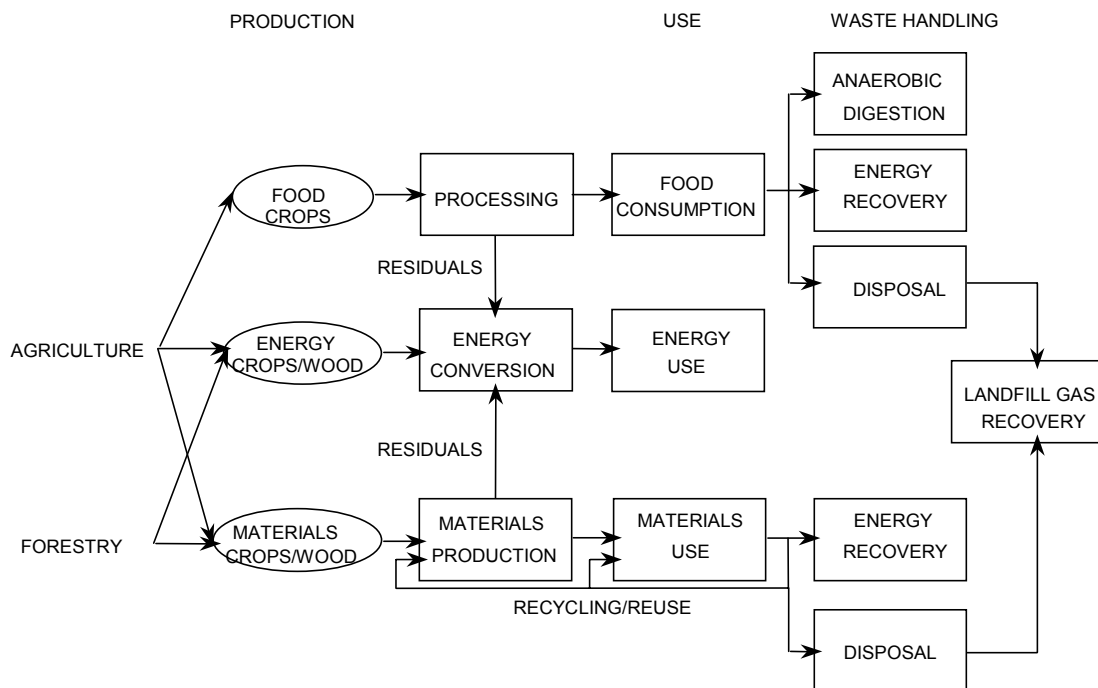


Figure 1.1 Structure of the biomass module of the MARKAL MATTER 4.2 model

The structure of the biomass module is comprehensively described in a separate report (Gielen et al., 1998d). The model input parameters will be discussed in four separate chapters:

- Electricity production (Chapter 2)
- Heat production (Chapter 3)
- Transportation fuels (Chapter 4)
- Gaseous fuels (Chapter 5).

The input parameters are presented in tables and should be interpreted taking into account the following guidelines and definitions:

Input/Output	<ul style="list-style-type: none">• relate to the defined physical inputs or outputs,• the amount is expressed in relation to the main input or output, of which the quantity by the model definitions equals 1.
Costs	<ul style="list-style-type: none">• Are divided in investment costs and <u>o</u>perating and <u>m</u>aintenance (O&M), costs.
Investment costs	<ul style="list-style-type: none">• the total costs of 1 unit of installed capacity,• refer to greenfield (e.g. new) side and include all costs for engineering, construction, land purchase, interest charges and working capital.
O&M costs	<ul style="list-style-type: none">• can be split in fixed and variable O&M costs,• fixed O&M costs are annual operating and maintenance costs associated with the installed capacity and charged regardless of utilisation, they include all costs except the costs of the physical inputs and minus the revenues of the physical outputs,• variable O&M costs are annual operating costs, which are proportional to the production activity.
Bounds ¹	<ul style="list-style-type: none">• relate to the installed capacity,• may be lower or upper bounds.
Life	<ul style="list-style-type: none">• The time period capacity is utilised (technical life after investment).
Availability	<ul style="list-style-type: none">• The total annual availability of a process, should account for both forced and scheduled outages during the entire year.

¹ Bounds are applied to e.g. control the penetration rate of a specific technology. It must be noted that none of the imposed bounds appears to play a major role in the calculations, except for the maximum bounds on straw briquetting and co-combustion in natural gas fired power plants. Therefore, an extensive sensitivity analysis has been done to check the impact of these two constraints (see Gielen et al., 2000).

2. ELECTRICITY PRODUCTION

2.1 Co-combustion in natural gas fired power plants

Co-combustion of biomass without CO₂ removal

Table 2.1 shows input data for co-combustion of biomass in a large-scale (300 MW_e) natural gas fired power plant (Natural Gas Combined Cycle or NGCC). The data refer to a plant where biomass (wood chips) constitutes 25% of the heating value of the fuel input of the gas plant. Before combustion, the wood chips first must be gasified in a gasification unit. The data below refer to atmospheric biomass gasification for 2000, and pressurised gasification (at 15 bar) for 2010 and 2030. The electrical efficiency improvement in Table 2.1 is mainly due to the improvement of the gasifier efficiency. The gasifier has a gasification efficiency of 75% in 2000 (cold gas cleaning) and 93% in 2030 (dry gas cleaning at 500 °C). The investment costs for the gasifier are 410 EUR/kW_{th} biomass input for the year 2000 and 340 EUR/kW_{th} biomass input for the year 2030 (Jansen, 1998; based on Farmer et al., 1997; Jong, 1998). The investment costs in Table 2.1 refer to the complete installation (gasifier + subsequent co-gasification). The code in the table title refers to the code of this specific process in the MARKAL MATTER 4.2 model, but has no meaning for the report reader.

Table 2.1 *Co-combustion in NGCC without CO₂ removal (BE2/SQG)*

		2000	2010	2030
Electrical net efficiency	[%]	52.0	56.0	60.0
Fraction of fuels				
- Natural gas	[%]	75	75	75
- Wood chips	[%]	25	25	25
Investment costs	[EUR ₁₉₉₅ /kW _e]	640	590	560
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	30	30	30
Life	[yr]	25	25	25
Upper bound	[GW _e]	0.1	1	25

Co-combustion of biomass with CO₂ removal

Table 2.2 shows input data for biomass co-combustion in the same large-scale (300 MW_e) natural gas fired power plant as described above, but with subsequent CO₂ removal. The data are based on a study of Stork Engineering and Consultancy which states that the (stand alone) NGCC efficiency decreases from 56% to 47% due to the removal of CO₂ and its injection in an empty gas field. For CO₂ removal from biomass flue gas, a solution of MonoEthanolAmine (MEA, chemical absorption) is used. Compression to 150 bar takes circa 0.45 GJ_e per ton CO₂ removed. Removal takes 6 GJ low pressure steam per ton CO₂. The study shows that the additional costs for CO₂ removal amount to 450 EUR/kW_e. The data in Table 2.2 refer to Jansen (1998) (based on Dorsteen, 1997; Pruschek and Göttlicher, 1996; Oudhuis, 1992).

Table 2.2 *Co-combustion in NGCC with CO₂ removal (BE2/SQH)*

		2000	2010	2030
Electrical net efficiency	[%]	43.0	46.5	51.0
Fraction of fuels				
- Natural gas	[%]	75	75	75
- Wood chips	[%]	25	25	25
Investment costs	[EUR1995/kW _e]	1130	1060	1010
O&M costs	[EUR1995/kW _e /yr]	60	60	60
Life	[yr]	25	25	25
Upper bound	[GW _e]	0.1	1	25

2.2 Co-combustion and co-gasification in coal fired power plants

Co-combustion of biomass and coal is considered for existing pulverised coal fired power plants, as well as for an Integrated Gasification Combined Cycle (IGCC). Since a few years, another option for co-firing of wood chips in a pulverised coal fired power plant has been in the development stage; the so-called Torbed co-firing plant. This option has the advantage that the net generating efficiency of biomass conversion into power is higher than in conventional coal fired power plants. Moreover, the investment costs are lower. This option is also considered in the model. Data are taken from Gielen et al. (1998a).

Table 2.3 *Co-firing of chips in a Torbed reactor coupled with a pulverised coal fired power plant (BE5)*

		2000	2010	2030
Year average net efficiency	[%]	40.3	40.3	40.3
Fraction of fuels				
- Coal	[%]	92	92	92
- Wood chips	[%]	8	8	8
Investment costs	[EUR ₁₉₉₅ /kW _e] ¹	600	600	600
O&M costs	[EUR ₁₉₉₅ /kW _e /yr] ¹	20	20	20
Life	[yr]	15	15	15
Upper bound	[GW _e]	0.1	25	25

¹ Investment costs and O&M costs related to the capacity of biomass fuelled power. Source: BTG (1995).

At present, KEMA is working on the development of a stand-alone Torbed reactor. Based on a qualitative comparison with more developed and commercialised incineration techniques, it was concluded that Torbed has enough potential as a competitive incineration technique to current technologies with an installation size of 20-60 MW_{th} (Vos, 1998). In general, Torbed appears to be best suitable for burning fine material that needs no further pre-treatment. Stand-alone Torbed reactors are already in commercial use, but only in waste recovery processes (Dodson, 1998).

Co-firing of biomass in large-scale fossil fuel fired power plants is considered to be an attractive option, since it benefits from the economy of scale, and can potentially be realised at relatively low (additional) investment costs. Limiting the biomass input to 10% of the total thermal plant input in case of co-gasification avoids the use of expensive additional gas clean-up technologies (Ree et al., 1998a, 1998b).

Co-gasification of biomass without CO₂ removal

Table 2.4 shows input data for co-combustion in a large scale (450 MW_e) coal fuelled power plant (IGCC). The data are based on the assumption that biomass (wood chips) constitutes 10% of the heating value of the fuel input. Before combustion, the wood chips first must be gasified in a gasification unit. The data below refer to atmospheric biomass gasification for 2000, and pressurised

gasification (at 15 bar) for 2010 and 2030. The electrical efficiency improvement in Table 2.4 is mainly due to the improvement of the gasifier efficiency. The gasifier has a gasification efficiency of 85% in 2000 (cold gas cleaning) and 95% in 2030 (dry gas cleaning at 500 °C). Based on these assumptions the data are derived. The investment costs for the additional gasifier are 410 EUR/kW_{th} gasifier input for the year 2000, and 340 EUR/kW_{th} gasifier input for the year 2030. Data are taken from Jansen, 1998 (based on Pruschek et al., 1998; Ree et al., 1998a). The investment costs in Table 2.4 refer to the complete installation (gasifier + subsequent co-gasification).

Table 2.4 *Co-gasification in IGCC without CO₂ removal (BE6/SQK)*

		2000	2010	2030
Electrical net efficiency	[%]	47.5	50.5	54
Fraction of fuels				
- Coal	[%]	90	90	90
- Wood chips	[%]	10	10	10
Investment costs	[EUR ₁₉₉₅ /kW _e]	1110	1020	1010
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	65	60	60
Life	[yr]	25	25	25
Upper bound	[GW _e]	4	47	–

Co-gasification of biomass with CO₂ removal

Table 2.5 shows input data for biomass co-combustion in the same large scale (450 MW_e) coal fuelled power plant as described above, but with subsequent CO₂ removal. CO₂ removal from flue gas is achieved by means of physical absorption using SELEXOL. In this case, CO₂ is available at a pressure of 30–40 bar. The energy required for CO₂ removal is 0.3 GJ_e per ton. Compression takes circa 0.45 GJ_e per ton CO₂ removed. For each GJ of coal, 0.094 ton CO₂ is formed. We assume that 98% of the carbon supplied through coal is removed as CO₂. Coal gasification produces flue gas consisting of 65% CO and 30% H₂. For removal, CO must be converted to CO₂ by a shift reaction ($\Delta H = 0.94$ GJ/ton CO₂ produced). As a result of the shift reaction, 0.89 GJ_{th} steam is withdrawn from the steam system per ton CO₂. The additional investment costs for CO₂ removal are 140 mln EUR in case of a 450 MW_e plant.

Table 2.5 *Co-gasification in IGCC with CO₂ removal (BE6/SKL)*

		2000	2010	2030
Electrical net efficiency	[%]	40.5	43.5	47
Fraction of fuels				
- Coal	[%]	90	90	90
- Wood chips	[%]	10	10	10
Investment costs	[EUR ₁₉₉₅ /kW _e]	1662	1540	1518
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	100	90	90
Life	[yr]	25	25	25
Upper bound	[GW _e]	4	47	–

2.3 Biomass Gasification Combined Cycle (BIG-CC)

Demonstration projects²

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_e). Demonstration BIG-CCs are to be built in a number of countries. They have electrical efficiencies of 32–41% and total efficiencies (electricity and heat) 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 con-

² This section is based on Gielen et al. (1998d). Data is from Jansen, 1998 (based on Faaij et al., 1998; Ree, 1997a).

tent of 10% by weight is used as fuel. Generally, wood as received has a higher moisture content (up to 50% by weight). Figure 2.1 shows the investment costs and the electrical efficiency of a few demonstration projects (Basbucci and Neri, 1996; Beenackers and Maniatis, 1996; Pitchner, 1996; Sthl, 1996).

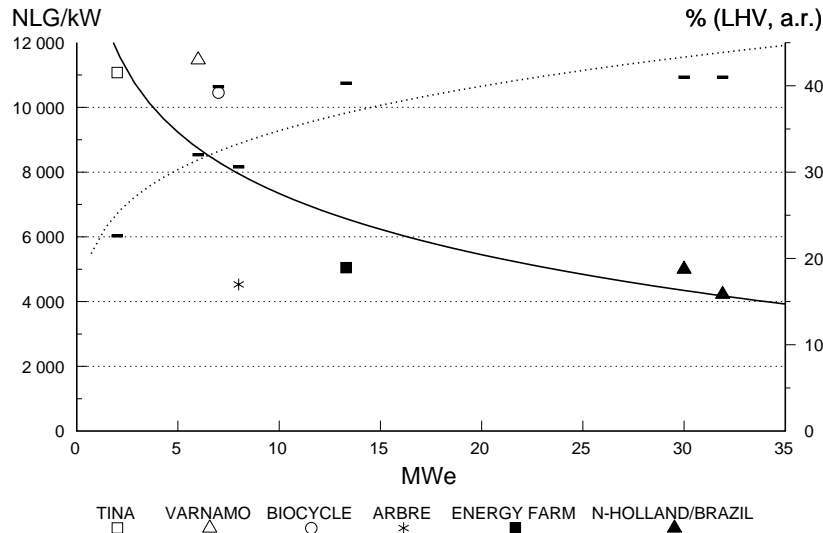


Figure 2.1 *Investment costs and efficiency of demonstration BIG-CC biomass gasification projects for power production or combined heat and power (Df 1 ≈ 0,45 EUR)*
 LHV, a.r. = Lower Heating Value, as received.

Relatively small biomass gasification projects are characterised by high specific capital costs, at least in the demonstration stage. For larger demonstration projects, investment costs are presumably of the order of magnitude of 2000-2500 EUR/kW_e. The 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 Fluidized Bed (ACFB) gasification.
- Pressurised Circulating Fluidized 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 fuelled IGCC. The use of air as a 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 (atmospheric or pressurised) and gasifying agent (air or oxygen).

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% (Morris, 1996). Using projects as ARBRE and World Bank/Brazil as a reference, investment costs of a commercial 60 MW_e BIG-CC could be as low as 1500 EUR/kW_e. Such a level of investment costs is also reported for a 30 MW_e BIG-CC in Faaij (1997): the 'Noord-Holland' project. For larger 120 MW_e BIG-CCs investment costs are estimated at 1200 EUR/kW_e in 2020. This level of investment costs is comparable with a cost estimation of 1500 USD/kW_e for a commercial 52 MW_e BIG-CC. Operation and maintenance costs are estimated at 12 EUR/MWh in 2000, decreasing to 9.5 EUR/MWh in 2020.

Table 2.6 gives input data for a biomass fuelled IGCC of 30 MW_e. Data are based on poplar wood as a fuel.

Table 2.6 *Costs and efficiencies of biomass fuelled IGCC (30 MW_e) (BE3)*

		2000	2010	2030
Year average net efficiency	[%]	40	47	53
Investment costs	[EUR ₁₉₉₅ /kW _e]	2040	1790	1620
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	200	160	90
Life	[yr]	25	25	25
Upper bound	[GW _e]	0.1	5	25

2.4 Biomass Gasification Solid Oxide Fuel Cells (BIG-SOFC)

VTT Energy in Finland (Makinen et al., 1994) 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 (Jansen et al., 1995). 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. Figures in Table 2.7 are taken from Jansen (1998) (based on Jansen et al., 1995) where a SOFC efficiency of 65-70%, and a biomass gasification efficiency of 80-90% is assumed.

Table 2.7 *Costs and efficiencies of BIG-SOFC system (available in 2010) (BE4)*

		2010	2020	2030
Year average net efficiency	[%]	50	55	62
Investment costs	[EUR ₁₉₉₅ /kW _e]	2600	2400	1720
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	260	200	160
Life	[yr]	20	25	25
Upper bound	[GW _e]	2	26	50

2.5 Biomass combustion Stirling engines

In addition to relatively large scale options such as 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.

The design of the Stirling engine makes it particularly suitable for difficult fuels, because the combustion does not take place in the cylinders but external as in a boiler. Depending on the design of the engine and the design of the firing equipment, it is possible to use gaseous, liquid and solid fuels (Centre for Biomass Technology, 1998). One of the future applications could be the 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 Ree (1997b). Figures in Table 2.8 are from Jansen (1998).

Table 2.8 *Industrial Stirling Engine for small scale CHP (BIC-SE) (BE1)*

		2000	2010	2030
Total Energy mode				
- Electrical efficiency	[%]	15	20	25
- Thermal efficiency	[%]	70	65	55
Investment costs	[EUR ₁₉₉₅ /kW _e]	1900	1600	1550
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	140	90	85
Life	[yr]	20	20	20
Upper bound	[GW _e]	10	12	16.5

2.6 Large scale industrial CHP

Western Europe, especially Denmark, has a long tradition in utilising waste and biofuels for thermal conversion. Combined heat and power (CHP) production however, has only been introduced recently (10 years ago) as a consequence of an energy policy agreement of 1986. This agreement laid down that decentralised CHP plants with a total power output of 450 MW fired with domestic fuels such as straw, wood, waste, biogas and natural gas were to be constructed up to 1995 (Centre for Biomass Technology, 1998; Anonymous).

A publication by the Centre for Biomass Technology (1998) gives figures for six straw-fired decentralised CHP plants that are already in operation and a 7th planned plant. Input data in Table 2.9 are based on Denmark's biggest CHP plant built in Måberg (and operated since 1993) which is fired with waste, straw, wood chips and natural gas. This station was established in order to utilise the domestic fuels in the region for the supply of heat required in two municipalities (Tranberg, 1998).

Table 2.9 *Large scale biomass CHP for district heating (30 MW_e) (BE7)*

		2000	2010	2030	
Total Energy mode					
-	Electrical efficiency	[%]	27	32	37
-	Thermal efficiency	[%]	61	56	51
Fraction of fuels					
-	Waste	[%]	56	56	56
-	Straw	[%]	27	27	27
-	Wood chips	[%]	6	6	6
-	Natural Gas	[%]	11	11	11
Investment costs	[EUR ₁₉₉₅ /kW _e]	1900	1500	1400	
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	145	100	95	
Life	[yr]	25	25	25	
Upper bound	[GW _e]	25	25	25	

3. HEAT PRODUCTION

3.1 Residential heating

For residential heating purposes, where biomass is used as a fuel, typically use is made of straw and wood (logs). Straw is a by-product resulting from the growing of commercial crops, primarily cereal grain, but also straw from rape and other seed-producing crops is included in the total production. Wood can be the (by-) product of forest thinnings or especially planted for energy purposes (short rotation species).

Of the total straw production, only a minor part is used for energy purposes. Straw used for fuel purposes usually contains 14-20% water that vaporises during burning. Combustion takes place in four phases. During phase 1, the free water vaporises. In phase 2, the pyrolysis (gasification) occurs, during which combustible gases are produced (depending on the temperature). Phase 3 is the combustion of gases. If sufficient oxygen is supplied, a complete combustion occurs. During phase 4, the charcoal burns (Centre for Biomass Technology, 1998).

Straw cannot be used directly as a fuel. First, it has to be compacted in order to increase its energy density. Two different compacted forms are possible: briquettes or pellets. Table 3.1 shows straw briquetting data. The data 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 an automatic pelletising installation with a high availability factor of 3000 hours per year (Bos, 1991).

Table 3.1 *Biomass straw briquetting plant (BBI)*

	Units	1990	2010	2030
Input				
- Electricity	[GJ]	0.053	0.035	0.035
- Straw	[GJ]	1.0	1.0	1.0
Output				
- Energy Wood (size > 5 cm)	[GJ]	1.0	1.0	1.0
Investment Costs	[EUR ₁₉₉₅ /GJ straw]	14.3	7.1	7.1
O&M Costs				
- Fixed	[EUR ₁₉₉₅ /GJ straw/yr]	3.1	0.3	0.3
- Variable	[EUR ₁₉₉₅ /GJ straw]	0.2	0.02	0.02
Availability factor		0.11	0.34	0.34
Life	[yr]	15	15	15
Upper bound	[PJ]	10	250	335

In Denmark, experiments have been carried out on the use of straw pellets, i.e. comminuted straw that has been pressed into pellets of a diameters of 8 or 10 mm. The caloric value of the pellets is 16.3 MJ/kg at 8% water, and the density is 4 times larger than that of straw baled into big bales. The density is approximately 550 kg/m³. The experiments mentioned showed that straw pellets can be used as a fuel in large boilers, whereas ash and particularly slagging problems make straw pellets less suitable for use in small boiler plants (Centre for Biomass Technology, 1998).

No cost data were given for the above mentioned pellets. Dahlström (1998) however, working in a pellet producing company, mentioned selling prices of circa 80 EUR/ton. These pellets are wood based and produced of waste products from sawmills and other industries (sawdust,

planer shavings, bark or similar). However, also other raw materials can be used for the production of pellets, for instance branches and tops from logging sites, paper waste and wood waste from industries. Pellets can be produced with a diameter maximum of 25 mm. For private house customers 6 and 8 mm are most suitable in order to achieve good combustion results.

Single- and multi-family dwellings

Kaltschmitt and Wiese (1993) give data for the heating of single as well as multi-family dwellings by means of biomass (straw residues and short rotation species). These are presented in Tables 3.2 to 3.5. According to these data, wood based fuels are cheaper in case of multi-family dwellings. There is no such difference for single family dwellings.

Table 3.2 *Single-family dwelling heating by straw residues*

		2000	2010	2030
Thermal efficiency	[%]	70	70	70
Investment costs	[EUR ₁₉₉₅ /GJ]	76	76	76
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ/yr]	1	1	1
- Variable	[EUR ₁₉₉₅ /GJ]	0.5	0.5	0.5
Life	[yr]	15	15	15
Availability factor		1	1	1

Table 3.3 *Multi-family dwelling heating by straw residues*

		2000	2010	2030
Thermal efficiency	[%]	74	74	74
Investment costs	[EUR ₁₉₉₅ /GJ]	62	62	62
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ/yr]	1.4	1.4	1.4
- Variable	[EUR ₁₉₉₅ /GJ]	0.5	0.5	0.5
Life	[yr]	15	15	15
Availability factor		1	1	1

Table 3.4 *Single-family dwelling heating by poplar*

		2000	2010	2030
Thermal efficiency	[%]	70	70	70
Investment costs	[EUR ₁₉₉₅ /GJ]	76	76	76
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ/yr]	1	1	1
- Variable	[EUR ₁₉₉₅ /GJ]	0.5	0.5	0.5
Life	[yr]	15	15	15
Availability factor		1	1	1

Table 3.5 *Multi-family dwelling heating by poplar*

		2000	2010	2030
Thermal efficiency	[%]	74	74	74
Investment costs	[EUR ₁₉₉₅ /GJ]	47	47	47
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ/yr]	1.2	1.2	1.2
- Variable	[EUR ₁₉₉₅ /GJ]	0.5	0.5	0.5
Life	[yr]	15	15	15
Availability factor		1	1	1

In above figures, it is assumed that heating by biofuels is achieved through new (i.e. efficient) stoves. These stoves use a sophisticated secondary combustion process that effectuates more complete combustion of wood, thereby increasing the fireplace's operating efficiency and reducing the amount of incomplete combustion products. The energy efficiency of advanced combustion fireplaces is approximately 50% to 70%, whereas the efficiency of conventional wood fireplaces is on average between -10% and +10% (Anonymous, 1996). Negative efficiencies are due to a created draft which results in cold air entering the buildings.

According to Okken et al. (1992), the efficiency of wood fireplaces can vary between -10% and +50%, depending on the excess air amount. Measurements of wood stoves in The Netherlands resulted in an average efficiency of 50%, also depending on the type (Heeden et al., 1984). According to calculations by Okken et al., every GJ wood input saves 0.45 GJ natural gas.

District heating plants

The term 'district heating plant' always refers to plants with heat production but without electrical power generation. In Denmark, straw-fired district heating plants have been constructed since 1980, and 58 are now in operation (average size 3.7 MW). Normally, an oil-fired boiler is installed next to the straw-fired one, so as to cover the entire heat output requirement to be used at peak loads, repair or damage of the straw-fired boiler.

Various types of straw boiler plants exist, having different firing principles that require different equipment for transport and handling of straw from storage to boiler. However, all boiler plants consist of the same main components. Details can be found in Straw for Energy Production (by Centre for Biomass Technology, 1998).

The Centre for Biomass Technology (1996) collected data about the costs of construction of straw fired heating plants in Denmark. As an example, Table 3.6 gives figures for a town where both a new plant and a new distribution net are established.

Table 3.6 *Straw-fired boiler for district heating (3 MW)*

		2000	2010	2030
Total Energy mode				
- Thermal efficiency	[%]	84	84	84
Fraction of fuels				
- Straw (12% water)	[%]	93	93	93
- Oil	[%]	7	7	7
Investment costs	[EUR ₁₉₉₅ /kW]	1250	1250	1250
O&M costs	[EUR ₁₉₉₅ /kW/yr]	200	200	200
Life	[yr]	20	20	20
Availability factor		1	1	1

CHP plants

VKW-Kaufmann GmbH & Co has been operating a biomass-fired CHP plant since 1995 in Reuthe (Austria). The plant is optimised entirely according to the heat requirement. The plant has a thermal capacity of 10 MW (Mathis, 1996 and 1998). Table 3.7 gives plant figures.

Table 3.7 *Biomass-fired boiler for district heating (10 MW)*

		2000	2010	2030
Total Energy mode				
- Electrical efficiency	[%]	13	13	13
- Thermal efficiency	[%]	64	64	64
Fraction of fuels				
- Energy wood (10% water)	[%]	70	70	70
- Wood chips	[%]	30	30	30
Investment costs	[EUR ₁₉₉₅ /kW]	1500	1500	1500
O&M costs				
- Fixed	[EUR ₁₉₉₅ /kW/yr]	50	50	50
- Variable	[EUR ₁₉₉₅ /kW]	25	25	25
Life	[yr]	20	20	20
Availability factor		1	1	1

3.2 Industrial boilers

Industrial heat generation based on biomass fuels, will generally be achieved by combined heat and power (CHP) plants. At a CHP plant, it is possible to regulate the turbine within certain limits, so the ratio between electrical power production and heat production is changed. In principle, the higher the heating requirement, the more steam can be produced by the boiler with the subsequently greater electrical power generation. Data for various CHP plants were given in earlier sections (see e.g. Section 2.6 and 3.1). Therefore, only new data on two lignin based CHP plants are added here.

Lignin is a by-product of the Kraft chemical pulping process in paper production. After pulping, the fibers are separated from the pulping liquor, and the resulting ‘black liquor’ (i.e. the mix of lignin and pulping chemicals) is evaporated to increase the solids content. This concentrate then goes to the recovery section where it is burned in a Tomlinson recovery boiler. Steam and electricity are generated by the Condensing Extraction Steam Turbine (CEST). Another option for energy recovery is gasification of the ‘black liquor’ with subsequent combustion in a Biomass Gas Turbine. The electricity produced is 2-3 times more than in conventional recovery boilers, resulting in a power output greater than the process demand level. The whole system, which is not yet a common technology, is referred to as Biomass Integrated Gasifier-Gas Turbine (BIG-GT) (Hekkert and Worrell, 1997; Larson, 1999, Dahlquist and Ringvall, 1999).

The Tomlinson type of recovery boilers has been used for many years in chemical recovery for Kraft pulp mills. Although the process has been developed and refined during many years, there still are some significant drawbacks (e.g. the risk of steam explosion). Therefore, there has been a significant interest to develop new processes using gasification. Dahlquist and Ringvall (1999) give an overview of recent developments and describe a dry black liquor gasification process based on steam reforming in a fluidized bed. They conclude that the process should be feasible also in large scale, but that it is still difficult to compete with proven technologies. In the MARKAL MATTER 4.2 model, we assume that from 2010 black liquor gasification will be common technology.

Table 3.8 *Lignin boiler for industrial CHP (BD1)*

		2000	2010	2030
Total Energy mode				
- Electrical efficiency	[%]	9	9	9
- Thermal efficiency	[%]	57	57	57
Investment costs	[EUR ₁₉₉₅ /kW _e]	2100	2100	2100
O&M costs				
- Fixed	[EUR ₁₉₉₅ /kW _e /yr]	100	100	100
Life	[yr]	30	30	30
Availability factor		1	1	1

Table 3.9 *Lignin gasifier for industrial CHP (available in 2010) (BD2)*

		2000	2010	2030
Total Energy mode				
- Electrical efficiency	[%]		26	26
- Thermal efficiency	[%]		44	44
Investment costs	[EUR ₁₉₉₅ /kW]		1000	1000
O&M costs				
- Fixed	[EUR ₁₉₉₅ /kW _e /yr]		50	50
Life	[yr]		20	20
Availability factor			1	1

3.3 Co-combustion in cement ovens

Conventional cement ovens are fired with coal. Substitution of coal by biomass is one possibility to save primary fuels. Recently, the Delft University of Technology has studied the perspectives of using combustible waste in the Belgian and French cement industry (Vanderborcht and Dijkema, 1996). The relatively high energy conversion efficiency in a cement oven makes it extremely suitable for energetic use of both high and low caloric waste matter.

According to Rosemann and Große (1995) and Knopf (1995), possibilities of utilising residues in the cement industry are numerous. The burning process in the production of cement clinker offers multiple possibilities for the utilisation of alternative raw materials and fuels due to high temperature technical processing. The utilisation of alternative materials has several advantages, but nevertheless must be examined thoroughly in each individual case. In general, the adaptability of alternative materials depends mainly upon its characteristics. Knopf (1995) mentions successful experiments with old tires, shredder scraps, municipal solid waste (MSW) and plastic waste. With MSW, percentages of up to 50% of the fuel energy could be realised without a deterioration of the clinker quality and maintaining the energy efficiency.

Rosemann and Große (1995) describe technological characteristics of a new rotary kiln near Hamburg with a capacity of 4500 ton cement clinker per day. This kiln has been designed according to precalciner processing in such a way, that up to 50% of the fuel and up to 16% of raw material can be substituted by residues. Applying the selected multi-stage combustion (MSC) technology, approximately 65% of the fuel will be put in the calciner at a temperature of 850°-900°C. Alternative materials in lump form such as waste paper, fuller earth and residue rubber are also burned here together with the regular fuel coal dust. Waste oil, that could contain chlorinated hydrocarbons, is burned in the rotary kiln at a combustion temperature of 2000°C.

The utilisation of modern precalcining technology results in a significant reduction of energy consumption in the production of clinker. Compared to the existing kiln technology, the fuel energy consumption with regard to clinker, will be reduced from approximately 4.1 MJ/kg clinker to 3.4 MJ/kg clinker. A 15% reduction in the clinker related electrical energy consumption is also to be expected.

Economical data concerning co-combustion in cement kilns are hardly mentioned in the referred literature. Investment costs of the above mentioned kiln are 66 mln EUR (Rosemann and Große, 1995). Knopf (1995) mentions that the additional investment costs for combustion of 22 kton MSW in a kiln with a capacity of 500 kton clinker per year are 750.000 EUR (35 EUR/t MSW). The additional O&M costs are 220.000 EUR (10 EUR/t MSW). Comparable costs for waste incineration are around 1000 EUR/t MSW (see also section 3.4).

Table 3.10 *Co-combustion in cement ovens (based on Rosemann and Große, 1995)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/ton clinker]	0.2	0.2	0.2
- Charcoal and cokes	[GJ/ton clinker]	1.7	1.7	1.7
- Mixed waste	[GJ/ton clinker]	1.7	1.7	1.7
Output				
- Portland cement clinker	[ton]	1	1	1
Investment costs	[EUR ₁₉₉₅ /ton clinker]	40	40	40
O& M costs				
- Fixed	[EUR ₁₉₉₅ /ton clinker/yr]	10	10	10
- Variable	[EUR ₁₉₉₅ /ton clinker]	10	10	10
Life	[yr]	25	25	25
Availability		0.95	0.95	0.95

3.4 Waste incineration

Grate firing in combination with a steam boiler working under moderate steam conditions is the most commonly used technique to recover energy from municipal solid waste (MSW). Due to the characteristics of MSW (i.e. its low energy content), energy recovery with a high efficiency is hard to achieve. In case of electricity production, the gross efficiency is comparatively low because of the steam cycle conditions. Moreover, the internal energy consumption is comparatively high (for cleaning of flue gasses, etc.). These two factors result in a net efficiency that is much lower than the usual electrical efficiencies in power production. Current grate firing systems achieve an efficiency of 20-22% (Pfeiffer, 1995).

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 (Moerdijk) and is currently operating. LT steam from the incinerator is used for combined heat and power production by a neighbouring power plant. Part of this HT steam is used as process heat by Shell and the resulting condensate is directed to the incinerator again. In this way, heat losses from the incinerator are minimised.

Table 3.11 *Waste-to-energy plant (grate firing) (EI1)*

		2000	2010	2030
Year average net efficiency	[%]	22.5	28	30
Investment costs	[EUR ₁₉₉₅ /kW _e]	5500	5000	4500
O&M costs				
- Fixed	[EUR ₁₉₉₅ /kW _e /yr]	67	67	67
Life	[yr]	30	30	30
Availability		0.95	0.95	0.95
Upper bound	[GW _e]	5	-	-

Besides grate firing, alternative techniques for the thermal treatment of MSW are also offered nowadays. These techniques, based on incineration, gasification and sometimes pyrolysis as a pre-treatment step, are already commercially available or will probably be within a few years. The alternatives for grate firing have mainly been developed in order to improve the environmental performance.

3.5 Waste gasification

The Lurgi Eco-gas process has been developed with a view to cost-effective thermal disposal of municipal waste. It depends on shredded and low-moisture waste feed for optimum process operation. After size reduction, the waste is fed to the circulating fluidized bed (CFB) gasifier (Löffler, 1997). Table 3.12 gives input data based on MSW.

Table 3.12 *Waste-to-energy plant (Lurgi gasifier) (EI2)*

		2000	2010	2030
Year average net efficiency	[%]	33	33	33
Investment costs	[EUR ₁₉₉₅ /kW _e]	9000	8000	6500
O&M costs				
- Fixed	[EUR ₁₉₉₅ /kW _e /yr]	67	67	67
Life	[yr]	30	30	30
Availability		0.95	0.95	0.95
Upper bound	[GW _e]	-	-	-

3.6 Waste pyrolysis

An alternative waste treatment technology is developed by Gibros PEC. Gibros PEC offers a technology based on a combination of two-stage gasification and pyrometallurgical smelting. This process converts waste materials into synthesis or fuel gas (for combined heat and power), metals/metal mixtures (for recycling) and construction material (synthetic basalt). This complete solution is named the Product and Energy Plant (Dutch acronym: PEC[®]) (Neeft et al., 1998). First pyrolysis takes place in an externally heated rotary kiln. The tar containing gases resulting from this pyrolysis step are subsequently gasified at high temperature (1200°-1300°C) to produce syngas. Gasification takes place in the presence of either air or oxygen (depending on the application of the product gas). The pyrolysis residue (char, including minerals and metals) is smelted into synthetic basalt and metal mixtures, using the remaining coal fraction as energy source and producing additional syngas.

Table 3.13 gives typical values for waste gasification based on PEC technology. These data are from Oudhuis (Oudhuis, 1998; based on AOO, 1998; CE, 1997; Gibros, 1999; Hazewinkel et al., 1998; Neeft et al., 1998) and are based on maximum electricity production. PEC technology is also adequate for CHP (including fuel cells) as well as syngas production.

Table 3.13 *Waste-to-energy plant (Gibros PEC 5-100 MW_e) (EI3)*

	2000	2010	2030
Year average net efficiency [%]	35	40	50
Investment costs [EUR ₁₉₉₅ /kW _e]	4600	4100	3250
O&M costs			
- Fixed [EUR ₁₉₉₅ /kW _e /yr]	230	205	160
- Variable [EUR ₁₉₉₅ /kW _e]	115	100	80
Life [yr]	25	25	25
Availability	0.91	0.91	0.91
Upper bound [GW _e]	-	-	-

4. TRANSPORTATION FUELS

Biofuels are liquid fuels produced from biomass feedstocks via a number of chemical processes. The two biofuels that have been advanced most are *biodiesel* (produced from vegetable oil) and *bio-ethanol* and its derived ether ETBE (Ethyl Tertiary Butyl Ether) (produced from plant sugars). Other biofuels that have been considered are biomethanol and its derivative MTBE (Methyl Tertiary Butyl Ether) from lignocellulose material. These fuels can substitute fossil fuels (with or without engine modification) and mainly have a transport application, although in certain countries they are used in small scale heat production also (ATLAS, 1997e). A third type of fuel that can be produced from (woody) biomass is referred to as '*biocrude*'. This product resembles crude oil and must be upgraded before it can be applied as a transportation fuel. Usually this upgrading (hydrogenation) step is a costly process. This chapter deals with advanced as well as 'new' biofuels (e.g. dimethyl ether and Fischer Tropsch).

Technologies for the production of these liquid biofuels are well understood chemical processes based on proven techniques. Typical feedstocks for these fuels are mainstream agricultural crops, such as rapeseed and sunflower oil, for biodiesel and wheat, sugar beet and sweet sorghum for bioethanol/ETBE. The main cost element for fuel production is the expensive feedstock. The main scope for innovation is the use of waste cooking oil or woody lignocellulose material as cheaper feedstocks. These feedstocks will help to reduce the costs of biofuel production quite considerably and help to make it more competitive with fossil fuels. Other cost reductions could be expected from increased scale and process improvements in pre-treatment and biological conversion (Lynd et al., 1996).

The main commercial potential for liquid biofuels is as a blend with mineral fuels for either private light vehicle use or public bus use. The use of pure biodiesel is promoted for private vehicle use in various European countries.

4.1 Methanol/Dimethyl Ether

Methanol can be produced on the basis of the advanced Battelle process design. Syngas from wood gasification is catalytically synthesised into methanol. This process is not yet applied on a commercial scale. Methanol production based on biomass is more expensive than methanol production based on conventional technology using natural gas. Table 4.1 shows input data from Gielen et al. (1998d) and Uil (1998), based on recent literature (IEA, 1996a; Williams et al., 1995).

Table 4.1 *Model input data for methanol production (Batelle process) (BF1/BF2)*

	Units	2000	2010	2030
Input				
- Straw/wood chips	[GJ/GJ methanol]	1.6	1.6	1.6
- Electricity	[GJ/GJ methanol]	0.1	0.1	0.1
Output				
- Methanol	[GJ]	1	1	1
Investment costs	[EUR ₁₉₉₅ /GJ methanol]	30	30	30
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ methanol/yr]	0.7	0.7	0.7
- Variable	[EUR ₁₉₉₅ /GJ methanol]	2.0	2.0	2.0
Availability factor		0.90	0.90	0.90
Life	[yr]	25	25	25
Bound Low	[PJ methanol]	0.001	0.0015	0.002
Bound High	[PJ methanol]	1	500	1000

Stucki (1996) describes an alternative process, referred to as 'Biometh', to produce methanol from biomass. The Biometh process is mainly intended to deal with biomass waste (wood and wood products). The process itself is based on thermochemical gasification in a fluidised bed with the subsequent catalytic synthesis of methanol from the resulting gas. The methanol produced is intended to be used as a fuel for vehicles (e.g. buses or delivery vans) or as an additive to normal petrol. Table 4.2 shows figures of the project, which is the world's first demonstration of the whole process. Data from 2010 onwards are estimates for future large-scale applications.

Table 4.2 *Model input data for methanol production (Biometh process) (BF3)*

	Units	2000	2010	2030
Input				
- Wood waste	[GJ/GJ methanol]	2.2	2.2	2.2
(20% water)	[GJ/GJ methanol]	0.5	0.5	0.5
- Waste paper	[GJ/GJ methanol]	0.3	0.3	0.3
- Plastics waste				
Output				
- Methanol	[GJ]	1	1	1
- Electricity	[GJ methanol]	0.2	0.2	0.2
- Heat	[GJ methanol]	1.1	1.1	1.1
Investment costs	[EUR ₁₉₉₅ /GJ methanol]	200	150	150
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ methanol/yr]	20	15	15
- Variable	[EUR ₁₉₉₅ /GJ methanol]	8	6	6
Availability factor		0.90	0.90	0.90
Life	[yr]	20	20	20
Bound Low	[PJ methanol]	0.001	0.0015	0.002
Bound High	[PJ methanol]	1	500	1000

For the production of dimethyl ether (DME) from biomass, Uil (1998) has argued that the energetic efficiency and costs will be comparable with those of methanol production from biomass since both processes are principally identical, except for the catalyst used. As a first approximation, we therefore copy the model data used for methanol. This is also suggested in IEA (1996a).

Table 4.3 *Model input data for Dimethyl Ether (DME) (BF4/BF5)*

	Units	2000	2010	2030
Input				
- Straw/wood chips	[GJ/GJ DME]	1.6	1.6	1.6
- Electricity	[GJ/GJ DME]	0.1	0.1	0.1
Output				
- DME	[GJ]	1	1	1
Investment costs	[EUR ₁₉₉₅ /GJ DME]	30	30	30
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ DME/yr]	0.7	0.7	0.7
- Variable	[EUR ₁₉₉₅ /GJ DME]	2.0	2.0	2.0
Availability factor		0.90	0.90	0.90
Life	[yr]	25	25	25
Bound Low	[PJ output]	0.001	0.0015	0.002
Bound High	[PJ output]	1	500	1000

Methanol is mainly used in the USA. It is used in passenger cars as well as in heavy-duty vehicles. Most of the passenger cars are able to run on any mixture of methanol and gasoline, up to 85 v% of methanol. Heavy-duty methanol vehicles use methanol with a small percentage of additives. Besides adding methanol in its pure form, it can be converted into its ether MTBE. MTBE is becoming increasingly important as an anti-knock agent in the fuel market. Methanol cannot be solved in diesel (IEA, 1996b).

DME is currently being used as a propellant in spray cans. Research on the use of dimethyl ether as a road vehicle fuel has only started recently. Before being used as a fuel, DME was used as an ignition improver in methanol engines. Because of its good ignition properties, DME is very suitable for use in diesel engines. The physical properties of DME are very similar to those of LPG. Compared to methanol, DME has a higher caloric value, and unlike methanol is not toxic for man and does not cause corrosion to metals. Currently, all DME engines and vehicles are still in an experimental phase (IEA, 1996b).

4.2 Ethanol

Ethanol production is currently rapidly evolving. The main advances relate to the fermentation of cellulose and hemicellulose, where formerly only free sugars and starch could be fermented. As a consequence of these developments, it will be possible to ferment wood and grass, leaving only the lignin fraction as a residue. The advantage is the much higher yield (or lower costs) of these crops. While the cellulose fermentation has been proven, the hemicellulose fermentation is still in a research stage (Boer and Uil, 1997). As a consequence, the model data for hemicellulose fermentation represent an optimistic forecast, assuming that the process will become feasible in 5-10 years.

The ethanol production process can be split into:

1. Pretreatment to mobilise the biomass constituents.
2. Hydrolysis to convert biomass constituents into free sugars.
3. Fermentation of the sugars to produce ethanol.
4. Distillation of the water/ethanol mixture.

The main energy consumption occurs in step 4. However, steps 1-3 are also important from an energy point of view because the ethanol yield is determined in these steps. Biomass conversion into ethanol is based on biological processes. The micro-organisms that are used require energy and carbon for their own metabolism.

Pretreatment consists of a combination of chipping, milling and grinding and subsequent chemical treatment. Hydrolysis can be split into chemical hydrolysis, using sulphuric acid, and enzymatic hydrolysis. The enzymatic hydrolysis is expected to yield considerably more ethanol than the acid hydrolysis. Several types of fermentation processes are currently being developed (Lynd et al., 1996).

- Separate Hydrolysis and Fermentation (SHF): all process steps in different reactors.
- Simultaneous Saccharification and Fermentation (SSF): with separate fermentation of pentoses (C₅).
- Simultaneous Saccharification and Co-Fermentation (SSCF): with simultaneous fermentation of pentoses (C₅) and hexoses (C₆).
- Consolidated Bioprocessing (CBP): all process steps in one reactor.

The successive processes comprise less process steps, with lower investment costs as a consequence. However, technical problems and uncertainties will increase for instance due to the sub-optimal conditions under which enzymes have to operate (because of the integration of different process steps).

As mentioned earlier, the main energy consumption in ethanol production is related to the distillation process. Distillation energy requirements depend to some extent on the product specifications (the higher the purity desired, the more energy is required for distillation). The distillation energy requirements are currently in the range of 0.4-0.5 GJ/ton. There is however ample room for further improvements through introduction of molecular sieves and vacuum distillation. The latter technology is already partially implemented in the Netherlands (Novem, 1995). It is assumed that the energy requirements can gradually be reduced to 0.2 GJ/ton.

Ethanol from cellulose and hemicellulose

The hydrolysis product of cellulose is composed of well fermentable glucose (C₆). SSF is considered as one of the best routes for fermentation of cellulose to bioethanol (yield approx. 92,5%). In this process, hydrolysis and subsequent fermentation of the hydrolysis product take place in the same reactor. The SSF process is still being developed and tested now on semi-industrial scale (Boer and Uil, 1997).

Hemicellulose can well be hydrolysed by acid hydrolysis and yields mainly xylose (C₅). At present, fermentation of xyloses on an industrial scale is not yet possible and this process is being developed. A promising route seems isomerisation of xylose to xylulose, with subsequent fermentation of xylulose. Among others, the Simultaneous Fermentation and Isomerization of Xylose (SFIX process) is being developed. The bioethanol yield is estimated at 80-85% (C-conversion). In the future, a yield of 92,5% seems possible (Boer and Uil, 1997).

The residual biomass fraction (mainly lignin) can be used for production of electricity and heat in a combined heat/power station. Tables 4.4 and 4.5 show model input data for bio-ethanol production from cellulose and hemicellulose (based on Reith, 1999).

Table 4.4 *Biomass/ethanol from cellulose (BH1)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ ethanol]	0.05	0.05	0.05
- Low Temperature Heat	[GJ/GJ ethanol]	0.45	0.4	0.3
- Cellulose	[GJ/GJ ethanol]	1.75	1.35	1.35
Output				
- Ethanol (95%)	[GJ]	1.0	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ ethanol]	25	15	15
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ ethanol/yr]	1	1	1
- Variable	[EUR ₁₉₉₅ /GJ ethanol]	1	1	1
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ ethanol]	0.001	0.001	0.002
Bound Up	[PJ ethanol]	5	5	2000

Table 4.5 *Biomass/ethanol from hemicellulose (available in 2010) (BH2)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ ethanol]		0.05	0.05
- Low temperature heat	[GJ/GJ ethanol]		0.4	0.3
- Hemicellulose	[GJ/GJ ethanol]		1.49	1.49
Output				
- Ethanol (95%)	[GJ]		1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ ethanol]		25	15
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ ethanol/yr]		1	1
- Variable	[EUR ₁₉₉₅ /GJ ethanol]		1	1
Availability			0.9	0.9
Life	[yr]		25	25
Bound Low	[PJ ethanol]		0.001	0.002
Bound Up	[PJ ethanol]		5	2000

Ethanol production from sugar/starch

Production of ethanol from sugar and starch containing plants is already well developed. Table 4.6 gives input data (based on Reith, 1999). Table 4.7 shows data on distillation (from Gielen et al., 1998d).

Table 4.6 *Biomass/ethanol from sugar/starch (BH3)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ ethanol]	0.05	0.05	0.05
- Low Temperature Heat	[GJ/GJ ethanol]	0.35	0.2	0.2
- Sugar/Starch	[GJ/GJ ethanol]	1.35	1.35	1.35
Output				
- Ethanol (95%)	[GJ]	1.0	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ ethanol]	25	20	15
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ ethanol/yr]	1	1	1
- Variable	[EUR ₁₉₉₅ /GJ ethanol]	1	1	1
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ ethanol]	0.0015	0.002	0.002
Bound Up	[PJ ethanol]	1000	2000	2000

Table 4.7 *Biomass/ethanol purification 95% to 99% (BH4)*

	Units	2000	2050
Input			
- Electricity	[GJ/GJ ethanol]	0.09	0.03
- Low Temperature Heat	[GJ/GJ ethanol]	0.09	0.03
- Ethanol (95%)	[GJ/GJ ethanol]	1.0	1.0
Output			
- Ethanol (99%)	[GJ]	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ ethanol]	2.2	2.2
O&M costs			
- Fixed	[EUR ₁₉₉₅ /GJ ethanol/yr]	0.1	0.1
- Variable	[EUR ₁₉₉₅ /GJ ethanol]	0.25	0.25
Life	[yr]	25	25

Ethanol, produced from sugar cane, is used on a large scale in Brazil. In the USA, ethanol is made from corn. During the last few years ethanol has been tested in the USA, Canada and Europe as a fuel for buses. Ethanol can be used directly as a neat or pure fuel. However, in order to be able to use pure alcohol in a conventional engine, it is necessary to adjust the engine and the fuel system. Ethanol is also directly blended with gasoline to displace gasoline use, increase the octane number of the blended fuel and provide oxygen that ensures more complete combustion (thus reducing urban air pollution). The amount of ethanol in blends varies from 10-22 v% and (in Brazil) varies with the crude oil price. By reacting with isobutylene, ethanol can be converted into its ether ETBE. ETBE is a good additive for octan index implementation. It is usually used in blends of 5-15 v% with gasoline (ATLAS, 1997e). With the use of ETBE as an additive in gasoline vapour emissions are lowered.

4.3 Rapeseed Methyl Ester

Soybean, palm, sunflower and rapeseed are the four most important sources for vegetable oil production. Esterified vegetable oils are called 'biodiesels'. Biodiesel is typically produced through the reaction of a vegetable oil with methanol in the presence of a catalyst to yield glycerine and methyl esters. This esterification process is rather simple and well known (IEA, 1996b).

The main vegetable oil feedstock in Europe is rapeseed. Based on rapeseed rapeseed methyl ester (RME) is produced. The glycerine by-product is particularly important, since its high world selling price supports the economic viability of biodiesel production. Biodiesel can be used in neat form, or blended with petroleum diesel (in any ratio) for use in diesel engines. The physical and chemical characteristics of biodiesels are similar to ordinary diesel fuel. Important differences are the viscosity (about twice as high as diesel fuel) and the high biodegradability (ATLAS, 1997e). The high viscosity will have an influence on the atomisation of the fuel during fuel injection and on the cold start behavior of the engine (IEA, 1996b).

As already mentioned, RME is produced from rapeseed. Rapeseed oil is obtained by pressing and extraction. This oil is subsequently esterified with methanol to obtain RME. Since these processes are considered mature, major technological improvements are not to be expected and cost benefits can only be obtained from increased scale. Data in Table 4.8 are based on Gielen et al. (1998d) and Reith (1999).

Table 4.8 *Biomass/RME from rapeseed (BGI)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ RME]	0.05	0.05	0.05
- Low Temp. heat	[GJ/GJ RME]	0.2	0.2	0.2
- Diesel	[GJ/GJ RME]	0.025	0.025	0.025
- Methanol	[GJ/GJ RME]	0.03	0.03	0.03
- Rapeseed (excl. straw)	[GJ/GJ RME]	1.66	1.66	1.66
Output				
- RME	[GJ]	1.0	1.0	1.0
- Glycerol + fodder	[GJ/GJ RME]	0.83	0.83	0.83
Investment costs	[EUR ₁₉₉₅ /GJ RME]	55	50	30
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ RME/yr]	5	5	5
- Variable	[EUR ₁₉₉₅ /GJ RME]	1	1	1
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Up	[PJ output]	1050	2000	2000

4.4 Hydrothermal Upgrading

Hydrothermal upgrading (HTU) is a process, which contacts biomass (in the form of wet chips or slurry) with liquid water at temperatures of 300°-350°C at pressures of 120-180 bar for 5-10 minutes. The oxygen content of the biomass is reduced from 40%w to about 10-15%w by the selective formation of CO₂. Under these conditions an organic liquid (or 'biocrude') is formed, which resembles crude oil and which can be transported. HTU biocrude as such can be used for direct combustion as a liquid, for (co)combustion as a solid fuel or for electrical power generation. Further upgrading of the biocrude is also possible by removal of the remaining oxygen (by catalytic hydrodeoxygenation). This has been proven (by laboratory experiments) to produce a good quality gasoil, but requires considerable amounts of hydrogen. However, upgrading costs are compensated by the higher product value. The upgraded product can be used as a transport fuel, as a fuel in high-efficiency gas turbines or it can be used as a feedstock for the production of chemicals (via ethylene cracker).

The HTU process can use different feedstocks, and can be an attractive option for feedstocks with a higher water content such as agricultural and domestic waste or biosludge, since no drying is required (Goudriaan et al., 1994). It is further assumed here that the residual lignin from ethanol production would be a suitable feedstock for the HTU process, resulting in a 'biorefinery' that produces both gasoline substitutes (ethanol) and gasoil substitutes (biodiesel). Little is

known about the use of lignin, but the principle itself has been demonstrated. Probably, yields of HTU oil are a little lower than those achieved from wood and the product quality might be less. Input data on HTU oil are based on personal communication with the company developing the HTU process (Goudriaan, 1999) and on recent literature (Dinkelbach, 1998; Gielen et al., 1998d; Goudriaan and Naber, 1997; Lamm and Arlt, 1995; Naber et al., 1997 and 1999).

Table 4.9 *HTU biocrude production from wood (plant capacity 130 kton dry wood/yr) (BI1)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ HTU oil]	0.017	0.016	0.015
- Wood chips	[GJ/GJ HTU oil]	1.32	1.25	1.18
Output				
- HTU oil	[GJ]	1.0	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ HTU oil]	15	13	10
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ HTU oil/yr]	2	1.5	1.0
- Variable	[EUR ₁₉₉₅ /GJ HTU oil]	0.5	0.3	0.2
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ HTU oil]	0.001	0.001	0.002
Bound Up	[PJ HTU oil]	1000	1000	-

Table 4.10 *HTU biocrude production from lignin (BI2)*

	Units	2010	2030	2050
Input				
- Electricity	[GJ/GJ HTU oil]	0.017	0.016	0.015
- Lignin + other residues	[GJ/GJ HTU oil]	1.40	1.32	1.25
Output				
- HTU oil	[GJ]	0.5	0.5	0.5
- Residual fuel oil	[GJ/GJ HTU oil]	0.5	0.5	0.5
Investment costs	[EUR ₁₉₉₅ /GJ HTU oil]	15	13	10
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ HTU oil/yr]	2	1.5	1.0
- Variable	[EUR ₁₉₉₅ /GJ HTU oil]	0.5	0.3	0.2
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ HTU oil]	0.001	0.001	0.002
Bound Up	[PJ HTU oil]	1000	-	-

Data for upgrading to diesel fuel quality are based on hydrocracking in the oil industry (Oostvoorn et al., 1989). Data for co-combustion are copied from Table 2.1, assuming comparable efficiencies and costs as for co-combustion of wood chips.

Table 4.11 *HTU biocrude upgrading to diesel (plant capacity 54 kton diesel/yr) (BI3)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ diesel]	0.05	0.05	0.027
- Hydrogen	[GJ/GJ diesel]	0.12	0.12	0.12
- HTU-oil	[GJ/GJ diesel]	0.9	0.9	0.9
Output				
- Diesel	[GJ]	1.0	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ diesel]	10	10	10
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ diesel/yr]	1	1	0.6
- Variable	[EUR ₁₉₉₅ /GJ diesel]	1	1	0.6
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ diesel]	0.001	0.001	0.002
Bound Up	[PJ diesel]	1000	1000	-

Table 4.12 *Co-combustion of HTU oil in NGCC (BI4)*

		2000	2010	2030
Electrical net efficiency	[%]	52.0	56.0	60.0
Fraction of fuels				
- Natural gas	[%]	75	75	75
- HTU oil	[%]	25	25	25
Investment costs	[EUR ₁₉₉₅ /kW _e]	640	590	560
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	30	30	30
Life	[yr]	25	25	25
Upper bound [GW _e]		0.1	1	25

4.5 Flash pyrolysis

Pyrolysis is thermal degradation in absence of oxygen. Heat is usually added indirectly in a variety of forms (e.g. firing a rotary kiln with product gas). Relatively low temperatures of 400°-800°C are employed. Gas, liquid and charcoal are produced, the relative proportions of which depend very much on the reaction parameters such as temperature, reaction time and rate of reaction. Much of the present interest in pyrolysis currently centres on the liquid products due to their high energy density and potential for premium liquid fuel substitution (Heuvel et al., 1994). Several liquid products can be produced directly or indirectly: oil and slurries of charcoal with water or oil.

Pyrolysis oil is produced by very fast pyrolysis (so-called 'flash' pyrolysis, residence time below 1 second) at a temperature of 500°C. Very high heating rates at moderate temperatures and rapid product quenching cause the liquid intermediate products of flash pyrolysis to condense before further reaction breaks down higher molecular weight species into gaseous products. These fast reaction rates also minimise charcoal formation, and can be used to either maximise gaseous or liquid products. Flash pyrolysis can produce up to 80% mass yields (dry basis) of pyrolysis liquids (or 'bio-oil'). The problems relating to pyrolysis are heat transfer into the feedstock, process control to give the required product mixture and separation of the products (Bridgwater and Evans, 1993).

The oxygen content of the pyrolysis liquid is very high, at up to 40-50w% on a wet basis. It typically has a lower heating value of 13-17 MJ/kg on a wet basis. The water content is considerable (15-30w%), which is important since this influences both chemical and physical stability and could affect the subsequent upgrading processes. Since the water is difficult to remove,

utilisation on a wet basis is preferred (Bridgwater and Evans, 1993). The pyrolysis product can be used directly as liquid fuel oil for (co) combustion or it can be upgraded to a hydrocarbon fuel. The quality of the original product is in no way comparable with gasoline, and cannot be used as a transport fuel. Upgrading is necessary to get a product that is compatible with conventional fuels, but this is expensive and leads to lower yields (Bridgwater and Double, 1991; Neeft, 1999).

Pyrolysis oil can be catalytically upgraded, which is proven in concept but has not been developed well so far. Most attention has been paid to either hydrotreating or zeolite cracking to give synthetic gasoline and other hydrocarbons. Hydrotreating is based on technology that is well established in the petroleum industry and is in principle readily adaptable. Neither technology is yet available commercially, nor have robust mass balance and performance data been produced (Bridgwater and Evans, 1993).

The production costs of pyrolysis oil were only roughly estimated up to now. Some figures are given in literature (Beckman and Graham, 1994; Bridgwater, 1989; Cottam and Bridgwater, 1994; Diebold et al., 1994; Kovac and O'Neil, 1989; Milne et al., 1997). It is important to note that these figures mostly relate to the production of the 'crude' product and that costs for upgrading are not taken into account. At present, research activities focus on the improvement of the properties of the light crude oil (Neeft, 1999).

Bridgwater and Evans (1993) have made an extensive survey of gasification and pyrolysis plants which are developed worldwide. Data below are based on the Rapid Thermal Process (RTP) by Ensyn Technologies Inc. (Canada) as described by Bridgwater and Evans (1993) and on an internal ECN survey by Neeft (1999). The Ensyn process was first optimised for specialty chemicals production (extracted and concentrated from the crude liquid product). In the production of chemicals, a residual oil remains which can be used as a boiler fuel. Alternatively, the crude bio-oil product can be directly burnt in a boiler. Now work is continuing on the optimisation of the process for fuel oil production.

Table 4.13 *Bio-oil production from wood by flash pyrolysis (scale 25 t/d) (BL1)*

	Units	2000	2010	2030
Input				
- Wood chips	[GJ/GJ bio-oil]	1.65	1.65	1.65
- Electricity	[GJ-/GJ bio-oil]	0.02	0.02	0.02
Output				
- Bio-oil	[GJ]	1.0	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ bio-oil]	12	12	12
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ bio-oil /yr]	1	1	1
- Variable	[EUR ₁₉₉₅ /GJ bio-oil]	0.1	0.1	0.1
Availability		0.8	0.8	0.8
Life	[yr]	10	10	10
Bound Up	[PJ bio-oil]	1000	1000	2000

As mentioned, upgrading technology is not well developed yet. Some preliminary estimates of production costs of upgraded liquids indicate that product costs (per GJ) are doubled compared to crude pyrolysis oil costs. Since upgrading technology will probably be based on this, data for upgrading to diesel fuel quality are based on hydrotreating in the oil industry (Oostvoorn et al., 1989). Higher investment costs are assumed, because the oxygen content has to be lowered as well.

Table 4.14 *Pyrolysis oil upgrading to diesel (BL2)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ diesel]	0.05	0.05	0.027
- Hydrogen	[GJ/GJ diesel]	0.12	0.12	0.12
- Bio-oil	[GJ/GJ diesel]	0.9	0.9	0.9
Output				
- Diesel	[GJ]	1.0	1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ diesel]	15	15	15
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ diesel/yr]	1	1	0.6
- Variable	[EUR ₁₉₉₅ /GJ diesel]	1	1	0.6
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ diesel]	0.001	0.001	0.002
Bound Up	[PJ diesel]	1000	1000	2000

4.6 Biodiesel from algae

Algae can be grown in special ponds. These algae contain lipids (fat or oil compounds) that can be converted into biodiesel. The remaining algae biomass is converted into biogas (methane) through anaerobic digestion.

Table 4.15 *Biomass/biodiesel from algae lipids (Gielen et al., 1998d) (BJ1)*

	Units	2000	2010	2030
Input				
- Electricity	[GJ/GJ diesel]	0.025	0.025	0.025
- LT Heat	[GJ/GJ diesel]	0.2	0.2	0.2
- Diesel	[GJ/GJ diesel]	0.025	0.025	0.025
- Methanol	[GJ/GJ diesel]	0.03	0.03	0.03
- Lipids from algae	[GJ/GJ diesel]	1.8	1.8	1.8
Output				
- Diesel	[GJ]	1.0	1.0	1.0
- Glycerol + fodder	[GJ/GJ diesel]	0.83	0.83	0.83
Investment costs	[EUR ₁₉₉₅ /GJ diesel]	15	15	15
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ diesel/yr]	5	5	5
- Variable	[EUR ₁₉₉₅ /GJ diesel]	1	1	1
Availability		0.9	0.9	0.9
Life	[yr]	25	25	25
Bound Low	[PJ diesel]	0.001	0.002	0.002
Bound Up	[PJ diesel]	100	2000	2000

4.7 Fischer Tropsch

By means of Fischer Tropsch (FT), syngas can be converted into a multi-component mixture of hydrocarbons. The FT-process is catalysed by both iron, cobalt and ruthenium at pressures of 10 to 60 bar and temperatures of 200° to 300°C. The product stream consists of various fuel types, such as LPG, gasoline, gasoil (diesel fuel) and kerosene (jet fuel), the relative amounts of which are dependent on the process conditions (catalyst, temperature, etc.).

Fuels produced with the FT- process are of high quality (due to a very low aromaticity and absence of sulphur) and can be used as blending agents for transportation fuels derived from crude oil. The value of FT-derived fuels as blending agents is higher than those of oil-derived fuels due to their excellent properties (Ree et al., 1999).

Several concepts of the FT-process exist. Changes mainly refer to the configuration of the reactor. Reactor type and operation are governing factors in the control of product distribution during the FT-synthesis. Table 4.16 shows the input data in the MARKAL MATTER 4.2 model, which are based on the three phase fluidized bed (or slurry) reactor. Under the chosen operating conditions, the product distribution shows a maximum value for the gasoline fraction (Paasen).

Table 4.16 *Fischer Tropsch biomass gasification process (BE9)*

	Units	2000	2010	2030
Input				
- Wood chips	[GJ/GJ FT]	2.8	2.8	2.8
- Natural gas	[GJ/GJ FT]	1.15	1.15	1.15
Output				
- FT-fuel	[GJ]	1.0	1.0	1.0
- Electricity	[GJ/GJ FT]	0.85	0.85	0.85
Composition FT-fuel				
- Gasoline	[%]	54	54	54
- Diesel	[%]	10	10	10
- LPG	[%]	25	25	25
- Residual fuel oil	[%]	11	11	11
Investment costs	[EUR ₁₉₉₅ /GJ FT]	81	67	54
O&M costs	[EUR ₁₉₉₅ /GJ FT/yr]	3.2	2.7	2.2
Availability		0.75	0.75	0.75
Life	[yr]	25	25	25
Bound Up	[PJ FT]	37	946	1855

By integrating a once-through Fischer Tropsch production process into the BIG-CC technology, resulting in a trigeneration system producing biofuel, electricity and heat, it is expected that the biofuel production costs will be reduced compared to 'conventional' produced biofuels. Cost reductions are expected because of lower necessary specific investment costs and the possibility to use relatively low cost biomass fuels (Ree et al., 1999).

5. GASEOUS FUELS

5.1 Anaerobic digestion

Anaerobic digestion is the digestion of plant and animal material by various types of bacteria in absence of oxygen. Optimal temperatures are around 35°-37°C. The main product is biogas, which consists mainly of methane CH₄ (50-70%) and has a LHV of 19-27 MJ/Nm³ (Heuvel et al., 1994). Anaerobic digestion and production of biogas is a process which has been widely used for years. Production for energy purpose is common on a small scale in the tropical area of the world. During the last decade a technological breakthrough has occurred in Western Europe regarding animal manure co-digested with industrial organic waste and household waste (Al-tener, 1998).

A biogas plant can be established in areas with a concentration of animal manure, wastes and a market for the energy produced. Production on a world level is estimated to be 52·10⁹ m³ biogas (≈ 1 EJ) annually (Ørtenblad, 1998). Most of it comes from treatment of sewage sludge, but the largest potential of biogas production is in digestion of farm yard manure and agro-industrial wastes. According to Ørtenblad (1998) animal manure accounts for 90% of the available biomass amount in Western Europe.

Typically, between 40 and 60% of the organic matter present is converted to biogas. The remainder consists of odour free residue with appearance similar to peat which has some value as a soil conditioner and also, with some systems, a liquid residue which has potential as a fertiliser (ATLAS, 1997d).

Table 5.1 shows the model input parameters for anaerobic digestion of kitchen waste. The data refer to large-scale plants (> 100 kton per year) and are derived from Doorn and Oudhuis (1999), based on recent literature (Antuma et al., 1998; Boo, 1998; IEA, 1997; Haskoning, 1993; LIOR). The investment costs of anaerobic digestion of animal manure (see Table 5.2) are estimated 50 EUR₁₉₉₅/ton. Fixed costs are estimated 10 EUR₁₉₉₅/ton (20% of investment costs).

Cost prediction for 2010 and onwards are highly uncertain so a conservative approach has been taken which assumes that costs will not decrease after the year 2000. However, it is possible that environmental drivers and economies of scale may reduce costs. It is conceivable that environmental pressures will lead to farmers paying to dispose of animal slurries. This will mean that anaerobic digestion plants could attract a gate fee for agricultural wastes in the same way as they do for MSW. If this happens, then costs are likely to fall.

Table 5.1 *Anaerobic digestion kitchen waste (DXK)*

	Units	2000	2010	2030
Input				
- Kitchen waste (30% H ₂ O)	[ton]	1	1	1
Output				
- Natural Gas	[GJ/ton waste]	1.5	1.5	1.5
- Compost (15% H ₂ O)	[ton/ton waste]	0.6	0.6	0.6
Investment costs	[EUR ₁₉₉₅ /ton waste]	200	200	200
O&M costs				
- Fixed	[EUR ₁₉₉₅ /ton waste/yr]	40	40	40
Life	[yr]	25	25	25
Availability		0.95	0.95	0.95
Bound Low	[Mt waste]	5	5	5
Bound Up	[Mt waste]	7	30	30

Table 5.2 *Anaerobic digestion animal manure (DXL)*

	Units	2000	2010	2030
Input				
- Animal manure (d.m.)	[ton]	1	1	1
Output				
- Natural Gas	[GJ/ton manure]	1.5	1.5	1.5
- N-Fertiliser	[ton/ton manure]	0.02	0.02	0.02
Investment costs	[EUR ₁₉₉₅ /ton manure]	50	50	50
O&M costs				
- Fixed	[EUR ₁₉₉₅ /ton manure/yr]	10	10	10
Life	[yr]	25	25	25
Availability		0.95	0.95	0.95
Bound Up	[Mt manure]	10	50	200

5.2 Landfill gas recovery

Landfill gas (LFG) is a mixture of circa 50% methane and carbon dioxide, resulting from the anaerobic degradation of organic landfilled waste. The gas is collected and cleaned and then either burned to provide process heat or used for electricity generation. There are other uses for which landfill gas could be used, such as a chemical feedstock or for use in fuel cells, but these are still at the research and development stage. Additional incentives for collecting and using landfill gas arise from the increasingly stringent environmental legislation now being applied to existing and new landfill sites (ATLAS, 1997f; ETSU, 1996).

An important consideration in the use of LFG, is the timescale over which the gas is available. Although landfill gas is produced once anaerobic conditions are established within the landfill, it may take several years before the LFG production rate is large enough to sustain a landfill gas use scheme. Gas production rates decline as the degradable material within the landfill is used and the quality of the gas will also decline to a point where it can no longer be used as a fuel. For a typical well engineered and well operated landfill, the expected period over which gas will be produced may range from 50-100 years, but a useable gas production rate can be expected for only 10-15 years.

Table 5.3 gives values of methane emissions from disposal without landfill gas recovery (Sattler and Emberger, 1992). Landfill gas can only be collected at well engineered and well managed sites. Therefore, for some countries, waste management practices must improve before energy recovery becomes an option. On the longer term (> 2025), recovery potential will probably diminish, as less organic material is landfilled.

Table 5.3 *Methane emissions from disposal without landfill gas recovery*

	[kg CH ₄ /t]	[t CO ₂ eq./t waste]
Demolition wood	65	1.4
Waste fibre	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 EUR per kg methane (i.e. 6-23 EUR/t CO₂ equivalents). The maximum recovery efficiency for the whole landfill life cycle is 55%. The closer the drainage pipes, the higher the efficiency, but the higher the costs. The total potential of landfill gas recovery in the EU is estimated at 150 PJ (70 Mt CO₂ equivalents) (Gielen et al., 1998b).

It must be mentioned that LFG production and recoverability depend on various factors (e.g. size and geometry of site) and are difficult to predict in advance. Table 5.4 shows data for electricity generation from landfill gas (based on ATLAS, 1997f; ETSU, 1996).

Table 5.4 *Electricity from landfill gas (typical unit size 1-1.5 MW_e)*

	Units	2000	2010	2030
Electrical net efficiency	[%]	35	35	35
Investment costs	[EUR ₁₉₉₅ /kW _e]	950	900	850
O&M costs	[EUR ₁₉₉₅ /kW _e /yr]	50	50	50
Life	[yr]	20	20	20
Availability		0.95	0.95	0.95
Bound Up	[GW _e]	2.0	5.0	5.0

Landfill gas can be utilised in several ways. The most common are local heating and power generation, since the gas has a high CO₂ content and a relatively low caloric value, which prevent it from being introduced into natural gas distribution systems. It is possible however, to upgrade the gas to natural gas quality, when it may be sold as pipeline gas. However, where there is no direct use available, electricity generation is likely to be the method of utilisation. Generating efficiency varies with the technology being used, but is usually in the range of 30-40% (Greenhouse Issues).

5.3 Hydrolysis into synthetic natural gas

Hydrolysis is gasification of carbon-containing feedstocks in a hydrogen atmosphere. It has been identified as a promising option for converting biomass and hydrogen to synthetic natural gas (SNG). The quality of the produced SNG (e.g. composition, caloric value) is quite comparable with that of natural gas (mainly CH₄). On the short term hydrogen required for the process may be obtained from hydrogen-rich gases available as by-products in industrial processes (Uil et al., 1999).

At ECN, a project is carried out to evaluate the potential of chemical storage and transport of hydrogen in the future renewable energy supply. This should eventually lead to a demonstration project in The Netherlands. One of the selected chemical storage processes is hydrogen conversion in SNG by biomass hydrolysis. In Mozaffarian (1998) the feasibility of this process is described. The complete process has been modelled in the flowsheet simulation package ASPEN^{PLUS} and calculations have been performed in order to determine the overall mass and energy balances. Data in Table 5.5 are based on the developed model.

Table 5.5 *Biomass hydrolysis to SNG (available in 2010) (BMI)*

	Units	2000	2010	2030
Input				
- Biomass ¹	[GJ/GJ SNG]		0.57	0.57
- Hydrogen	[GJ/GJ SNG]		0.67	0.67
Output				
- SNG	[GJ]		1.0	1.0
Investment costs	[EUR ₁₉₉₅ /GJ SNG]		20	20
O&M costs				
- Fixed	[EUR ₁₉₉₅ /GJ SNG/yr]		2	1
- Variable	[EUR ₁₉₉₅ /GJ SNG]		2	1
Availability			0.9	0.9
Life	[yr]		25	25
Bound Up	[PJ SNG]		1000	2000

¹ Poplar sawdust (30 wt% moisture) with LHV of 14.53 MJ/kg.

At present, hydrolysis of biomass is not yet applied on a commercial scale and no cost data are given in Mozaffarian (1998). In the MARKAL MATTER 4.2 model, it is assumed that the process becomes available in 2010. ECN has defined a R&D programme for hydrogasification, the next phases comprising experimental work to determine the optimum operating conditions, and a pre-feasibility study to assess the technical and economic prospects of the process. For the moment, cost data are estimated based on hydrotreating in the oil industry.

6. FUTURE WORK

All processes described in this report are or will be incorporated in the MARKAL MATTER 4.2 model. Based on this model, a selected number of scenarios will be analysed. The results of the calculations will be described separately in the final report of the BRED project (Gielen et al., 2000). As a part of the model runs and scenario analysis, also a large programme for uncertainty analysis is planned. This is extremely important since long term ex-ante analyses such as this study are subject to large uncertainties. These uncertainties can be split into a number of categories:

- Input data for technologies.
- Data for resource prices and resource availability.
- Future energy and materials service demand.
- Model structure.
- Future policy initiatives (including other than energy and environment policies).

Different methods have been applied to treat these uncertainties. One way to handle these uncertainties is by means of scenario analysis (see Gielen et al., 2000). Regarding individual technology parameters, sensitivity analysis is a well established method. Comparison of the results of this study to the results of other studies and peer review is another important approach.

Important uncertainties exist with regard to the technological feasibility of new processes. Especially the flash pyrolysis process for the production of petrochemical intermediates and the production process of ethanol from lignocellulose crops must be considered in this respect. On the other hand, comparing this database with databases from a decade ago shows that many new technologies have been considered. Naturally, additional new technologies may emerge in the next decades, which have not been included yet.

The general conclusion that biomass will gain a prominent place in case of GHG emission reduction is considered to be robust. The new insight that transportation fuels and petrochemical feedstocks will gain an important position is also considered to be robust. The results for individual technologies should be considered with care, especially in the case of new technologies, which are still in the R&D stage. The results for individual regions such as Southern Europe depend to some extent on the model structure. Data are currently refined in order to improve the representation of different yields and different land use costs within the regions, because these variables determine the biomass resource price.

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