

STATUS AND PERSPECTIVES OF BIOMASS-TO-LIQUID FUELS IN THE EUROPEAN UNION



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PREFACE

The objective of the Sustainable Energy Technologies Reference and Information System (SETRIS) of the Directorate-General Joint Research Centre of the European Commission is to collect, harmonise and validate information on sustainable energy technologies and perform related techno-economic assessments to establish, in collaboration with all relevant national partners, scientific and technical reference information required for the debate on a sustainable energy strategy in an enlarged EU, and in the context of global sustainable development.

In the context of SETRIS, this study aims at performing a techno-economic analysis of the production of biomass-to-liquid (BTL) fuels and their potential for automotive application in the EU by 2010 and beyond. This includes a critical review of a large number of literature sources on the subject, complemented by the author's analysis. Special emphasis is given on the biomass gasification step (production of syngas), which is the most challenging part of BTL chains. Dr. Harold Boerrigter from the Energy research Centre of the Netherlands (ECN) is thanked in particular for his contribution to chapter 3 "Production of syngas from biomass". Marc Steen, David Baxter, Evangelos Tzimas, Fred Starr, Karel Svoboda, Stylianos Arvelakis, Jon Davies and Anna Maciejewska (JRC-IE) are also thanked for their contribution with comments, remarks and suggestions.

GUIDANCE FOR THE READER

In addition to the briefings in the "Executive Summary" and the "Conclusions" chapters, each analytical chapter contains a summary box at the end. The bibliographic indexes of the data and information sources or of the sources, where more data and/or information can be found on a certain issue or subject, are given in brackets []. Hence, often a large number of references is indicated. For simplicity reasons although the data and information sources are listed in alphabetic order, their indexes in the text are numerical.

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LIST OF USED ABBREVIATIONS

BD – biodiesel

BE - bioethanol

BFB – bubbling fluidised bed (gasifier)

BLG – black liquor gasification

bpd – barrels per day

BTL – biomass-to-liquid

CAP – Common Agricultural Policy (of the European Union)

CFB – circulating fluidised bed (gasifier)

CGH₂ – compressed gaseous hydrogen

CHP – combined heat and power generation (co-generation)

CI – compressed-ignited

CIS – Commonwealth of Independent States

CNG – compressed natural gas

d – dry

DI – direct injection

DME – di-methyl-ether

DMFC – direct methanol fuel cell

EC – European Commission

EEA – European Environmental Agency

EF, EFG – entrained flow (gasifier)

eq. – equivalent

EtOH – ethanol

EU – European Union

EU-15 – The 15 old member states of the European Union until 30 April 2004 (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden and the United Kingdom.)

EUR, € – Euro

FC – fuel cell

F-T – Fischer-Tropsch

g – gram

G – Giga

GCV – gross calorific value

GHG – greenhouse gas(es)

GMO – genetically modified organism(s)

GTL – gas-to-liquid

H – hybrid / hybridisation

HC – hydrocarbons

HDO – hydro de-oxygenation

HDV – heavy-duty vehicle(s)

HEC – herbaceous energy crops

HTU – hydro-thermal upgrading
ICE – internal combustion engine
IGCC – integrated gasification combined cycle
J – joule
k – thousand
kg – kilogram
l – litre
LCM – ligno-cellulosic material
LDV – light-duty vehicle(s)
LGH2 – liquefied gaseous hydrogen
LNG – liquefied natural gas
LPG – liquid petroleum gas
m – metre, milli
M – million, Mega
MeOH – methanol
NCV – net calorific value
NG – natural gas
NMS-10 – The 10 new member states of the European Union as from 01 May 2004 (Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovak Republic and Slovenia)
NMVOC – Non-Methane Volatile Organic Compounds
OF – ordinary forestry
PC – passenger car(s)
PEM – proton-exchange membrane /fuel cell/
PI – port injection
PM – particulate matters
PMF – particulate matters filter
ppb – parts per billion
ppm – parts per million
SI – spark-ignited
SNG – substitute natural gas
SRF – short-rotation forestry
T – temperature
THC – total hydrocarbons
TTW – tank-to-wheel
USD, \$ - United States Dollar
vol. – volumetric
w – weight
WGS – water-gas-shift
WTT – Well-To-Tank
WTW – Well-To-Wheel

EXECUTIVE SUMMARY

The European Union (EU) is heavily dependent upon energy imports and in particular on oil imports. The EU is also a large emitter of greenhouse gases (GHG), which contribute to global warming. Transport is a main oil consuming and GHG-generating sector in the EU. Thus, securing and diversifying the energy supply for transport in an environmentally-friendly way is a key transport, energy and environmental policy objective for the EU. Road transport is the largest energy consumer and GHG emitter amongst transport modes. Hence, the introduction of cleaner alternative fuels in road transport, whose production patterns differ from those of conventional oil-based fuels, is a crucial factor for meeting these EU policy objectives.

The European Commission considers biofuels as a major feasible alternative to contribute to these policy goals in the near to medium term¹. Target shares of biofuel penetration in the transport fuel market in the EU have been therefore set up – 2% by the end of 2005 and 5.75% by the end of 2010 of all petrol and diesel, on energy content basis, for transport purposes². The market potential of conventional biofuels – bioethanol and biodiesel – from agricultural feedstock is estimated as modest, because of tight supply base (due to limitations in the feasible land availability) and very high production costs. Thereby, finding alternative biofuel production pathways with a larger market potential is necessary. Biomass-To-Liquid (BTL) fuels are often suggested to be such a biofuel alternative.

The goal of this study is to perform a techno-economic analysis of the production of BTL fuels and their potential for automotive application in the EU by 2010 and beyond. It relies on a critical review of a large number of literature sources on the subject and is complemented by the author's analysis. The investigation is trying to identify the optimum fuel chains (from extraction of raw materials to final utilisation of fuels) in which the limited biomass resource can be used as an energy source for road transport. The comparative assessment of various BTL fuel chains is based on four main criteria – contribution to the security and diversity of energy supply, energy efficiency, environmental performance and costs. Two types of raw materials and feedstocks are considered – woody (stem wood, short-rotation forestry, wood waste and residues, transformed into wood chips, powder, and pellets; sawdust and shavings) and herbaceous (dedicated energy crops and straw). Special emphasis is given on the biomass gasification step, which is the most challenging part of BTL chains. The fuels considered are BTL naphtha, BTL diesel, methanol, di-methyl-ether and hydrogen. The automotive powertrain technologies taken into account are internal combustion engine and fuel cell.

¹ COM (2001) 547

² Directive 2003/30/EC

Based on the analysis performed in the study, the following three main conclusions about the production of BTL fuels and their automotive applications in the EU by 2010 and beyond can be highlighted:

1. At present BTL production is at an experimental stage. Significant contribution of BTL fuels to the automotive fuel supply by 2010 should not be expected. However, BTL fuels appear to have a much larger production potential and thus bigger contribution to the security and diversity of energy supply than conventional biofuels beyond 2010. The lower energy efficiency along fuel chains, compared to conventional oil-derived fuels, is offset by the diversity of supply advantages. In addition, the production of BTL fuels can be a more energy-efficient way to exploit the available limited biomass resource than power generation from biomass.
2. BTL fuels offer larger environmental benefits over conventional biofuels in terms of GHG and local-polluting emissions. Respectively, the environmental performance of BTL fuels is far better than that of conventional oil-derived fuels.
3. The production costs of BTL fuels have the potential to become lower than those of conventional biofuels beyond 2010. However, the production costs of BTL fuels will remain 2-3 times higher than those of conventional oil-derived fuels in the near to medium future. The key reserves for cost reduction are associated with increasing the scale of production, exploiting the learning curve and applying process optimisation and integration. BTL plants have to be regarded as a kind of refinery run on biomass. The cost-benefit analysis should be based on a combined market realisation of fuels, non-energy products (waxes, lubricants, kitchen oils, etc.), power and heat. This means that the maximisation of the revenue from all BTL products by optimising the overall energy efficiency of BTL plants might be a more appropriate strategy, rather than aiming at maximising solely the BTL fuel yield.

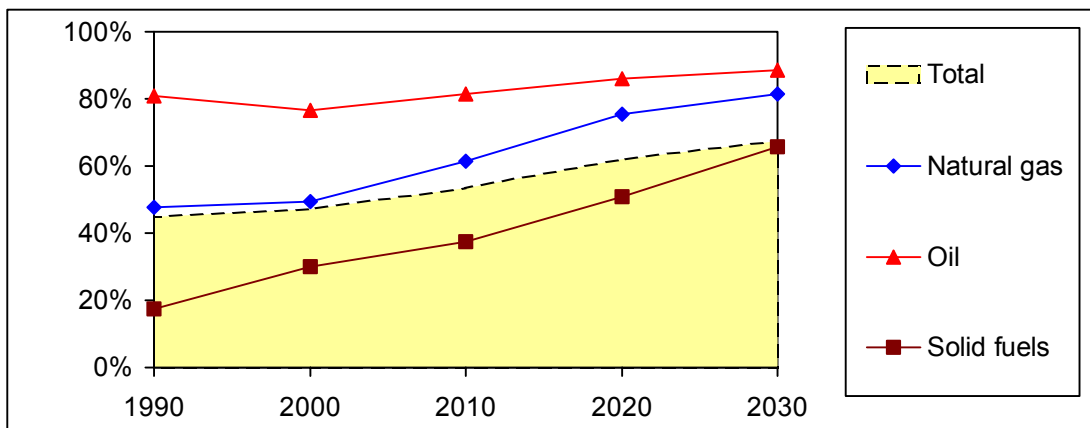
The above conclusions are drawn, based on the following key considerations and approaches in the course of the study:

- ✓ All BTL technologies are at a very early stage of development. The data and information availability is generally modest and it is characterised by a large extent of uncertainty. Therefore, the ability to perform thorough comparative analyses is extremely limited.
- ✓ The aspects of BTL production and application with relation to their potential automotive applications are only considered in this study. BTL production for other energy (e.g. power generation) and non-energy uses (ammonia, lubricants, other chemicals) is considered only to the extent to which it touches upon fuel applications.
- ✓ The analysis is based exclusively on publicly available data and information.
- ✓ A great deal of the information comes from U.S. sources. Where appropriate, the original U.S. measurement units are adjusted / recalculated according to the European standards.

1. BACKGROUND

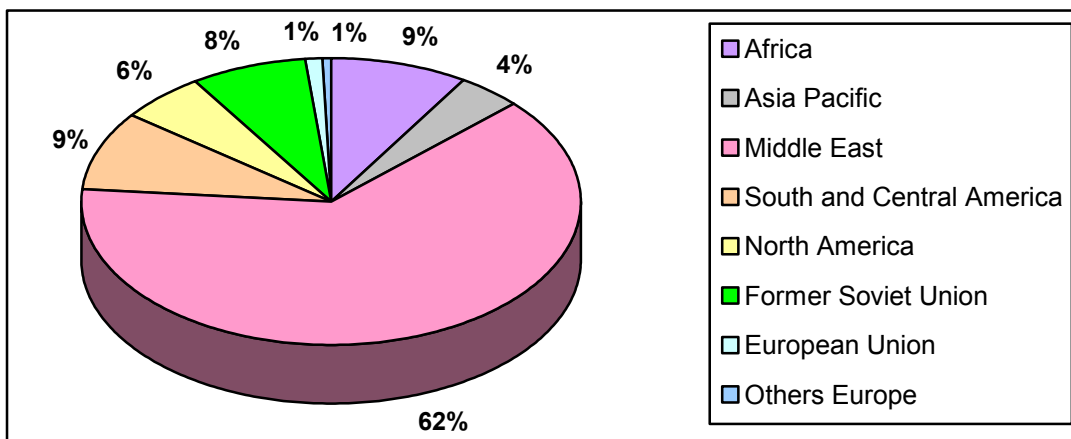
EU-15 are heavily dependent upon energy imports. The share of imports in their total energy consumption, currently standing at about 50%, could reach 70% by 2030. With regard to oil, the prevailing high (76% [75]) import dependence could get up to 90% by 2020 [62], due to depletion of own oil resources [20]. The enlargement of the EU that took place in May 2004 will not reduce this import dependence either – Figure 1, as NMS-10 are also heavily dependent on oil imports – currently 90%, projected to reach 94% by 2010 [62, 138]. Since world oil reserves are geo-politically concentrated – Figure 2, such an import dependence threatens the security of the EU oil supply [62].

Figure 1
Retrospective (1990-2000) and projected (2010-2030) import dependence of EU-25 – total and by fuels, (%)



Source: Adapted from [74, 75]

Figure 2
Breakdown of proved oil reserves by regions in the world at the end of 2003, (%)

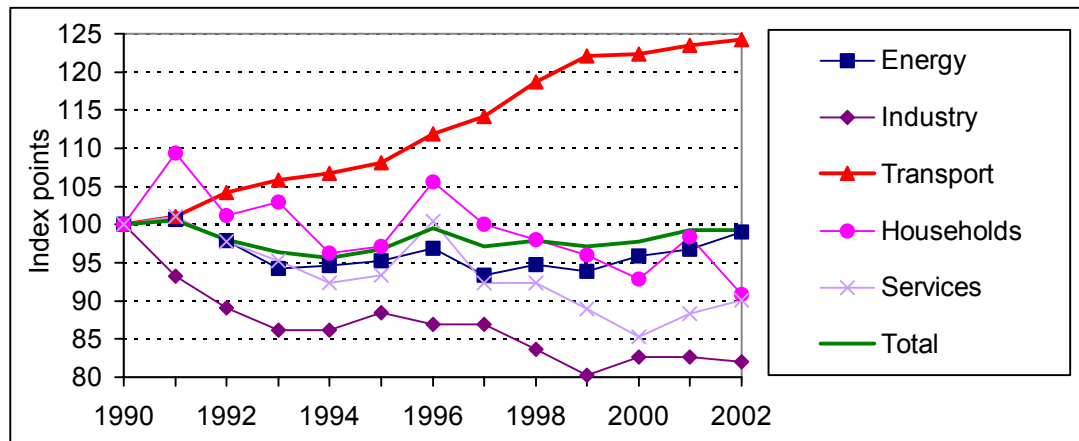


Source: Adapted from [20]

Recently global warming and climate change, caused by the emissions of greenhouse gases (GHG), have become a growing concern in the world. Aiming at improving global environment, various countries undertook under the Kyoto Protocol to the United Nations

Framework Convention on Climate Change (UNFCCC) to reduce their GHG emissions. The EU committed to cut within 2008-2012 its GHG emissions by 8% from their 1990 level. However, the decrease in GHG emissions achieved so far raises concerns about reaching the target [95, 96]. This is due mainly to the emissions of carbon dioxide (CO₂) – the main GHG, accounting for 82% of all GHG emissions in the EU – whose reduction over the period 1990-2002 was negligible – Figure 3.

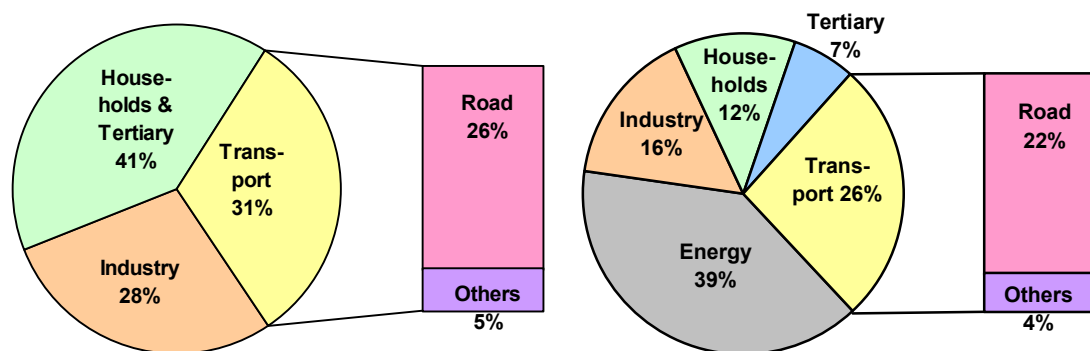
Figure 3
CO₂ emissions from fuel combustion in EU-25 within 1990-2002 (Index points, 1990 = 100)



Source: Adapted from [76]

Transport is a key energy-consuming sector, responsible for 31% of final energy demand in the EU – Figure 4. Transport is also a main contributor to the growth in energy demand [138] with its energy consumption increasing faster than total gross energy consumption – Figure 5.

Figure 4
Breakdown of final energy consumption and CO₂ emissions by sectors in EU-25 in 2002, (%)



Final energy consumption

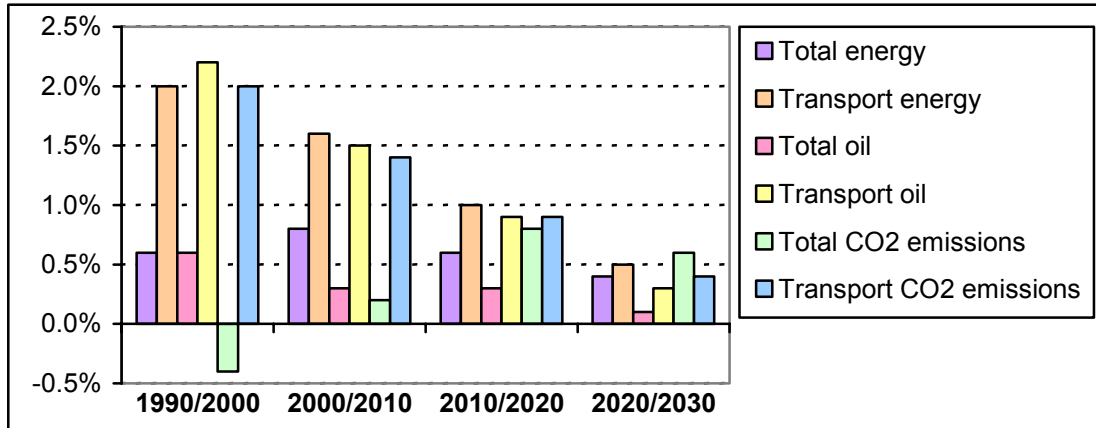
CO₂ emissions

Source: Adapted from [76]

Transport is almost fully dependent on oil-derived products (Figure 6) and accounts for 67% of final oil demand in the EU. Similar to total energy, oil consumption in transport grows faster than total oil demand – Figure 5. Road transport is even more dependent on oil (Figure 6).

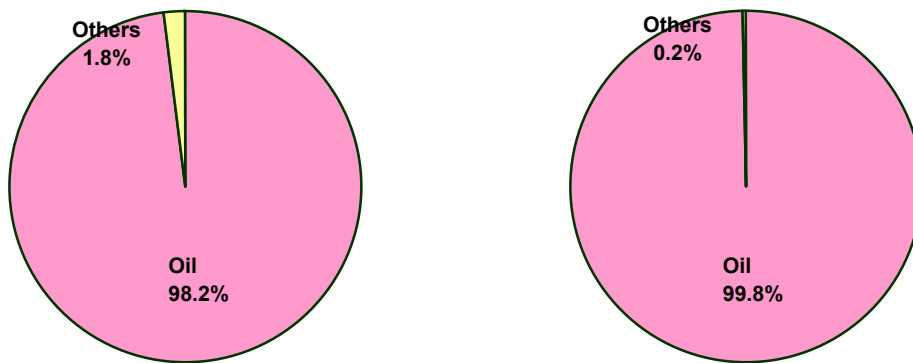
Amongst transport modes, it has the major share in oil consumption, as most passenger and freight traffic in the EU goes by road [63, 180].

Figure 5
Retrospective (1990/2000) and projected (2000-2030) average annual growth in total gross energy demand and energy consumption in transport, total oil demand and oil consumption in transport, total CO₂ emissions and CO₂ emissions from transport in EU-25, (%)



Source: Adapted from [75]

Figure 6
Breakdown of energy consumption of total transport and road transport by fuel sources in EU-25 in 2002, (%)



Total transport energy consumption

Road transport energy consumption

Source: Adapted from [88]

Transport represents a key GHG and CO₂ generating sector, responsible for 20% of total GHG and 26% of all CO₂ emissions in the EU – Figure 4 [73, 91]. Amongst all sectors, transport is the only one, which did not show any improvement in its CO₂ performance since 1990 – Figure 3. Over the period 1990-2000, instead of declining, the CO₂ emissions from transport grew fast (Figure 5), mainly due to the impact of road transport [91]. Road transport is the core CO₂ emitter amongst transport modes (Figure 4), accounting for 84% of all transportation CO₂ emissions [74]. With current trends, the baseline projections [75, 94] foresee a further growth in GHG emissions from transport (Figure 5), amounting to 28% in total by 2010, again coming predominantly from road transport.

For these reasons, securing and diversifying the energy supply for transport and in particular for road transport in an environmentally-friendly way is a prime objective for the EU transport, energy and environmental policies [62]. In this context, the EC identified biofuels as a feasible and promising tool to achieve these policy goals [64]. Two indicative targets for the use of biofuels in transport have been set up. Their reference values are 2% by the end of 2005 and 5.75% by the end of 2010 of all petrol and diesel³, used in transport, measured on an energy content basis [100]. In fact, these indicative targets address mainly road transport, since other modes of transport (rail, waterborne and air) run on other fuels⁴.

Amongst different biofuels, suitable for application in transport, bioethanol and biodiesel seem to be the most feasible ones at present. The key advantage of bioethanol and biodiesel is that they can be mixed with conventional petrol and diesel respectively⁵, which allows using the same handling and distribution infrastructure. Another important strong point of bioethanol and biodiesel is that when they are mixed at low concentrations – up to 10% bioethanol in petrol and up to 20% biodiesel in diesel, no engine modifications are necessary.

Both bioethanol and biodiesel are currently produced in the EU exclusively from agricultural feedstock. Bioethanol is obtained via fermentation of sugar-bearing and starch crops (sugar beet, wheat, maize, potato, etc) [52]. Biodiesel is produced from vegetable oil, obtained via oil extraction from oilseed crops (mainly rapeseed and sunflower), mixed with a small amount of methanol [51]. The production of transport biofuels from agricultural feedstock is however constrained by several important factors – strong competition with other prime applications of agricultural land, e.g. for food and feed production, cultivation specifics of biofuel crops (e.g. long crop rotation periods), etc. [145]. As a result, the biofuel production in the EU is lagging behind the necessary growth rate to reach the indicative targets – Figure 7. In the NMS-10 biofuel production is almost non-existent at present, while their feasible production potential does not appear so large as it is sometimes assumed [143]. The reserves for further increase of biofuel production from agricultural feedstock in the EU-25 might therefore not be sufficient to meet the policy targets and in particular the 2010 one. Hence, alternative biofuel production pathways need to be investigated.

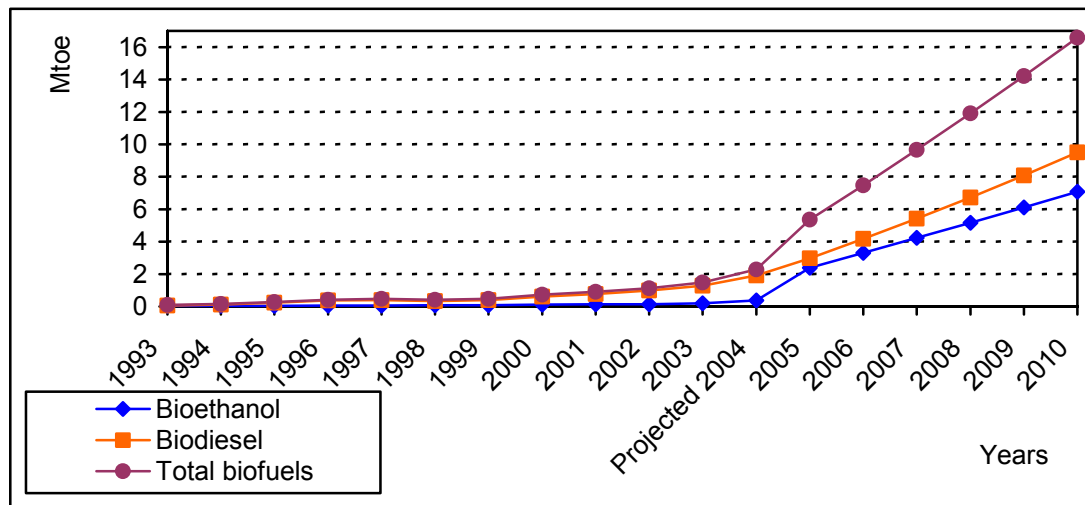
The production of biofuels from ligno-cellulosic material is such an alternative. This production pathway is based on a fuel synthesis from gaseous feedstocks – carbon monoxide (CO) and hydrogen (H₂). The technology is known as “Gas-To-Liquid” (GTL) processing. Besides biomass, the input components for GTL – CO and H₂, commonly called also “synthesis gas” or “syngas”, can be obtained from various hydrocarbon feedstocks, e.g. natural gas, coal, municipal waste, etc.

³ Petrol and diesel are the key transport fuels in the EU, accounting for more than 85% of all used transport fuels [75].

⁴ Beside road transport, small quantities of diesel fuel are consumed also in rail and waterborne transport.

⁵ It is also possible to mix ethanol with diesel. However, due to fuel quality concerns, this option is not yet considered as practical [145].

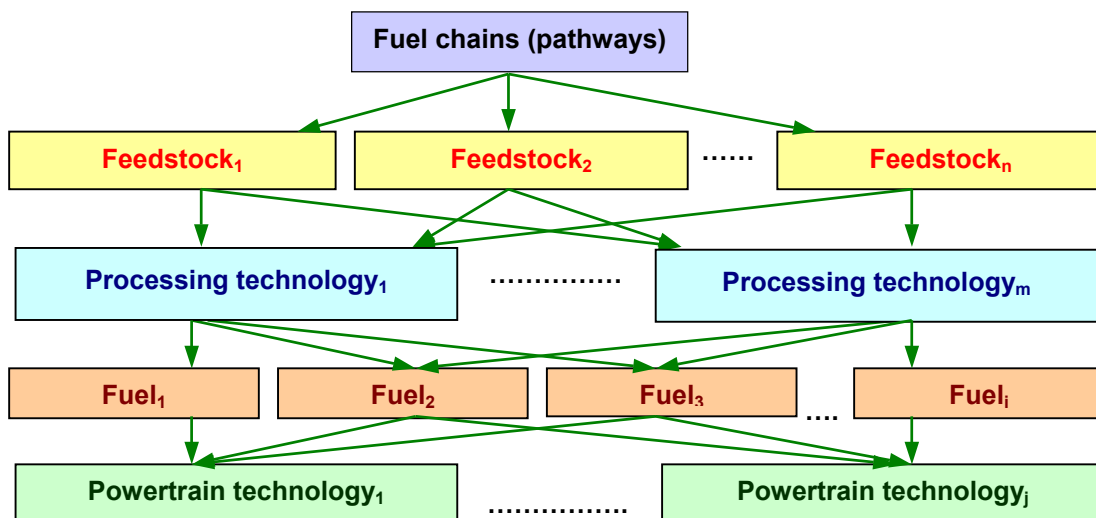
Figure 7
 Retrospective (1993-2003) biofuel production, projected (2004) growth in biofuel processing capacities and needed prospective biofuel output to meet the indicative targets in 2005 and 2010 for EU-25, assuming a linear growth within 2006-2009 – total and by type of biofuel⁶ – (Mtoe)



Sources: Adapted from [56, 58, 240]

With regard to the above, the goal of this work is to perform a techno-economic analysis of the production of fuels from biomass via gas-to-liquid technologies [biomass-to-liquid (BTL) fuels] and their potential for automotive application in the EU by 2010 and beyond. The investigation aims at identifying the optimum ways in which the limited biomass resource can be transformed into fuels for transport. The evaluation of different BTL options is based on an assessment of whole fuel chains from extraction of raw materials to final use of fuels – Figure 8.

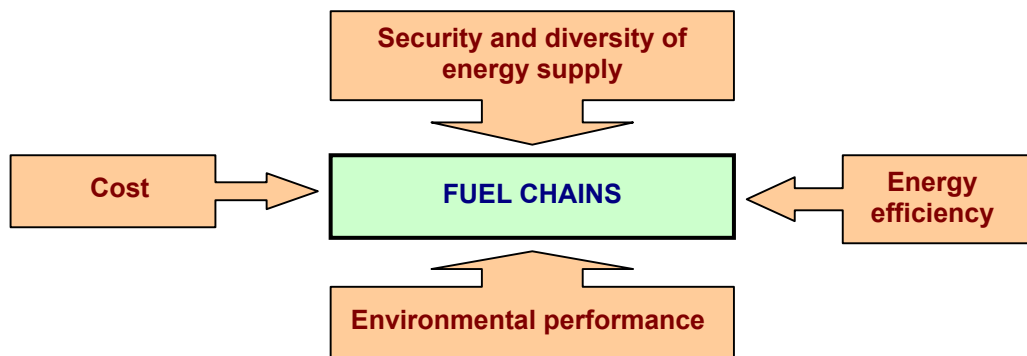
Figure 8
 General structure of fuel chains (pathways)



⁶ Bioethanol and biodiesel, assuming bioethanol replaces petrol and biodiesel substitutes diesel

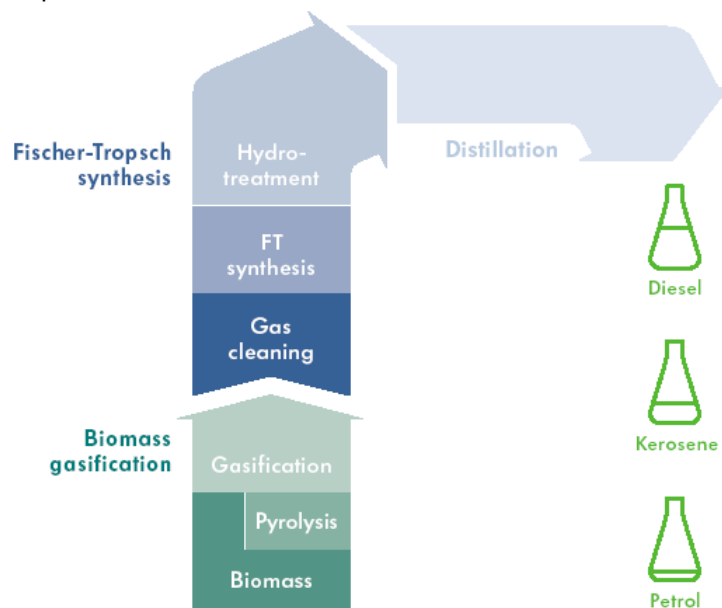
The analysis of alternative BTL fuel pathways is based on four main criteria, presented in Figure 9. The engine performance, compared to conventional (diesel and petrol) and other alternative motor fuels, should also be considered. The criteria from Figure 9 are to a certain extent inter-related and sometimes mutually-contradicting. For instance, a further transformation of feedstock may improve the environmental performance of a fuel chain, but at the expense of poorer energy efficiency and higher costs. Thus, the assessment of fuel chains and the selection of optimum pathways should take into account simultaneously the combined direct and secondary impacts of these four criteria altogether.

Figure 9
Criteria to assess the viability of different fuel chains



Referring to Figure 8, the main steps of the production of BTL fuels are summarised in Figure 10.

Figure 10
Main steps of BTL production of fuels



Source: [242]

Since the production of several other fuels – methanol, di-methyl-ether (DME) and hydrogen – follows synthesis processes similar to GTL, they can be also regarded as GTL products and

thus, are investigated in this work. Particular emphasis in the analysis is given to the biomass gasification step (production of syngas), which is indeed the novel and hence, the most challenging part of the BTL chains from a techno-economic point of view⁷.

Securing and diversifying the energy supply for road transport in an environmentally-friendly way is a main challenge for transport, energy and environmental policies in the EU. Biofuels are a feasible tool to achieve these policy goals, thus indicative shares for market penetration of biofuels have been set up in the EU. The production potential of conventional biofuels, based on agricultural feedstock, seems insufficient to meet these policy targets. Producing biofuels from ligno-cellulosic material via gas-to-liquid technologies – biomass-to-liquid (BTL) fuels – could potentially overcome these limitations. The selection of optimum BTL fuel chains is based on four main, inter-related and sometimes mutually-contradicting criteria: security and diversity of energy supply, energy efficiency, environmental performance and costs.

⁷ The production of GTL fuels from fossil feedstocks (coal and natural gas) is a mature technology that has been already commercialised at a large scale.

2. BIOMASS INPUTS TO BTL PROCESSING

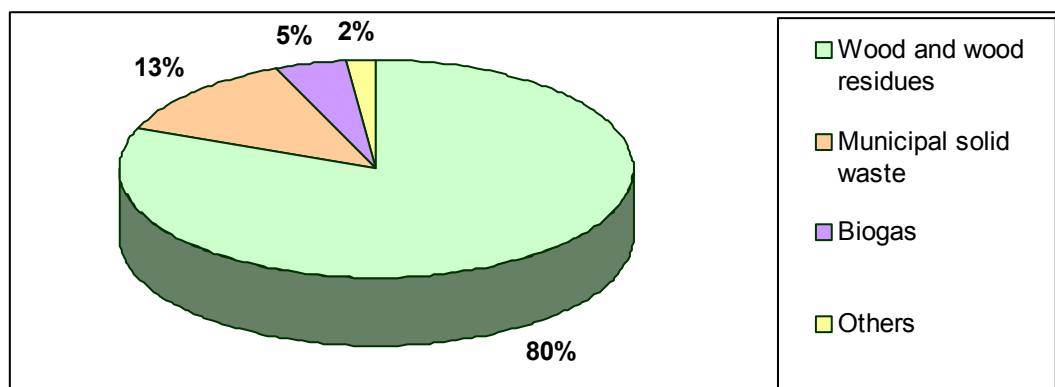
In principle, the larger the carbon and hydrogen content in raw materials, employed in GTL processing, is, the easier and more efficient the CO and H₂ production. Hence, the natural gas pathway is the most convenient one, since natural gas is gaseous and contains virtually carbon and hydrogen only – Figure 12. Solid raw materials (biomass, coal) involve more processing, because first they have to be gasified and then the obtained product gas should be cleaned up from other components: NO_x, SO_x, particles, etc., to the extent of getting as high as possible purity of syngas, i.e. as much as possible CO and H₂.

Two core types of biomass raw material are distinguished – woody and herbaceous. Currently woody material accounts for about 50% of total world bioenergy potential. Another 20% is straw-like feedstock, obtained as a by-product from agriculture. The dedicated cultivation of straw-like energy crops could increase the herbaceous share up to 40% [18, 238]. The main technical specifications of biomass raw materials and feedstocks, which could be used to produce BTL fuels, are presented in Figure 12. For comparative purposes, Figure 12 gives also the properties of coal and natural gas – other possible inputs to GTL processing.

2.1. WOODY RAW MATERIAL

At present wood is the largest single renewable energy source in EU-25, accounting for 53% of all renewable energies in 2002⁸ [88]. It is respectively the most important bioenergy resource in the EU as well – Figure 11. Owing to climate specifics, some European countries (Austria, Denmark, Finland, France, Germany, Sweden) are amongst world leaders in the development of wood energy applications [89, 87, 249]. The woody biomass comprises stem wood from ordinary forestry, dedicated (short-rotation) forestry, as well as various residues and wood wastes [197].

Figure 11
Breakdown of primary bioenergy production in EU-25 in 2002 (%)



Source: Adapted from [88]

⁸ Large hydropower being not considered

Figure 12

Main properties of coal, natural gas and various woody and herbaceous raw materials and feedstocks

	Bituminous Coal	Natural gas	Wood ⁹	Bark	Willow	Forest residues ¹⁰	Wood chips	Wood pellets	Cereal straw	Dedicated energy crops
Ash, d%	8.5-10.9	0	0.4-0.5	3.5-8	1.1-4.0	1-3	0.8-1.4	0.4-1.5	3-10	6.2-7.5
Moisture, w%	5-10	0	5-60	45-65	50-60	50-60	20-50	7-12	14-25	15-20
NCV, MJ/kg	26-28.3	48	18.5-20	18.0-23	18.4-19.2	18.5-20	19.2-19.4	16.2-19	16.5-17.4	17.1-17.5
Density, kg/m ³	1100-1500	n.a. ¹¹	390-640	320	120 ¹²	n.a. ¹³	250-350, 320-450 ¹⁴	500-780	100-170 ¹⁵	200 ⁹
Volatile matter, w%	25-40	100	>70	69.6-77.2	>70	>70	76-86	>70	70-81	>70
Ash melting point, T°C	1100-1400	-	1400-1700	1300-1700	n.a.	n.a. ¹⁶	1000-1400	>1120	700-1000	700-1200
C, d%	76-87	75	48-52	48-52	47-51	48-52	47-52	48-52	45-48	45.5-46.1
H, d%	3.5-5	24	6.2-6.4	4.6-6.8	5.8-6.7	6.0-6.2	6.1-6.3	6.0-6.4	5.0-6.0	5.7-5.8
N, d%	0.8-1.5	0.9	0.1-0.5	0.3-0.8	0.2-0.8	0.3-0.5	<0.3	0.27-0.9	0.4-0.6	0.50-1.0
O, d%	2.8-11.3	0.9	38-42	24.3-42.4	40-46	40-44	38-45	≈40	36-48	41-44
S, d%	0.5-3.1	0	<0.05	<0.05	0.02-0.10	<0.05	<0.05	0.04-0.08	0.05-0.2	0.08-0.13
Cl, d%	<0.1	-	0.01-0.03	0.01-0.03	0.02-0.05	0.01-0.04	0.02	0.02-0.04	0.14-0.97	0.09
K, d%	0.003	-	0.02-0.05	0.1-0.4	0.2-0.5	0.1-0.4	≈0.02	n.a.	0.69-1.3	0.3-0.5
Ca, d%	4-12	-	0.1-1.5	0.02-0.08	0.2-0.7	0.2-0.9	≈0.04	n.a.	0.1-0.6	9

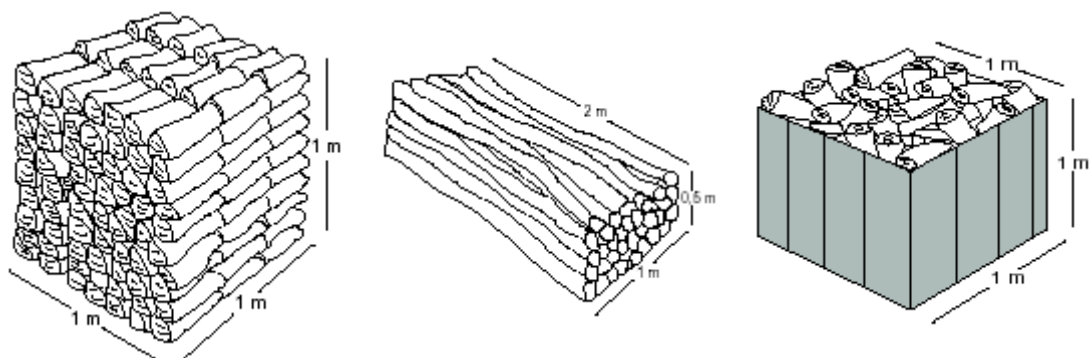
Sources: Adapted from [29, 30, 42, 59, 120, 131, 148, 170, 200, 201, 209, 218, 249, 266, 272, 273, 304]

⁹ Without bark¹⁰ Coniferous trees with needles¹¹ Depends on the aggregate state (compression and temperature)¹² Willow chips¹³ Large variations are possible¹⁴ The first range is for soft wood, the second range – for hard wood¹⁵ Bales¹⁶ Large variations are possible

2.1.1. Wood logs (stem wood) from ordinary forestry

Wood logs represent forest fuel of trimmed or untrimmed stem wood – Figure 13.

Figure 13
Different shapes of stem wood (the NCV are given for beach with 20% moisture content)



Sawn, split and stacked
wood, NCV = 7.6-8.6 GJ
Source: [29]

Stacked whole-tree wood,
NCV \approx 6.5 GJ

Loose volume wood logs,
NCV \approx 4.8 GJ (40 cm pieces)

Wood logs are the first ever-known energy application of biomass – burning wood for heating and lighting has been known by humanity for millennia. Stem wood is a perfect feedstock for BTL processing, since being a pure wood (a hydrocarbon material), it has negligible content of impurities and harmful substances that have to be removed during gasification compared to e.g. waste wood. However, the use of wood logs for energy purposes in Europe nowadays strongly competes with other alternative, non-energy appliances of higher value, e.g. for pulp and paper production, furniture industry, etc. As a result, the market price of good quality stem wood is typically high, which significantly precludes its bioenergy application.

2.1.2. Short-rotation forestry

The dedicated cultivation of short-rotation (over a total period of 3-30 years) wood species is recently getting an increasing popularity in Europe. Willow (*Salix*) and to a lesser extent – poplar (*Populus*) are the favourite species – Figure 14. Willow is harvested in 2-4 year intervals, when the shoots are approximately of 6 meters of height, normally in the winter in order to reduce the moisture content. After harvesting, willow stumps are left to coppice and another crop grows in 2-4 years. Poplar needs longer harvest intervals – 8-15 years. Current yields of short-rotation forestry (SRF) reach 10-15 tonnes per hectare per year, that is higher than the wood yields from ordinary forestry (usually 5-10 tonnes per hectare per year [41, 303]). A value of 30 tonnes per hectare per year from SRF is targeted in the future, whilst preserving environment (e.g. biodiversity, visual changes of landscape¹⁷) and maintaining pest and disease tolerance.

¹⁷ SRF is tall and fast growing thus the rate of change of landscape can be rapid.

Figure 14
Short-rotation forestry – willow harvesting in Sweden (left hand side) and poplar felling in the USA (right hand side)



Source: [199]



Source: [125]

Achieving high yields is only possible under specific cultivation conditions. For instance, poplar and especially willow require substantial quantities of water, i.e. the growth rate is reduced in dry conditions or dry years. The cultivation of SRF could also result in groundwater depletion. Nevertheless, planting perennial SRF brings some clear environmental benefits, compared to growing conventional annual crops – less soil disturbance and more soil cover (leading to reduced soil erosion), lower fertiliser and pesticide inputs. The cultivation and harvesting of SRF is also very energy efficient, since it consumes little energy – only 4-5% of the energy content of the harvested material. The core drawback of dedicated woody crops is the much higher cost compared to various wood residues from thinning, pulp and paper industries, etc. Hence, the reduction of cultivation costs of SRF is a main challenge and prerequisite for its larger utilisation. Another drawback of woody crops is the typically high moisture content (Figure 12) that is not appropriate for the gasification process. Thus, the woody feedstock from SRF normally needs pre-drying [6, 7, 26, 28, 29, 53, 125, 131, 155, 169, 177, 195, 199, 201, 203, 207, 208, 214, 215, 216, 303].

2.1.3. Residual woody biomass

A residual (waste) product can be defined as a material, which is a refuse without objective value within a specific context, otherwise it constitutes a material at the end of its usefulness [5]. Ensuing from this definition, a number of woody materials can be included in the group of residues and waste: thinning and logging residues from forest industry (tops, branches and small size stems), demolition wood and railway sleepers, fibreboard residues, cutter shavings, plywood residues, etc. – Figure 15. Residual woody material is believed to be a very promising bioenergy resource, since it is available at much lower or negligible cost compared to wood logs and short-rotation forestry.

Figure 15
Residual wood – small trees from early thinning of pine (left hand side) and wood waste (right hand side)



Source: [203], original source – VTT



Source: [59]

Synergies are also earned with other industries e.g. regular thinning improves wood yields and prevents forest fires. However, the availability of residual woody biomass depends on the primary wood yield and accounts for 25-45% of all harvested wood on average [125]. The heterogeneous composition of the residual and waste woody biomass (content of moisture, impurities, etc.) might sometimes preclude its application for BTL production. Hence, some preliminary treatment of the residual and waste woody biomass may be necessary, in order to make it appropriate for BTL processing [26, 29, 131, 164, 196, 198, 203, 217].

2.2. WOODY FEEDSTOCK

As already indicated, for various reasons – too large or too dissimilar particle size, content of impurities and water, etc. straight gasification of woody raw materials is usually not possible. Hence, woody biomass normally undergoes preliminary treatments and transformations into feedstocks, which are more suitable for gasification and further processing. Such feedstocks could be wood chips, sawdust, bark from spruce and wood pellets – (Figure 16)

Figure 16
Potential woody feedstocks for BTL production – from left to right: forest chips, sawdust, bark from spruce and wood pellets



Source: [29]

2.2.1. Wood chips

Wood chips (Figure 16) represent chopped with special facilities (chippers) woody raw material – whole trees (usually soft wood), short-rotation forestry, wood residues (branches, tops, etc.) with particle size 5-60 mm. The chips from stem wood and short-rotation forestry are of higher quality and contain fewer impurities than the chips from residual and waste woody material, but conversely they are also more expensive.

Wood chips are gaining an increasing popularity as they allow utilisation of various residual and waste woody materials, which otherwise are not suitable for gasification. By combining different woody materials, the poorer qualities of a given material can be partly compensated with the better properties of another material. In addition, chipping ensures a homogeneous feedstock with guaranteed qualities, which is a mandatory pre-requisite for efficient gasification. Chipping is also energy efficient, as it requires only 1-3% of the energy content of woody biomass on average. The energy cost for wetter raw materials is lower, due to their lower internal friction [4, 29, 42, 131, 197, 198, 201, 203].

As already mentioned, chipping allows a more complete utilisation of woody biomass. On the other hand, the re-production of forests and the maintenance of high wood yields require leaving in the soil part of the nutrients (nitrogen, phosphate and potassium), contained in wood. A more complete utilisation of forest resources means also a larger removal of nutrients. If this process is not carefully controlled, it can result not only in reduced wood yields, but also in destroyed biodiversity and deserted areas. It is therefore of prime significance to find the right balance between short-term yields and long-term fertility of forest soils. Achieving such a balance is relatively easy in practice, since the largest part of the woody biomass, i.e. of the hydrocarbon content, is bound in stems, while the majority of nutrients are contained in needles and branches. Hence, after felling, the whole trees are often left on the ground for a couple of months. During this period, the needles and small branches fall down, owing to gradual drying, and the nutrients are absorbed by the forest soil [29, 164, 198, 201, 203, 279].

When chipping fresh wood, the moisture content of chips can be very high (45-55% on weight basis). Such high moisture levels can obstruct gasification, so the wetness has to be brought down to 5-25% [1, 28, 178, 245]. There are three ways of decreasing the moisture content of woody biomass in general and of wood chips in particular, which can be used also consecutively to optimise the financial and energy costs:

- Natural drying of woody raw material: When the whole trees are left on the ground for the needles and the small branches to drop away and to remain in the forest, the stems also dry. If the trees are felled between January and March, when the moisture content of wood is normally at its lowest and then are left for the summer to dry, the moisture content can naturally go down from 50-55% to 35-45%. Besides the advantages of

natural drying, leaving woody biomass in outdoor storages may result in weight loss, due to natural biological decomposition and/or insect infection (especially for soft wood species). The rate of biological degradation can be rather high, in particular for wet material in the beginning of the storage period. The decomposition rate depends largely on the particle size – the larger the particles, the lower the rate. In order to prevent great weight losses from insect infections, trees left on the ground should be regularly inspected.

- Natural drying of wood chips: Wood chips can be stored outdoor (in the summer) or indoor (in the winter) near the gasification plant for further drying. The summer outdoor storage is preferred, as it is cheaper – due to their low bulk density (Figure 12), chips need large drying space. The reduction of wetness is similar to that of natural drying of whole trees – from 50% to about 30%. Outdoor storage of biomass with moisture content less than 30% is not recommended, since it can increase due to rainfall. As already stated, in case of outdoor storage and natural drying of chips, special attention should be paid to the rate of biological degradation. Due to the small size of chips, it can be really high – up to 5% per month for fresh chips or bark in the beginning of the period, later on getting down to 1-2%.
- Forced drying of woody biomass: Dedicated drying of woody biomass at gasification plants should be avoided in general, since it reduces their energy efficiency and increases costs. Thus, as much as possible natural drying is recommended. When natural drying is not sufficient and/or heat, which otherwise is lost, is employed for drying (e.g. heat from fuel synthesis), the application of forced drying is justifiable – it even increases the overall energy efficiency of plants. In any case, the additional benefits should be always set against the additional capital and running costs [4, 29, 131, 200, 201, 203, 230].

2.2.2. Wood powder and sawdust

Apart from chipping, another option to utilise various residual or waste woody materials is as powder. Wood powder represents fine shredding of woody biomass with particle size below 3 mm, usually about 1 mm [29, 198]. This is an important advantage over chips, since the smaller the particle size, the better the gasification. Conversely, the energy consumption of mills is typically much higher than that of chippers. The energy penalty grows exponentially with the reduction of the size of wood powder particles below 1 mm¹⁸. Wood mills are robust and reliable systems, which can process materials of various quality (including with impurities) and particle size. When demolition wood is shredded, a removal of the metallic contaminants (with magnets) may be necessary before the material enters the mill.

Besides dedicated and energy-expensive milling of various woody materials, feedstock with similar particle size can be obtained also directly – sawdust, which is a residual material from

¹⁸ Pulverisation down to 200µm costs about 10% of the primary wood energy, while the 100µm particle size takes as much as almost 20% of the energy content of woody feedstock [239]

sawmills – Figure 16. Similar to chips, when sawdust is left after processing fresh wood, its moisture content could be high so pre-drying might be necessary [29, 131, 198, 200, 304].

2.2.3. Wood pellets

Pellets are normally of 10-30 mm of length at 8-12 mm of diameter – Figure 16. Notwithstanding the fact that they get an increasing popularity as a solid biofuel for heat and to a lesser extent for power generation, their employment in BTL production is modest, more as a kind of exception. Pellets are usually produced from powder obtained from various residual biomass (woody and/or herbaceous) and waste, or sawdust. To form the pellets, the powder is usually forced through a matrix under high pressure, followed by immediate cooling for durability and stability¹⁹. The main advantage of pellets over powder, sawdust and other residual biomass is the much higher energy density (Figure 12), which reduces significantly transportation, storage and handling costs per energy unit. The drawback of pellets is the lower energy efficiency compared to powder (2 processes instead of just 1). If dry raw material is used, the energy costs may reduce to that of chips – 1.5-2% of the energy content of pellets. If drying is actually necessary, the energy costs may raise up to 7-13%. Additional 10% can be spent for preliminary crushing of the raw material [29, 60, 131, 200]. With regard to BTL production, pelletising can be justified only when remote biomass has to be brought to the BTL plant, if no other more cost-effective options are available.

2.3. HERBACEOUS FEEDSTOCK

The energy application of herbaceous biomass in the EU is still at an experimental stage (Figure 11), except for Denmark [120, 249]. Nonetheless, it is widely believed that the energy potential of herbaceous biomass is promising, because most of it represents residual material from agriculture (straw), which could be available at relatively low cost. The transformation of herbaceous raw material into a feedstock for gasification is simpler than that of woody raw material, since herbaceous biomass only requires chaffing. Hence, unlike woody biomass, a distinction between raw material and feedstock is not made for herbaceous biomass.

2.3.1. Herbaceous energy crops

Growing dedicated herbaceous crops for energy purposes is a relatively novel practice, thus complete information about various aspects of their cultivation is still scarce [155]. The main herbaceous species currently considered in Europe for energy application are miscanthus (Figure 17), red canary grass and switchgrass. Miscanthus is an attractive option, since growing requires lower input of fertilisers and pesticides compared to agricultural crops, while yields can reach 15 tonnes per hectare per year under optimum conditions. Its main disadvantage is that it can be difficult to rehabilitate the land for other uses due to the deep

¹⁹ It is also possible to obtain pellets via cold compaction, however this technology gives a much lower quality pellets.

root structure of miscanthus. Slightly lower maximum yields (up to 10 tonnes per hectare per year) are earned from switchgrass. Red canary grass gives even lower yields per hectare per year (5-7 tonnes) without the need for crop rotation for approximately 10 years, but it fits well the climate conditions of Nordic countries. Red canary grass is however very invasive of wetlands and is not a suitable alternative to agricultural crops on high grades of arable land.

Figure 17

Initial planting (left hand side) of miscanthus and its re-planted growth after 2 years (right hand side – the yardstick in the middle indicates height of 1.35 m)



Source: [209]

Compared to short-rotation forestry, herbaceous species have lower moisture content (Figure 12) and under certain conditions can be slightly cheaper. However, herbaceous species show some disadvantages compared to woody biomass: lower bulk density, which increases transportation and handling costs; a larger content of undesirable compounds (potassium, chlorine, sulphur, ash), which reduces syngas yield, may cause corrosion, agglomeration, intensive slagging and fouling, etc. For these reasons herbaceous biomass usually is not directly gasified for BTL production, but it is processed into a semi-finished product – pyrolysis oil²⁰ [7, 30, 59, 78, 131, 177, 200, 207, 209, 214, 215, 266].

2.3.2. Residual herbaceous biomass (straw)

Straw (Figure 18) is the main residual herbaceous material for energy application nowadays. As it is a residual product, its availability for energy purposes is driven by the cereals markets and does not have autonomous market behaviour. In addition, farms consume significant quantities of straw internally – as bed material for livestock, grain drying, etc. Some straw is also chaffed and returned back to the field as soil ameliorator. The net straw yield per hectare for energy application also depends on the crop, the grain yield per hectare, climate and cultivation conditions, etc. Nevertheless, one can roughly estimate that the average straw

²⁰ The production of pyrolysis oil is discussed in chapter 3.

yield per hectare is approximately 50%-65% of the grain yield per hectare from cereals and oilseeds [282, 294].

Figure 18
Straw collection and baling



Source: [215]

Similar to herbaceous crops, straw usually has lower moisture content than woody biomass. Conversely, it has a lower calorific value, bulk density, ash melting point and higher content of ash, problematic inorganic component such as chlorine, potassium and sulphur, which cause corrosion and pollution (Figure 12). The last two drawbacks can be relatively easily overcome by leaving straw on the field for a while. In such a way rainfall “washes” it naturally from a large part of potassium and chlorine. Alternatively, fresh straw can be directly shipped to the gasification plant, where it is washed by dedicated facilities at moderate temperatures (50-60°C). Due to washing, the initially low moisture content of straw becomes higher in both cases and hence a mandatory drying is applied afterwards. In both cases also the content of corrosive components is reduced, but not completely taken out. In order to decrease handling costs, straw and dedicated herbaceous energy crops are usually baled (Figure 18) before being shipped to the gasification plant. The weight and the size of bales depend on the baling equipment and on the requirements of the gasification plant. The weight may vary from about 10 kg to about 500 kg, while the density of baled straw increases up to 100-170 kg/m³ [30, 131, 169].

There are two types of biomass feedstock that can be employed to produce BTL fuels – woody and herbaceous. Woody feedstock comprises wood chips, wood powder and sawdust, obtained from ordinary forestry (wood logs), short-rotation forestry, various wood residues and wood waste. Herbaceous feedstock includes chaffed dedicated energy crops and straw. Owing to biomass composition, woody feedstock is better suited for energy applications than herbaceous feedstock. Woody biomass has also a larger production potential for energy (including BTL) application, however the production potential of herbaceous biomass is currently under-explored.

3. PRODUCTION OF SYNGAS FROM BIOMASS

The production of high-quality syngas from biomass, which is later used as a feedstock for BTL production, requires particular attention. This is due to the fact that the production of synthesis gas from biomass is indeed the novel component in the GTL concept – obtaining syngas from fossil raw materials (natural gas and coal) is a relatively mature technology.

Gasification can be defined as thermal degradation in the presence of an externally supplied oxidising (oxygen containing) agent e.g. air, steam, oxygen [131]. Various gasification concepts have been developed over the years (Figure 19), mainly for the purposes of power generation. However, efficient BTL production imposes completely different requirements for the composition of the gas. The reason is that in power generation the gas is used as a fuel, while in BTL processing it is used as a chemical feedstock to obtain other products. This difference has implications with respect to the purity and composition of the gas.

Figure 19

Main components and properties of gas from biomass feedstock, obtained via different gasification concepts

	A-CFB-air	A-CFB-O ₂	P(N ₂)-CFB-O ₂	P(CO ₂)-CFB-O ₂	A-indirect-H ₂ O	P-EFG-O ₂
CO, vol.% dry	19.3	26.9	16.1	16.1	42.5	46.1
H ₂ , vol.% dry	15.6	33.1	18.3	18.3	23.1	26.6
CO ₂ , vol.% dry	15.0	29.9	35.4	46.9	12.3	26.9
CH ₄ , vol.% dry	4.2	7.0	13.5	13.5	16.6	0.00
N ₂ /Ar, vol.% dry	44.5	0.7	12.3	0.8	0.0	0.4
C ₂ , vol.% dry	1.4	2.4	4.4	4.4	5.5	0.0
NCV, (MJ/m ³)	5.76	8.85	8.44	8.05	13.64	7.43
H ₂ /CO ratio	0.81	1.23	1.14	1.14	0.54	0.58

Legend:

A-CFB-air: atmospheric air-blown direct circulating fluidised bed gasifier

A-CFB-O₂: atmospheric oxygen-blown direct circulating fluidised bed gasifier

P(N₂)-CFB-O₂: pressurised with nitrogen oxygen-blown direct circulating fluidised bed gasifier

P(CO₂)-CFB-O₂: pressurised with carbon dioxide oxygen-blown direct circulating fluidised bed gasifier

A-indirect-H₂O: atmospheric steam-blown indirect gasifier

P-EFG-O₂: pressurised oxygen-blown direct entrained flow gasifier

Source: Adapted from [16]

The calorific value of the gas is the prime factor for power generation – the higher the value, the better. Hence, the availability in the gas of any compounds that increase calorific value is generally welcomed – product gas, which contains carbon monoxide (CO), hydrogen (H₂), various hydrocarbons [methane (CH₄), ethylene (C₂H₄), ethane (C₂H₆) tars and chars]. The presence of inert components [water (H₂O), carbon dioxide (CO₂), nitrogen (N₂)] is also acceptable, provided it is kept within certain limits. In contrast, for BTL production the amount of CO and H₂ is only important (the larger the amount, the better), while the calorific value is

irrelevant – synthesis gas / syngas. The presence of other hydrocarbons and inert components should be avoided or at least kept as low as possible. This can be achieved via the following ways:

- The amount of components other than CO and H₂ (primarily hydrocarbons) can be reduced via their further transformation into CO and H₂. This is however rather energy intensive and costly (two processes – gasification & transformation). As a result, the overall energy efficiency of syngas production and of BTL processing is also reduced, leading to higher production costs.
- The amount of various components can be minimised via a more complete decomposition of biomass, thereby preventing the formation of undesirable components at the gasification step. This approach seems to be more appropriate from an energy efficiency and cost point of view. The minimisation of the content of various hydrocarbons is achieved by increasing temperatures in the gasifier, along with shortening the residence time of feedstocks inside the reactor. Because of this short residence time, the particle size of feedstocks should be small enough (in any case – smaller than in gasification for power generation) in order that complete and efficient gasification can occur.
- In gasification for power generation typically air is employed as oxidising agent, as it is indeed the cheapest amongst all possible oxidising agents²¹. However, the application of air results in large amounts of nitrogen in the product gas (Figure 19), since nitrogen is the main constituent of air²². The presence of such large quantities of nitrogen in the product gas does not hamper (very much) power generation, but it does hamper BTL production. Removing this nitrogen via liquefaction under cryogenic temperatures is extremely energy intensive, reduces substantially the overall BTL energy efficiency and increases costs. Amongst other potential options (steam, CO₂, O₂), from a techno-economic point of view oxygen appears to be the most suitable oxidising agent for BTL manufacturing. It is true that the oxygen-blown gasification implies additional costs compared to the air-blown gasification, because of the oxygen production. Nevertheless, the energy and financial cost of producing oxygen seems to be far lower than the alternative energy and financial cost of cleaning up the product gas from air-blown gasification from nitrogen [11, 16, 19, 26]. This is partly due to the fact that the production of high-purity oxygen (above 95% O₂) is a mature technology.

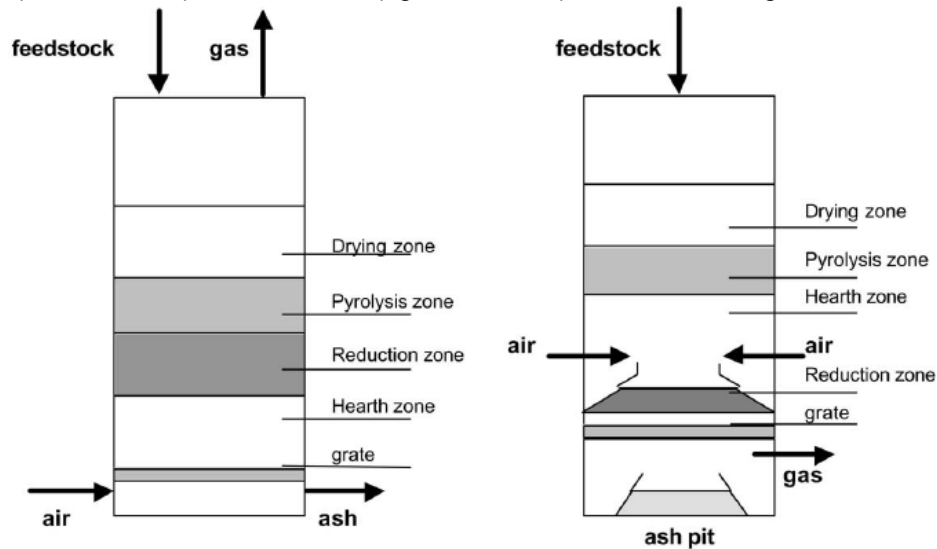
There are three main types of gasifiers – fixed bed, fluidised bed and entrained flow. The air-blown direct gasifiers operated at atmospheric pressure and used in power generation – fixed bed updraft and downdraft (Figure 20) and fluidised bed bubbling and circulating (Figure 21) – are not suitable for BTL production. In addition, downdraft fixed bed gasifiers face severe constraints in scaling (typically up to 1MW [5]) and are fuel inflexible, being able to process

²¹ In fact, air is not a completely “free of charge” oxidising agent, because its application involves secondary costs for flue gas cleaning.

²² Nitrogen accounts for more than 78% of total air composition on volumetric basis. Oxygen accounts for another 21%, while all other components (CO₂, H₂, etc.) fill the remaining less than 1% [293]

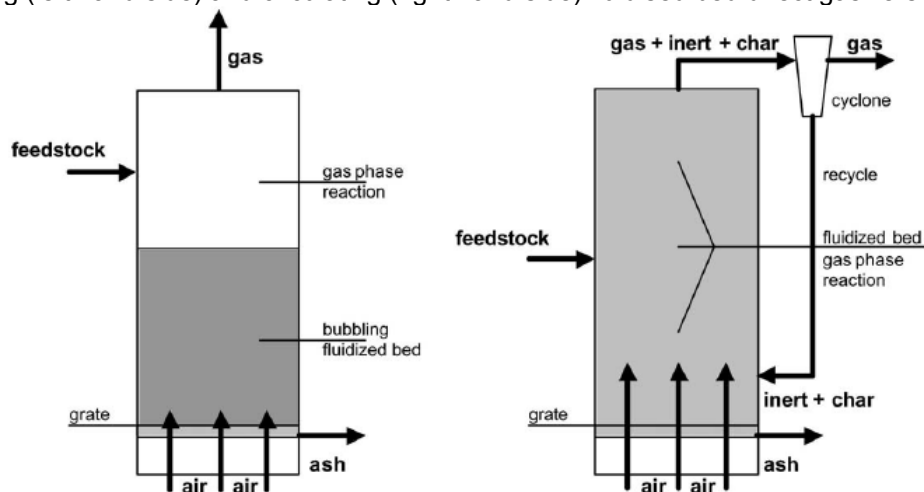
only fuels with well-defined properties. Updraft fixed bed gasifiers have fewer restrictions in scaling (usually up to 10MW), but the produced gas contains a lot of tars and methane.

Figure 20
Updraft (left hand side) and downdraft (right hand side) fixed bed direct gasifiers



Source: [11]

Figure 21
Bubbling (left hand side) and circulating (right hand side) fluidised bed direct gasifiers

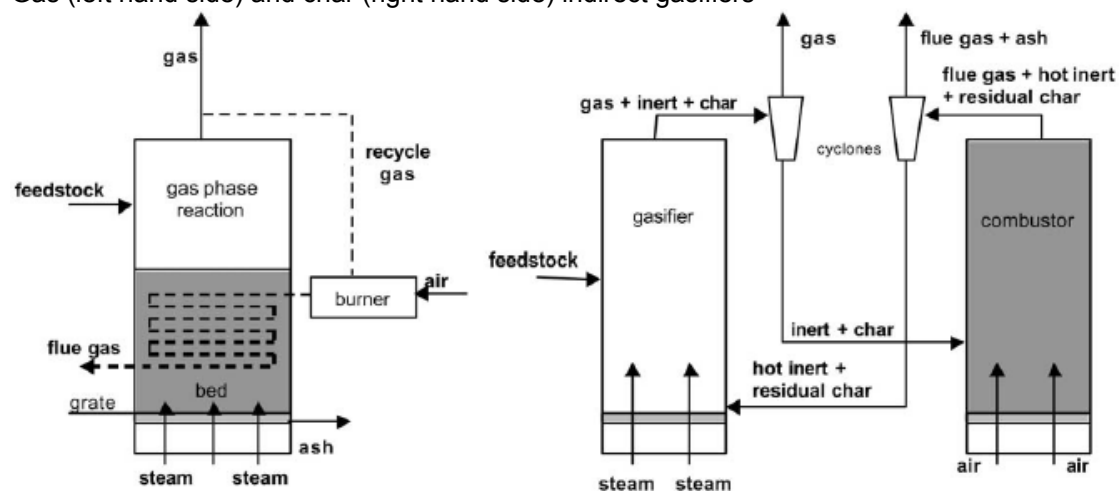


Source: [11]

Fluidised bed gasifiers generally do not encounter limitations in scaling and are more flexible concerning the particle size of fuels. Nevertheless, they still have limited fuel flexibility, due to a risk of slagging and fouling, agglomeration of bed material and corrosion. The operating temperatures of air-blown fluidised bed gasifiers are therefore kept relatively low (800-1000°C), which implies incomplete decomposition of feedstocks, unless long residence times are used. Fluidised bed gasifiers (especially the bubbling bed ones) tend to contaminate the product gas with dust [18, 120]. The oxygen-blown atmospheric or pressurised circulating fluidised bed gasifiers and the steam-blown gas or char indirect gasifiers (Figure 22) are better solutions for BTL production. Both gasifying concepts reduce significantly the amount

of nitrogen in the product gas – Figure 19. In the first case it is achieved via substituting air with oxygen. In the second case nitrogen ends up in the flue gas, but not in the product gas, because gasification and combustion are separated – the energy for the gasification is obtained by burning the chars from the first gasifier in a second reactor [16] – Figure 22.

Figure 22
Gas (left hand side) and char (right hand side) indirect gasifiers



Source: [11]

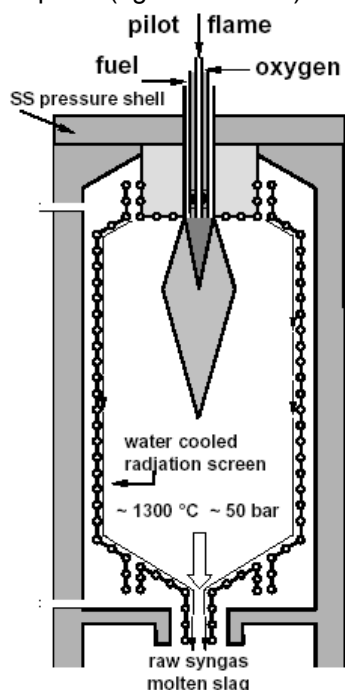
Nonetheless, both oxygen-blown circulating bed gasifiers and steam-blown indirect gasifiers still present some major weak points with regard to BTL production. In the former case the issues related to the necessity for further cracking of the unconverted hydrocarbons and with the high dust emissions are still relevant. In the latter case these two drawbacks can be overcome (Figure 19), but at the expense of a significant increase in capital costs, since two reactors are needed instead of just one [26] – Figure 22, right hand side. In fact, the case of the gas indirect gasifier also involves a second reactor – Figure 22, left hand side. Finally, indirect gasifiers carry a higher risk of malfunctioning and are less reliable, because of their more sophisticated configuration [18, 44].

Considering the above reasons and the results from Figure 19, the pressurised oxygen-blown direct entrained flow gasifier appears to be the most suitable gasification concept to obtain synthesis gas for later BTL processing – Figure 23. Entrained flow gasifiers do not encounter severe scaling restrictions – their capacity can easily be of several hundreds of MW. They represent also a mature technology for coal (not for biomass!), which has been employed for years. Entrained flow gasifiers operate at elevated pressures (10-60 bar) and much higher temperatures (1200-1500°C) than other gasifiers (usually below 900°C). The residence time of the fuel is also much shorter (a few seconds) compared to that in other gasifiers.

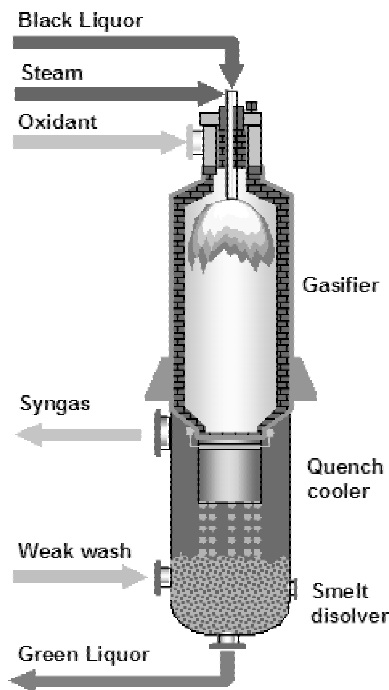
As already mentioned, for a complete transformation of the feedstock into synthesis gas within such short residence time its particle size also has to be smaller than that required for

Figure 23

Diagram of slagging entrained flow gasifier for biomass & pyrolysis slurry (left hand side) and for black liquor²³ (right hand side)



Source: [120]



Source: [253]

other gasifiers – not larger than 1 mm, typically below 0.1 mm (100 μm) [18, 238]. With such extreme conditions almost tar-free synthesis gas with high content of CO and H₂ is obtained – Figure 19 [16, 17, 18, 19, 26, 44, 45, 120, 205, 238, 239]. This high conversion rate is also facilitated by the high reactivity and volatility of biomass [18, 131]. Conversely, the maximisation of the BTL yield, i.e. of the content of CO and H₂ in the product gas, results in 10-15% lower total transformation efficiency (when other useful products from gasification are also counted) compared to other gasifying concepts – Figure 24. Hence, there is a trade-off between syngas (and respectively – BTL) conversion efficiency and total energy conversion efficiency. On the other hand, Figure 24 indicates that BTL synthesis is more energy efficient than power generation from biomass, which means that on equal terms BTL is a better option to exploit the limited biomass potential than bioelectricity. However, this statement concerns the generation efficiency only but not the final energy efficiency along fuel pathways (Figure 8), which depends on the energy transformation efficiency of different appliances (electrical or such employing BTL fuels)²⁴.

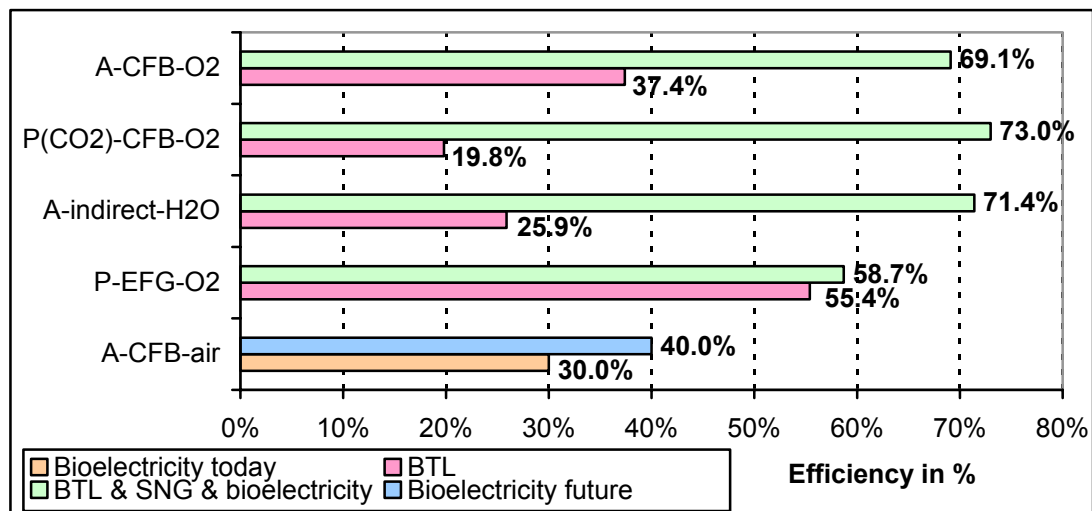
Owing again to the extreme process conditions, entrained flow gasifiers are fuel flexible, able to convert a wide range of feedstocks – biomass, coal, oil residues, waste [18]. This implies also that simultaneous processing of various feedstocks (e.g. coal and biomass or waste) in entrained flow gasifiers is possible, which enhances the feedstock supply base.

²³ Liquid substance, obtained as a residual product from pulp and paper production. A more detailed discussion on black liquor gasification is proposed in paragraph 5.2.

²⁴ A more complete discussion on energy efficiencies along fuel chains is proposed in chapter 7.

Figure 24

Average efficiency of BTL production, optimised versus maximising the yield of liquid hydrocarbons with carbon chain >C5, of combined BTL & substitute natural gas (SNG) & electricity production and of power generation from biomass for various gasification concepts, (%)



Legend:

A-CFB-O₂: atmospheric oxygen-blown direct circulating fluidised bed gasifier

P(CO₂)-CFB-O₂: pressurised with carbon dioxide oxygen-blown direct circulating fluidised bed gasifier

A-indirect-H₂O: atmospheric steam-blown indirect gasifier

P-EFG-O₂: pressurised oxygen-blown direct entrained flow gasifier

A-CFB-air: atmospheric air-blown direct circulating fluidised bed gasifier

Source: Adapted from [16]

Many feedstocks have high content of ash, which under high temperature turns into molten slag²⁵. Molten slag also retains some undesirable compounds of biomass, e.g. heavy metals [130]. The removal of molten slag from the bottom of the reactor has to be incorporated into its design – a slagging type entrained flow gasifier (Figure 23, left hand side). In order to improve slag properties, the addition of fluxing material (silica sand or limestone) is necessary. In contrast, in non-slugging entrained flow gasifiers the removal of molten slag is not foreseen. Hence, non-slugging gasifiers are fuel inflexible, suitable only for clean feedstocks with low mineral & ash content (less than 1%), e.g. oils [18, 239].

Summing up, the energy efficient (with a carbon conversion rate more than 99% [18, 45]) and cost effective production of synthesis gas for further BTL processing is characterised by:

- ✓ Slagging entrained flow gasifier;
- ✓ Oxygen as oxidising agent;
- ✓ High temperatures (1200-1500°C);
- ✓ Elevated pressure (10-50 bar);
- ✓ Short residence time of feedstock (a few seconds);
- ✓ Small size of feedstock particles (typically below 100 μm, in some cases – below 1mm);

²⁵ Molten ash becomes solid closer to the walls of the reactor (owing to the water cooling – Figure 23, left hand side), which solid layer preserves them from over-heating [18].

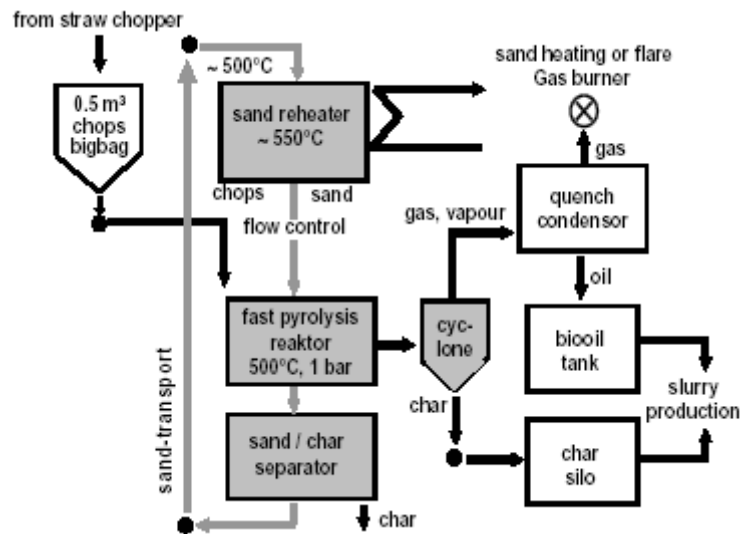
These base conditions however present many challenges. Getting so fine particle size for biomass is particularly challenging from an energy and cost efficiency point of view. Wood milling is very energy intensive, consuming a lot more energy than other materials milling e.g. approximately 5 times more than coal milling [18, 120, 238]. Chopping herbaceous biomass to such small particle size is even more difficult, if possible at all. The energy efficiency of gasification is further reduced by the removal of large quantities of inert gas (usually CO₂) from the product gas. Inert gas is employed as a medium for lock hopper pressurisation and pneumatic feeding of pulverised material (a mandatory feeding option for finely pulverised fuels) into the reactor. The amount of inert gas depends on the bulk density of fuels – the lower the density, the larger the amount. The low bulk density of biomass (Figure 12) implies large consumption of CO₂ [18, 120, 239]. Thus, alternative forms of biomass feedstock (via pre-treatment) have to be considered for entrained flow gasifiers. The most feasible biomass pre-treatment options are torrefaction, pyrolysis and pre-gasification.

Torrefaction represents thermal treatment of biomass (mainly wood) in the absence of oxygen for 15-60 min at 200-300°C and at atmospheric pressure [12, 239]. As a result, biomass is converted into a coke-like product. Torrefaction transformation is highly efficient – 85-95% conversion rate [12, 239]. The energy spent on torrefaction is fully paid off by the 8-10 times lower energy consumption of torrefied wood milling compared to fresh wood milling. As the properties of torrefied wood and coal are similar, the conventional coal-feeding facilities can be used for torrefied wood. This synergy can earn economies of scale and significant cost reductions, owing to potential co-gasification of torrefied wood and coal or waste [12, 18, 238, 239].

In pyrolysis (Figure 25), solid biomass (mainly herbaceous) is transformed into liquid state semi-finished material – “pyrolysis slurry”, that is later on fed into the gasifier [18]. Unlike gasification, pyrolysis represents thermal degradation of feedstock in the absence of an externally supplied oxidising agent. As a result, pyrolysis yields mainly liquids (up to 80% on mass basis via gas condensing) and some tars and chars, while gasification output consists predominantly of gaseous products [43, 120, 131]. For syngas (and later BTL) production, the so-called “flash pyrolysis” is typically employed. Similar to entrained flow gasification, in flash pyrolysis the residence time of fuel is very short – a few seconds. Unlike entrained flow gasification however, the optimum process temperature is much lower – about 500°C [120] and the operating pressure is nearly atmospheric – around 1 bar (Figure 25). The chopped biomass (particles of less than 5 mm [28]) is not heated directly, but with a hot sand medium (similar to fluidised bed gasification) in proportion 1:20 respectively. The process takes place in a twin-screw pyrolysis reactor, which is a mature technology [120] – Figure 26. The pyrolysis gases are cooled down as quickly as possible (in a few seconds) to temperatures below 100°C and a liquid condensate (pyrolysis oil) is obtained – Figure 26 [120, 161].

Figure 25

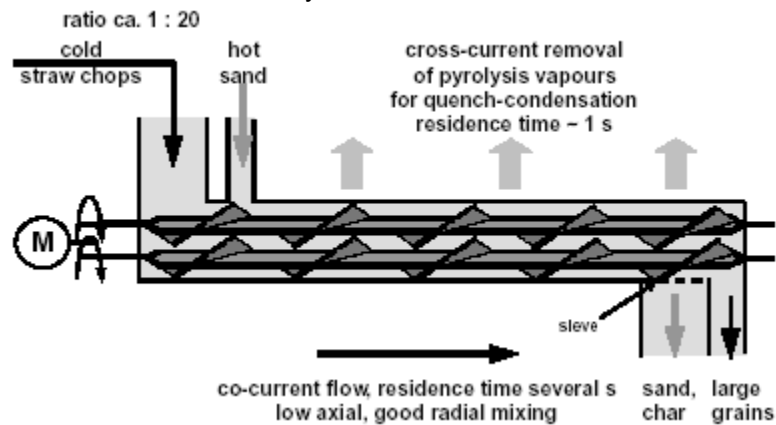
Simplified flow chart of biomass (straw chops) pyrolysis with hot sand medium /Note: The grey boxes and arrows indicate the 500°C hot sand loop/



Source: [45]

Figure 26

Pyrolysis reactor with twin-screw conveyor



Source: [120]

The char from pyrolysis is separated from the sand in a cyclone and then milled. The char powder is mixed with the pyrolysis oil, forming pyrolysis-char slurry, which increases the overall carbon conversion efficiency. The sand separation from chars does not have to be 100% effective, since some material of similar type should anyhow be added to the entrained flow gasifier to improve molten slag properties [120]. All in all, the energy conversion efficiency of slurry production is high – 85-90% [45, 120, 238]. The 10-15% energy transformation losses are fully paid off by the significant cutback in handling, transportation and storage costs, owing to the much higher energy density of pyrolysis slurry compared to woody and in especially – herbaceous feedstock (Figure 27 and Figure 12). Pyrolysis is particularly suitable for herbaceous biomass also because its alternative pre-treatment – fine shredding – is much more difficult and costly compared to that of wood [18, 120, 161, 238].

The pyrolysis slurry feeding into the gasifier with sufficient extent of atomisation to ensure full and complete gasification is, however, still a major technical challenge [18].

Figure 27
Main properties of pyrolysis oil from ligno-cellulosic material²⁶

Parameters	Value
Low calorific value	13-20 MJ/kg
Density	1200-1300 kg/m ³
Moisture content	15-30
PH	2-3
Flash point	60-100°C
Outer appearance	Dark brown liquid with smoky odour
Health hazards	Irritates eyes and skin, harmful by inhalation

Source: Adapted from [43, 45, 120, 161]

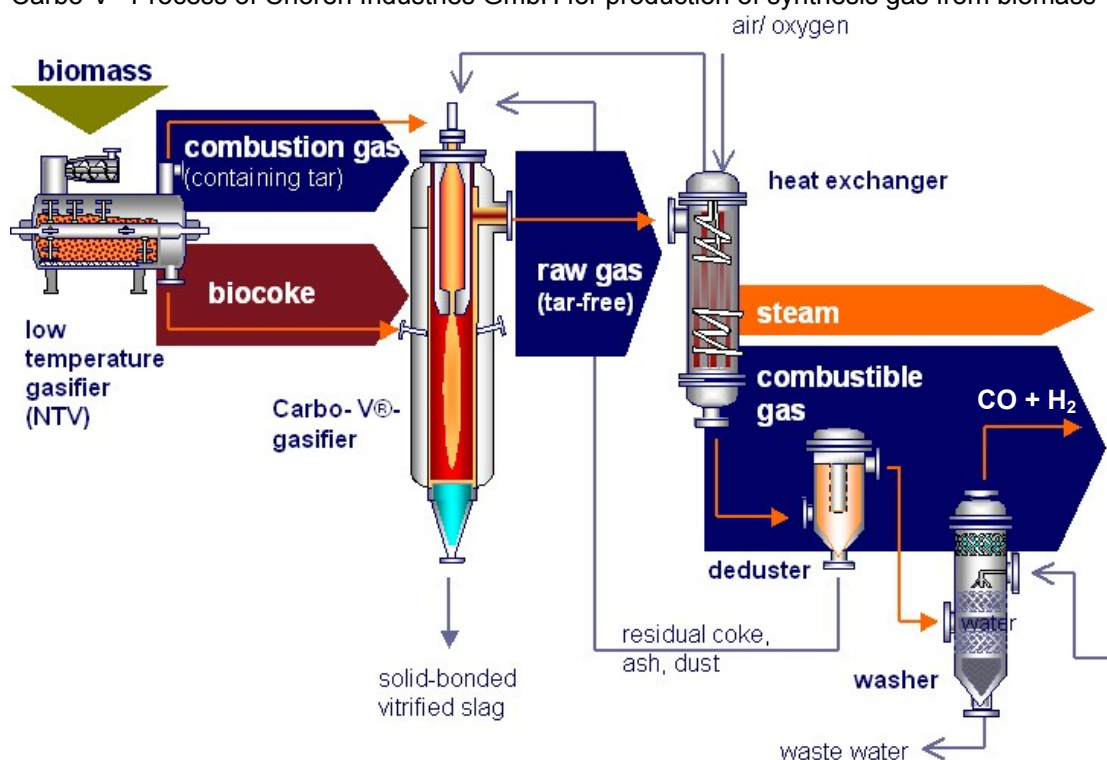
Nevertheless, on a large scale pyrolysis slurry could present some problems, which deserve additional examination. Pyrolysis oil is a strong acid (Figure 27), which means it is a powerful corrosive substance. Its handling, storage and transportation therefore require sophisticated and expensive materials, i.e. stainless steel tanks. In addition, there are some concerns about the potential carcinogenic impact of pyrolysis slurry. The relatively low flash point of pyrolysis oil also imposes additional safety requirements for handling, storage and transportation.

The preliminary gasification of biomass in (preferably) pressurised circulating fluidised bed reactor (Figure 22, right hand side) with secondary processing of the obtained product gas in a slagging entrained flow gasifier – Figure 23, left hand side [18], is another option. The strong points of this configuration are that no or only little pre-treatment of biomass is needed (particle size up to 5 cm is acceptable) and that a wide range of biomass feedstock can be processed. Similar to pyrolysis, the availability of some bed material in the product gas, which is fed into the entrained flow gasifier, is not a concern either, as it improves the properties of molten slag. Besides the already stated weak points of this gasifying concept, maintaining the stability of the feed flow, which is a “must” for the safe operation of entrained flow gasifiers, could be a problem, because circulating fluidised bed gasifiers are characterised by some variations in the product gas flow [18]. In order to keep the amount of nitrogen in the product gas under control, the first step circulating fluidised bed gasification is performed with steam, not with air [239].

With regard to the above explanations, Figure 28 presents a complete system configuration for production of synthesis gas from biomass with preliminary pyrolysis for further processing into BTL fuels.

²⁶ Average values, which can vary depending on the exact feedstock, pyrolysis and condensation conditions [120]

Figure 28
Carbo-V® Process of Choren Industries GmbH for production of synthesis gas from biomass



Source: [254]

After being pyrolysed (in a low-temperature gasifier /NTV/), biomass pyrolysis gas and char (biocoke) are fed to an entrained flow gasifier (the Carbo-V® gasifier) and a tar-free gas with high content of CO and H₂ is obtained. The clean gas is cooled down to about 200°C in a heat exchanger, increasing thereby the overall energy efficiency of the process by producing high-quality steam for power and/or heat generation. Next, the gas is cleaned from dust particles (in a deduster) and from components, other than CO and H₂ (in a washer). At the end, clean synthesis gas, consisting of CO and H₂, is obtained. Sufficient gas cleaning represents a key point in syngas and BTL production [5, 18, 194]. The catalysts for the synthesis of BTL fuels and chemicals are easily poisoned even by small amounts of alkali metals, halides, sulphur compounds, CO₂, etc. which therefore have to be removed to ppm and even ppb levels (Annex 1, Figure 93). Technological solutions for removing the majority of these compounds exist and seem to be sufficiently reliable, but their cost is still quite high. The hot gas cleaning (above 500-600°C), which would be more energy efficient, is a particular technical and technological challenge [5, 18].

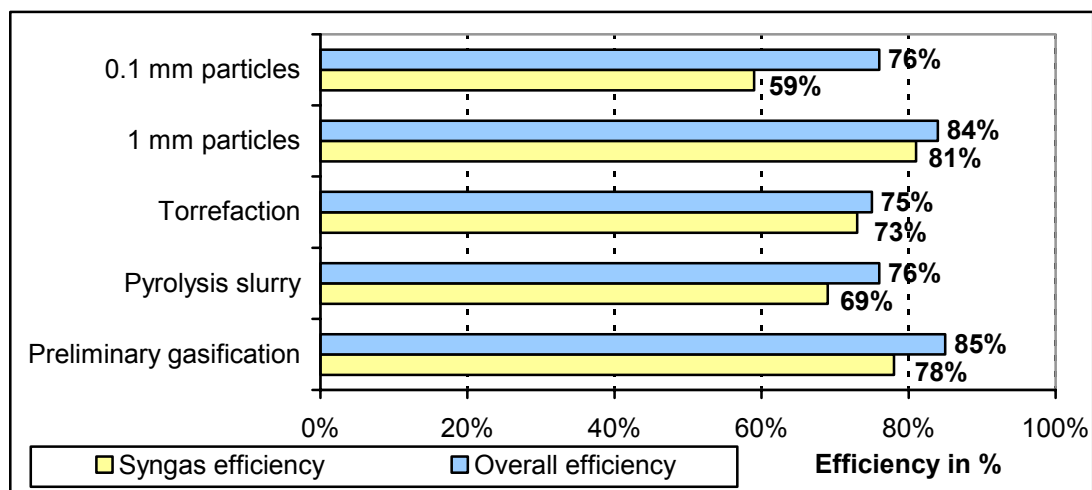
Besides torrefaction, pyrolysis and pre-gasification, there is a fourth option to convert biomass into a semi-finished material, which, under certain conditions, could be considered also as a pre-treatment alternative. This is the so-called Hydro-Thermal Upgrading (HTU) process. Here biomass is treated for 5-20 min in water at temperatures of 300-360°C and pressure of 100-180 bar. As a result, most of the oxygen is removed from the biomass feedstock, mainly as CO₂ and to a lesser extent – as water, and the energy density of the remaining product is

increased²⁷. The product obtained is a heavy organic liquid with 10-20% oxygen content on weight basis and 30-35 MJ/kg net calorific value. The claimed thermal efficiency of the conversion process is 75-80%. Since the properties of the HTU product resemble those of crude oil, it is called “biocrude”. In principle, biocrude could be fed into an entrained flow gasifier, similar to pyrolysis slurry. Nevertheless, it is more often considered for further upgrading via catalytic Hydro De-Oxygenation (HDO) to middle distillate products (kerosene, diesel) and refinery feedstock. The HDO process appears to be rather costly, partly because it requires large quantities of hydrogen [43]. The main advantage of the HTU process is its suitability for wet biomass [112, 113, 135, 140]. Nonetheless, considering that the entrained flow gasification releases as by-product a lot of waste heat, which anyhow has to find useful application, this advantage becomes less important. Since the HTU process does not represent a true pre-treatment technology, as well as because of the currently modest availability of data and information on the subject (partly due to the very early stage of development of the technology), it is not considered in this work anymore.

Summarising the above, Figure 29 presents the syngas production efficiency and total energy efficiencies of different feeding and pre-treatment options for the gasification concept with the highest yield of BTL products – entrained flow gasification (Figure 24).

Figure 29

Ascertained average syngas production efficiency and overall energy efficiency (syngas & electricity as by-product at optimistically assumed 40% generating efficiency) for various pre-treatment pathways for entrained flow gasifiers, (in %)



Source: Adapted from [18, 238, 239]

Figure 29 indicates that the highest syngas conversion efficiency and thus, highest BTL yield is earned when woody biomass with particle size of about 1 mm is directly fed to the gasifier, followed by the pre-gasification option. These two configurations give also the highest overall energy efficiencies. The energy efficiency of the 1 mm option is increased also by the less

²⁷ Amongst the main components of biomass (Figure 12), carbon and hydrogen increase energy content, while oxygen reduces it [130].

energy-consuming and cheaper feeding – compression by piston feeder and subsequent feed into the gasifier by a screw conveyor, instead of lock hopper pressurisation and pneumatic blowing that is mandatory for all pulverised products (in the case of Figure 29 – the 0.1 mm and the torrefaction options). The use of piston feeders also results in much lower amounts of inert gas brought into the gasifier, compared to lock hoppers and pneumatic feeding [18, 238, 239]. The main challenge of the 1 mm option is that it is proven only at a lab-scale so far [238, 239]. Hence, the suitability of screw feeders is not yet 100% confirmed, as well as whether the 1 mm particles would be sufficiently small for a complete gasification to occur [239]. The key drawbacks of the pre-gasification option have been already mentioned – more sophisticated, vulnerable and expensive system configuration. Torrefaction can be used as a back-up alternative of the 1 mm and the pre-gasification options for woody biomass, as it also results in relatively high syngas conversion efficiencies. Despite the pyrolysis slurry pathway gives relatively low syngas conversion efficiency, it deserves special attention, since this is indeed the most appropriate option for herbaceous biomass²⁸. It is particularly appropriate for residual herbaceous material (straw), whose low cost fully compensates the lower processing efficiency. The 0.1 mm alternative is the option with both the lowest syngas and total energy efficiencies, owing to the huge energy consumption during biomass milling and to a lesser extent to the pneumatic feeding. However, the energy efficiency of all pathways largely depends on the extent of useful utilisation of the by-product heat (e.g. for power generation), released along with the high temperature entrained flow gasification²⁹ [120].

In power and heat generation, the gas obtained from gasification is used as a fuel (product gas), while in BTL production the gas is used as a chemical feedstock (synthesis gas). The gasification concepts for power and heat generation are therefore not suitable for BTL production. The most appropriate gasification concept for BTL production is the oxygen-blown pressurised high temperature slagging entrained flow gasifier. It ensures a BTL yield that is higher than the electricity yield from biomass. This gasification concept is also able to process simultaneously various feedstocks, e.g. biomass and coal.

The highest syngas efficiency of the oxygen-blown pressurised high temperature slagging entrained flow gasifier is achieved when 1 mm wood particles are fed, followed by feeding product gas from conventional gasification and torrefied (pulverised coke-like) wood. For herbaceous feedstock, the intermediate transformation into pyrolysis slurry appears to be the optimum solution.

²⁸ Owing to the higher content of ashes and alkali substances in herbaceous biomass compared to woody biomass (Figure 12), the pre-gasification of herbaceous biomass in fixed bed or circulating fluidised bed gasifiers could cause serious problems with ash behaviour, namely – intensive slagging, agglomeration and corrosion, which could significantly impede and even suspend the functioning of the gasifier [148].

²⁹ Generated from the water-cooling shield of the entrained flow gasifier from Figure 23, left hand side.

4. BTL FUELS

Despite that the GTL technology has been known for decades³⁰, it started to be considered for large-scale manufacturing of fuels and chemicals (mainly from coal and natural gas) only recently. The application of syngas from biomass in GTL production [biomass-to-liquid (BTL)] is more recent.

The typical fuels, which can be obtained from GTL processing and which are suitable for use in road transport, are given in Figure 30, while their main properties, together with the properties of their oil-derived analogues, are presented in Figure 31.

Figure 30
Fuels obtained via GTL processing of syngas

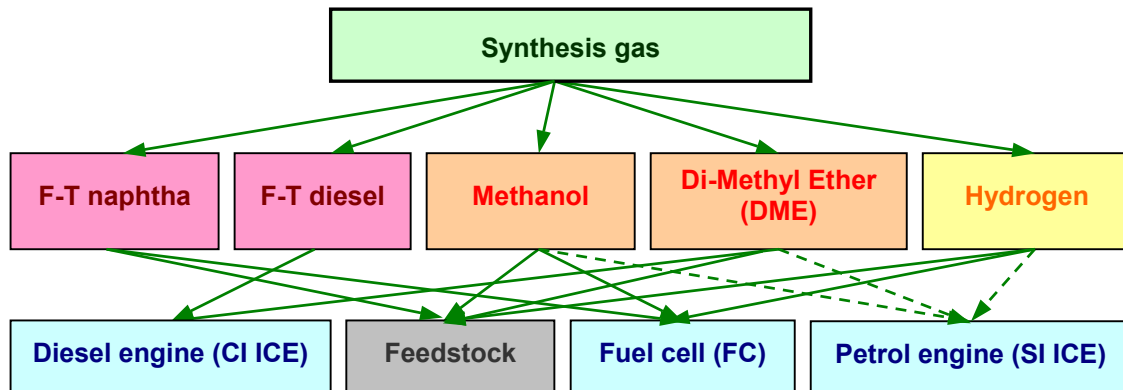


Figure 31
Main properties of oil-derived and BTL fuels

	Chemical formulae	Energy content, MJ/l ³¹	Density, kg/l ³²	Octane number	Cetane number	Chemical feedstock
Oil Petrol	C4-C12 ³³	31.2-32.2	0.72-0.77	90-95	-	No
Oil Diesel	C15-C20	35.3-36.0	0.82-0.84	-	45-53	No
Oil Naphtha	C5-C9	31.5	0.72	50	-	Yes
BTL Naphtha	C5-C9	31.5	0.72	40	-	Yes
BTL Diesel	C12-C20	33.1-34.3	0.77-0.78	-	70-80	No
Methanol	CH ₃ OH	15.4-15.6	0.79	110-112	5	Yes
Di-Methyl-Ether	CH ₃ OCH ₃	18.2-19.3	0.66-0.67	-	55-60	Yes
Hydrogen	H ₂	8.9	0.074	106	-	Yes

Source: Adapted from [1, 6, 16, 27, 32, 33, 49, 55, 57, 111, 118, 119, 126, 141, 156, 162, 170, 171, 176, 183, 187, 191, 223, 225, 233, 242, 269, 287, 288, 291, 300]

³⁰ The production of fuels via GTL processing was discovered in 1923 and patented in 1925 by the German scientists Franz Fischer and Hans Tropsch. Hence, the GTL processing is called sometimes also Fischer-Tropsch (F-T) synthesis [183, 191, 229, 290].

³¹ Net (low) calorific value

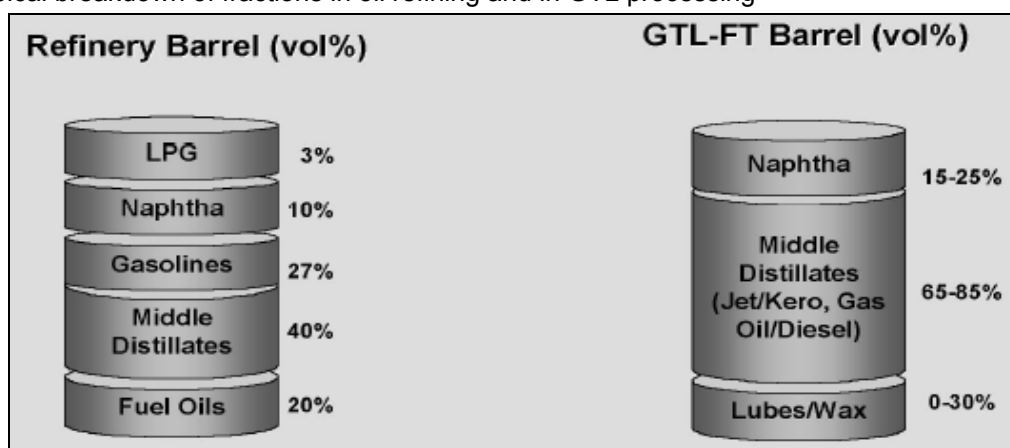
³² At 20°C, except for hydrogen, which becomes liquid at cryogenic temperature (-253°C)

³³ Length of carbon chain

4.1. PRODUCTS FROM F-T SYNTHESIS

As Figure 32 indicates, GTL processing is similar to oil refining, since a number of products is obtained. Thus, GTL synthesis can be regarded as an alternative refinery, run on feedstocks other than oil – natural gas, coal or biomass. The total energy efficiency of GTL processing is lower than that of oil refining (80% versus 85-90%), but the 20% GTL thermal losses can be partly recovered via heat integration in the process units [183].

Figure 32
Typical breakdown of fractions in oil refining and in GTL processing³⁴



Source: [103]

GTL processing has an important technological difference with oil refining. The optimum³⁵ oil refining output by fractions is spread amongst a number of products, is relatively constant and can vary within relatively narrow margins. Conversely, the optimum breakdown of fractions in GTL synthesis is more flexible [182, 288] and can be optimised to a larger extent versus certain products, most often versus middle distillates – Figure 32³⁶. Another feature of GTL processing is that the heavier fractions consist of high quality lubricants and waxes (<C20 [16]), but not of heavy fuel oils like in oil refining. GTL lubricants and waxes can easily find a good market, including in the food industry [183], while the market for heavy fuel oils is generally less profitable, along with the environmental burdens they cause [182, 288]. An additional and important environmental advantage of GTL products is that, unlike oil derivatives, they are quickly biodegradable [183] – the degradation rate of GTL diesel reaches 60% within only 28 days in anaerobic conditions [187].

GTL products consist almost entirely of linear paraffins (C_nH_{2n+2}), with less than 5% aromatics on mass basis, compared to 10-30% aromatics for oil derivatives [41, 119, 150, 183, 187, 202, 242, 287]. Since paraffins have higher hydrogen-to-carbon ratio than aromatics, this implies

³⁴ A small amount of light hydrocarbons (C1-C4) is also obtained from GTL processing, which are either transformed into higher hydrocarbons (C5-C20) or burnt to generate heat and/or power for GTL plants or for external users [183].

³⁵ In terms of minimum energy losses, polluting emissions and production costs

³⁶ The breakdown of fractions in GTL processing depends on the applied catalysts, pressure and temperature. A summary of GTL processing is given in Annex 1.

lower density (Figure 31) and higher (4-5%) energy content on a weight basis for GTL fuels compared to oil-based fuels. Due to the lower density, the volumetric energy content of GTL products is however lower than that of oil derivatives [119, 187, 287]. In addition, linear paraffins are more easily and efficiently transformed into other products than aromatics and branch paraffins [182, 287]. Finally, all GTL products are virtually sulphur free (sulphur content below 1 ppm), since a large part of sulphur compounds is removed during the syngas production step. The remaining small traces of sulphur are further separated before the GTL synthesis, because the catalysts for GTL processing are extremely sensitive even to very low contaminations of sulphur – Annex 1 [119, 182, 187, 287].

4.1.1. BTL (GTL, F-T) naphtha

Naphtha is a light fraction from oil refining and GTL processing (Figure 32) with similar to petrol properties. Nevertheless, naphtha is not appropriate for use in petrol engines (SI ICE) because of its low octane number – Figure 31. Due to the lack of any large direct application as a motor fuel, at present naphtha is used mainly as a feedstock for further conversion (at the expense of additional energy losses, emissions and costs) to petrol, ethylene, etc. [48, 183]. As such, it is even preferred in comparison with oil-derived naphtha, owing to its larger content of linear paraffins and lower content of sulphur [162, 182, 188, 287, 288]. In the future naphtha could also become an attractive energy option for FC [182, 180, 288]. When hydrocarbons are used as hydrogen carriers for FC, their relative hydrogen content (hydrogen-to-carbon ratio) is the governing “fuel” parameter, while the octane number and the energy content are not important. The higher the hydrogen-to-carbon ratio, the better the hydrogen carrier. The relative hydrogen content of naphtha is higher than those of oil-derived naphtha (due to the larger content of linear paraffins) and petrol (due to the slightly shorter carbon chain) – Figure 31. The lack of sulphur in BTL naphtha is an important advantage over oil-based fuels for FC applications, since the proton exchange membrane (PEM) FC³⁷ are very sensitive even to negligible sulphur contaminations. Such direct market realisation of BTL naphtha (without further processing to other products) would improve the efficiency of BTL processing in terms of energy use, emissions and costs.

4.1.2. BTL (GTL, F-T) diesel

Historically, F-T diesel was the first motor fuel obtained via GTL technologies³⁸. The feasible upper limit of the “natural” F-T diesel fraction in GTL processing is 75%. A larger F-T diesel yield can be achieved via transforming other GTL products, but always at the expense of additional energy losses, emissions and costs [6].

³⁷ The PEM FC is considered to be the most appropriate type of FC for mobile (transport) applications.

³⁸ The first F-T plants began operation in Germany in 1938. There were 9 plants with a total capacity of 660,000 tonnes of F-T products per year. These plants closed down after World War II [229].

GTL diesel has similar to oil-derived diesel physical and chemical properties. It is therefore fully compatible with current storage, handling and distribution infrastructure for oil-based diesel, thus its logistics would not involve additional capital costs [6]. For the same reasons the use of F-T diesel generally does not require modifications in diesel engines (CI ICE).

F-T diesel has poorer lubricity compared to conventional oil-derived diesel. This is due to the lack of polar molecules (including hydrocarbon-based and sulphur-based compounds), which are removed during the hydro-processing step of GTL [187, 287]. Hence, if a CI ICE is run on pure BTL diesel, the addition of some lubricant components is necessary [191]. Alternatively, if it is blended with conventional diesel up to 20-30%, no fuel additives or engine modifications are necessary [189]. Because of the lower volumetric energy content (Figure 31), on equal terms running a diesel engine on GTL diesel will result in a small fuel economy penalty – 3-8% [24, 119, 191, 228]. This fuel economy penalty can be compensated to a certain extent by injection timing changes [191]. Standards for F-T diesel quality are still missing and thus its fuel specifications vary largely by producers [219].

Nevertheless, GTL diesel demonstrates several clear performance advantages over conventional diesel. The cetane number is higher (Figure 31), because linear paraffins in the diesel boiling range have much higher cetane numbers than branch paraffins [187, 287]. Besides the better engine performance (smoother operation, improved start-up, less noise [180]), the higher cetane number of F-T diesel allows its blending with lower quality conventional diesel, which otherwise cannot be utilised as an automotive fuel [6, 182, 300]. In such a way secondary benefits are incurred at the refineries, since by such blending the extent of utilisation of the diesel refining fraction is enhanced. On the other hand, linear paraffins, which prevail in GTL diesel, have poorer cold flow properties than branch paraffins, which are more widely presented in oil-based diesel [187, 287]. The lack of sulphur in F-T diesel also cuts the SO₂ emissions from combustion. Apart from the reduced sulphur content, the lower density of F-T diesel also implies lower particulate matters (PM) emissions.

4.2. BIOMETHANOL

Methanol (CH₃OH), known also as “wood alcohol”³⁹, is a commodity chemical, one of the top ten chemicals produced globally [229]. It is liquid at ambient conditions, which facilitates transportation and handling. The main application of methanol is as feedstock for producing formaldehyde (H₂CO) – 65% of world methanol production – whose demand is driven by the construction industry⁴⁰ [229].

³⁹ Methanol synthesis actually began in the 1800s with isolation of “wood” alcohol from wood pyrolysis [229].

⁴⁰ Formaldehyde is used to make resins with phenol, urea, or melamine for the manufacture of various construction board products [229].

With regard to the automotive application, because of its high octane and low cetane number (Figure 31), methanol is better suited for SI ICE than for CI ICE. Besides the higher octane number, methanol has another advantage over petrol – the content of oxygen that improves combustion and thus, reduces local-polluting emissions. However, methanol contains only half of the energy of petrol, i.e. on equal terms a methanol tank would have to be twice as large as a petrol tank to give the same driving range.

Owing to its advantages, at the end of '80s / beginning of '90s methanol was widely used in the USA as an automotive fuel (mixed with petrol in low or high – up to 85%, concentrations) or converted into a petrol additive (methyl-tertio-butyl-ether, MTBE)⁴¹. However, at present the automotive application of methanol in ICE is completely abandoned [49, 202], while the use of MTBE is negligible and continuously declining. The reason is that methanol poses a number of serious health and safety concerns. The ingestion of only 25-100 ml methanol can cause blindness and even death. Methanol can be in-taken not only orally, but also via accidental spillage on the skin. The health hazard for unintended ingestion of methanol is further increased by its complete solubility in water. The risk for accidental spillage and contamination of ground water is strengthened by the powerful corrosiveness of methanol. For this reason the use of methanol requires application of only high-cost stainless steel storage components [127]. Methanol also burns with almost invisible flame, which makes difficult to detect fires in their initial stages [296]. As a consequence, methanol has shown 25 times higher fatalities than petrol [34]. Low blends (up to 5%) of methanol with petrol would reduce to a large extent (but not avoid completely!) these safety and health concerns. Nonetheless, low methanol blends appear to be difficult and costly for market implementation, due to the need to overcome consumers' resistance and the bad experience from the past.

Although methanol is not regarded as a feasible automotive fuel for ICE anymore, it is presently employed as ingredient in the production of biodiesel from oilseeds. On average, 1.1 weight units of methanol are mixed with 10 weight units of vegetable oil to obtain 10 units of biodiesel⁴².

It is considered (especially in Europe) that methanol could be a suitable hydrogen carrier for on-board reforming for FC in the future. Since FC vehicles are supposed to require a higher quality of servicing than the vehicles equipped with ICE, the FC application of methanol could reduce the health and safety risks. Conversely, methanol demonstrates some important advantages over other hydrocarbons – potential hydrogen carriers. It has one of the highest hydrogen-to-carbon ratios (4:1) amongst all hydrocarbons⁴³. Another key advantage of methanol is its low reforming temperature. Obtaining hydrogen from methanol requires 200-

⁴¹ MTBE is a mixture of methanol and isobutylene (product of oil refining), where the share of methanol is 36% [100].

⁴² Glycerol and fatty acids are also obtained as by-products from biodiesel production [51].

⁴³ For comparison, the hydrogen-to-carbon ratio of ethanol is 3, of naphtha – 2.22 to 2.4, of petrol – 2.16 to 2.5.

300°C, compared to 500°C for ethanol, 850°C for natural gas and 850-1000°C for petrol⁴⁴ [81, 123, 213]. The low processing temperature simplifies the layout of the reformer and reduces its cost. The infrastructure for conventional automotive fuels can be also relatively easily retrofitted (at a reasonable cost) to handle methanol. In addition, the application of methanol as a hydrogen carrier for FC could be facilitated by the mature status of methanol production from fossil feedstock⁴⁵. Methanol manufacturing from synthesis gas (Annex 1, Equation 3) is a well-established technology that already earned large economies of scale. In 2002 there were about 38 million tonnes of methanol production capacities worldwide, operated at 80% utilisation rate [276]. The near-term expansion of methanol capacities is projected to bring the world production potential up to 39-41 million tonnes per year [81, 82, 277]. This large-scale production is a key factor for methanol to be one of the few alternative fuels, which are cost-competitive to conventional fuels. Despite that currently biomass is not used in industrial methanol manufacturing, the availability of such refined production technologies and distribution infrastructure, along with the growing security of energy supply concerns, could facilitate the penetration of biomass as a feedstock for methanol synthesis.

Besides the on-board reforming to hydrogen, methanol could also be employed directly in FC, in the so-called direct methanol fuel cells (DMFC). In DMFC, methanol is injected straight to the cell's anode and reacts to form electricity and CO₂. Nevertheless, the direct application of methanol in FC is regarded mainly as a long-term option. DMFC are at a very early stage of development and have a much lower efficiency than PEM FC that use hydrogen – 15% versus 40% respectively [48, 49, 123, 151, 170, 231].

4.3. BIO-DI-METHYL-ETHER (BIO-DME)

DME (CH₃OCH₃) is a synthetic fuel, which does not occur naturally in petroleum. It represents a novel fuel (first tests started in the middle of the 90's) that is still at an experimental stage [168]. Originally DME has been manufactured via methanol de-hydration (Annex 1, Equation 4), but more recently the direct DME production from syngas has been examined (Annex 1, Equation 5). The direct production route appears to be more energy and cost efficient, since it involves one process instead of two processes – methanol synthesis (Annex 1, Equation 3) and methanol de-hydration. At present, the annual world output of DME is only 100,000-150,000 tonnes [82, 141, 162]. Currently the largest application of DME is in aerosol spray cans, but not as a fuel [141], therefore the availability of data about fuel DME is scarce.

Similar to LPG, DME is gaseous at ambient conditions, but liquefies at moderate pressure (5-8 bar) [1, 141], hence DME could be mixed with LPG. It is suggested that low-concentration DME blends with LPG (up to 10-20%) require none or only minor system modifications [104,

⁴⁴ Petrol is considered mainly in the USA. However, petrol for FC application must meet stricter quality requirements than those for conventional petrol that is employed in SI ICE [34, 158, 202].

⁴⁵ Nowadays natural gas accounts for approximately 90% of world methanol production [229].

105]. DME can also exploit the already existing LPG infrastructure (where available), which could become a prime factor for its market penetration. By analogy with LPG, DME might potentially be used for non-transport purposes as well, e.g. as a household fuel, moreover that DME handling is somewhat safer than that of LPG [141]. For safety reasons, the addition of an odour component to DME is however necessary, since naturally DME is odourless like LPG [1].

DME has a higher cetane number than oil-based diesel (Figure 31), which makes it more suitable for application in CI ICE rather than in SI ICE. Owing to its oxygen content that improves combustion and to the lack of carbon-to-carbon bonds, DME burns cleaner and quieter in CI ICE than oil-derived diesel [1, 141, 170, 269]. Conversely, DME contains only about half of the energy of oil-based diesel (Figure 31), which increases fuel consumption and requires more than a twice larger fuel storage tank aboard the vehicle. The additional storage volume is due to the mandatory 80-85% filling rate, as a safety margin in case of high ambient temperatures, similar to LPG [1, 141]. The use of DME in CI ICE also requires some engine modifications – replacement of all plastics and rubbers with metal-to-metal seals from non-sparking metals, more sophisticated injection system, etc. In particular, the dedicated injection system appears to be a key technical challenge for the automotive use of DME [141, 170]. Since the DME injection system completely differs from that for diesel, simultaneously running a CI ICE on DME and diesel (dual-fuel performance⁴⁶) is not possible [10]. DME has also poor lubricity and viscosity, hence lubricating additives are needed at 500-2000 ppm level [1, 10, 27, 114, 118, 141]. All these technical and technological drawbacks, combined with the prevailing high production cost, make DME more a medium- to long-term alternative, rather than a fuel of tomorrow [123, 128].

Owing to its high hydrogen-to-carbon ratio (3:1), DME could be in theory considered also as a hydrogen carrier for on-board reforming for FC. Nevertheless, due to the complications with the on-board storage of gaseous fuels and considering the availability of other, more suitable liquid hydrogen carriers (e.g. methanol and GTL naphtha), the option of using DME as a hydrogen carrier for FC does not appear promising.

4.4. BIOHYDROGEN

Hydrogen (H₂) is not available independently in the atmosphere, but is always combined with other elements. Hence, before being used, it has to be extracted from various compounds, e.g. via the syngas route. Currently, hydrogen is produced mainly from natural gas and to a lesser extent from oil derivatives (totally 77% of all hydrogen production), while its production from biomass is at an experimental stage [229]. This is due partly to the more sophisticated manufacturing of syngas from biomass compared to natural gas, but also to the much lower

⁴⁶ There are two ways of employing two different fuels in the same engine – bi-fuel, when the engine runs on either fuel, or dual-fuel, when the engine runs simultaneously on both fuels (fuel mixture).

relative hydrogen content of biomass vice-versa natural gas – Figure 12 [232]. About 60% of world hydrogen production is used in ammonia production, followed by 23% in oil refining and 9% in methanol synthesis. In such a way, only 8% of global hydrogen production is left as merchant hydrogen that potentially can be used as an automotive fuel [229].

In principle, it is more correct to consider hydrogen as an energy carrier but not as a fuel. Unlike all other automotive fuels, hydrogen is carbon-free that makes it the fuel with the cleanest combustion in ICE⁴⁷, as well as the most appropriate fuel option for FC. Another advantage of hydrogen is the higher octane number, compared to petrol (Figure 31), which favours its use in SI ICE. Nevertheless, hydrogen is regarded as a more viable energy option for FC, due to the much higher efficiency of FC compared to ICE⁴⁸. Despite these advantages, at present the application of hydrogen as an automotive fuel faces some techno-economic constraints – low volumetric energy density, complicated storage and handling, higher cost per kW of FC compared to ICE, etc. Due to these constraints, the application of hydrogen in SI ICE (either pure or blended with petrol) and/or in FC is currently at an experimental stage [6, 81, 82, 123, 170, 231]. However, a significant amount of work to improve the performance of hydrogen technologies is undergoing. The issues with hydrogen and FC are examined thoroughly in a number of other studies of the JRC Institute of Energy and in particular within the operation of the European Hydrogen and Fuel Cells Technology Platform, www.hfpeurope.org.

4.5. SUMMARY

Based on the above analysis, Figure 33 presents the relative suitability of various BTL fuels for application in SI ICE, CI ICE, FC and as a chemical feedstock.

Figure 33
Suitability of different BTL fuels for use in SI ICE, CI ICE, FC or as a feedstock for further processing

	SI ICE	CI ICE	FC	Feedstock
F-T Naphtha	--	--	+	++
F-T diesel	--	++	-	-
Methanol	-	--	+	++
DME	--	+	-	+
Hydrogen	-	--	++	++

Legend: (++) Very appropriate; (+) Appropriate; (-) Not appropriate; (--) Impossible

⁴⁷ A more complete discussion on the environmental performance of fuels is proposed in chapter 8.

⁴⁸ The engine efficiency of petrol SI ICE is about 21-22%, of diesel CI ICE – about 25%, while of hydrogen FC it ranges within 40-60% [111]

Similar to oil refining, GTL synthesis results in a range of products. Unlike oil refining, the GTL yield can be feasibly optimised to a larger extent for a certain fraction.

BTL naphtha is an excellent chemical feedstock for further processing and could be regarded also as a hydrogen carrier for FC in the medium to long-term.

F-T diesel is the only BTL fuel that is ready for a large-scale application in CI ICE even today.

Methanol is not regarded as a convenient fuel for SI ICE any longer, but it is still a potential hydrogen carrier for FC, provided its handling is made safer.

DME could become a prospective fuel for CI ICE or SI ICE in the medium to long-term. A key advantage of DME is that it is compatible with LPG and its infrastructure.

Hydrogen appears as a longer-term energy alternative for FC, rather than for ICE.

5. MAJOR BTL DEMONSTRATION PROJECTS IN THE EU

At present there are no commercially operated BTL plants either in Europe, or elsewhere in the world. Current BTL activities are at research, development and demonstration stage. Most of these activities are part of the European project RENEW [285], supported by the European Commission. The criteria used for selecting BTL projects for presentation here below were: extent of advancement, applied orientation of the research work, assumed market potential in the foreseeable future and availability of reliable information.

5.1. CHOREN INDUSTRIES GMBH, GERMANY

The BTL demonstration activities of Choren GmbH began in 1998 with the construction of a 1 MW pilot plant (alpha-plant) in Freiberg, Germany – Figure 34.

Figure 34

The 1 MW demonstration BTL plant (alpha-plant) of Choren Industries GmbH in Freiberg, Germany – external view (left hand side) and diagram of the syngas unit (right hand side)



Source: Adapted from [254]

A high-temperature oxygen-blown slagging entrained flow gasification, developed by Choren in 1994 and patented in 1995 as the Carbo-V® Process (Figure 28) is used [254]. The claimed thermal efficiency of the Carbo-V® process is 95-98%, while the gasification efficiency is stated as 82% for capacities larger than 10 MW [245]. The experiments started with pre-gasification of clean wood (Figure 28), waste and coal. More recently the use of pyrolysis slurry from herbaceous biomass has been investigated [45, 120]. The BTL automotive fuels option was added to the plant in 2002. With the support of the German Ministry of Economics and with the cooperation of DaimlerChrysler A.G. and Volkswagen A.G., the first quantities of

BTL fuels from wood chips were produced in 2003-2004. Under the methanol programme, totally 11,000 litres were produced in April and May 2003, while the first quantities of F-T liquids were produced in June 2003 [178]. In October 2003 Choren began the construction of its first industrial plant for manufacturing 15,000 tonnes of BTL fuels per year (the beta-plant), which is due for completion in 2005. The project preparation for a third, much larger plant with annual capacity of 200,000 tonnes of BTL fuels has been outlined. The plans of the company include installation of 1 million tonnes of annual BTL capacity in Germany by 2010, whose total cost is estimated to be about EUR 2 billion. Besides the co-operation of large corporations such as DaimlerChrysler A.G. and Volkswagen A.G., the BTL activities of Choren are strongly driven by the exemption from fuel tax of all renewable automotive fuels in Germany, which will be valid until 2009 so far [41, 254].

5.2. CHEMREC A.B., SWEDEN

The gasification technology, elaborated by Chemrec (Figure 23, right hand side), is designed to run on a specific feedstock – black liquor (Figure 35), which is a residual product from the production of chemical pulp and paper⁴⁹. The system was originally conceived for power generation, employing air-blown entrained flow gasification – Figure 36, left hand side. Recently the option of producing BTL transport fuels (methanol, DME and hydrogen) has been also investigated [253] – Figure 36, right hand side. The system configuration for black liquor gasification for BTL fuels is presented in Figure 37. The comparison between the black liquor gasification approach of Chemrec (Figure 37) and the biomass gasification approach of Choren (Figure 28) indicates many similarities.

Figure 35
Composition of black liquor and of syngas, obtained from pressurised oxygen-blown entrained flow gasification of black liquor

Black liquor composition & properties		Syngas composition from black liquor gasification	
C, mass %	35.7	CO, mole %	38.08
H, mass %	3.7	H, mole %	39.70
N, mass %	>0.1	CO ₂ , mole %	19.05
O, mass %	35.8	H ₂ O, mole %	0.18
S, mass %	4.4	CH ₄ , mole %	1.34
Cl, mass %	0.3	N, mole %	0.24
K, mass %	1.1	H ₂ S, mole %	1.88
Na, mass %	19.0	COS ⁵⁰ , mole %	0.06
NCV, MJ/kg dry	12.29		

Source: Adapted from [170]

⁴⁹ Chemical pulp accounts for 2/3 of total pulp production (for high quality white paper), while the remaining 1/3 is mechanical pulp (for lower quality yellowish paper). The production of chemical pulp generates 1.7-1.8 tonnes of black liquor on dry content basis per tonne of pulp [170].

⁵⁰ Carbonyl sulphide

Figure 36

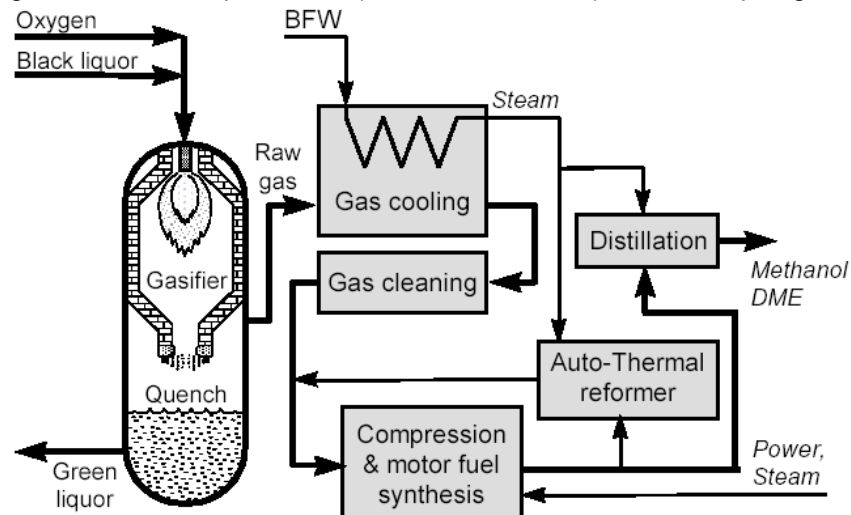
Chemrec's booster /in exploitation/ at the New Bern mill in North Carolina, USA (left hand side) and Chemrec's first demonstration plant "DP-1" for production of methanol, DME and hydrogen at the Kappa Kraftliner mill in Piteå, Sweden (right hand side)



Source: [253]

Figure 37

System diagram for BTL fuel production (methanol and DME) via black liquor gasification



Source: [170]

Chemrec A.B. patented the black liquor gasification concept (Figure 23, right hand side) in 1987 and since then various demonstrations have taken place. At present the booster system (based on air-blown entrained flow gasification at atmospheric pressure), which increases the black liquor recovery rate, is commercially available – Figure 36, left hand side. The black liquor gasification combined cycle (BLGCC) system, based on oxygen-blown entrained flow gasification at 15 bar, which increases the electricity output and aims at replacing the black liquor recovery boilers, is in a development phase, as well as the system for black liquor gasification for producing alternative motor fuels and hydrogen (BLGAMF/H₂), based on oxygen-blown entrained flow gasification at 30 bar. The first plant of such type for methanol, DME and hydrogen – “DP-1”, situated at the Kappa Kraftliner mill in Piteå, Sweden (Figure 36, right hand side), started in May 2005. The efficiency of biomass to methanol conversion of

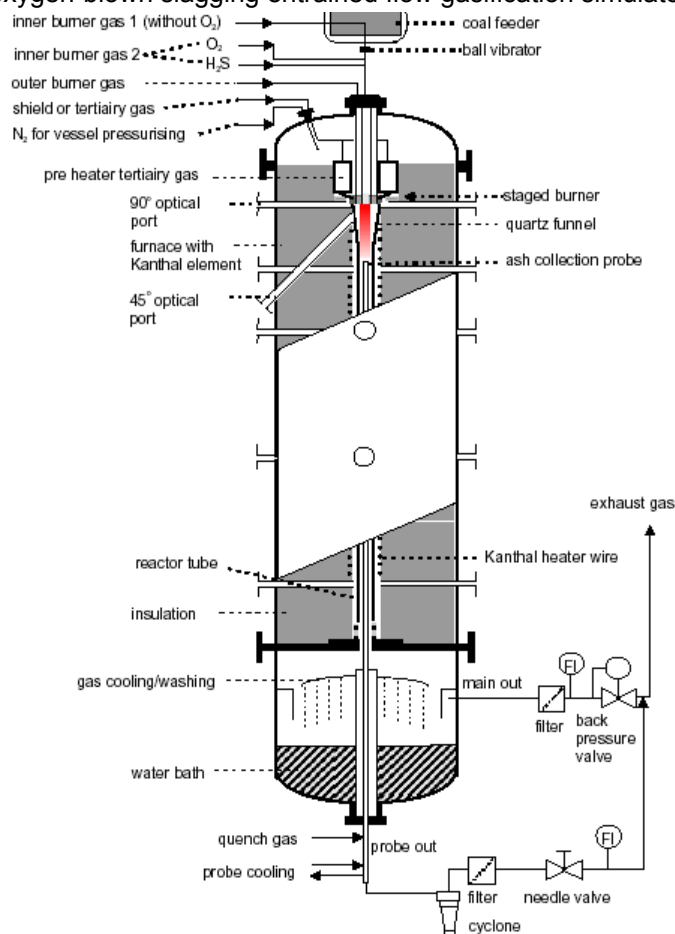
the plant is predicted to be 65-75% that is slightly higher than that of F-T synthesis (Figure 24) [6, 170, 253].

5.3. ECN & SHELL, THE NETHERLANDS

Since 2000 the Energy Research Centre of the Netherlands (ECN), in co-operation with Shell Global Solutions Int., has performed thorough research work on different biomass pathways to syngas for further processing into BTL fuels. Various gasification concepts and system configurations have been examined and evaluated. With respect to the production of bio-syngas, the pressurised oxygen-blown entrained-flow gasifier of slagging type (Figure 38) has been found to be the optimum system configuration. Although the experimental work has been performed at a lab-scale and for the moment there are no indications for development into a larger scale pilot plant, it deserves particular attention, since a detailed techno-economic analysis, including simulations of large-scale industrial applications, has been performed and has been made publicly available [16, 18, 19, 239]. The involvement of a major industrial stakeholder with experience in the development of GTL technologies as a partner in the project, puts additional value onto the research results.

Figure 38

The pressurised oxygen-blown slagging entrained flow gasification simulator of ECN



Source: [239]

5.4. VÄRNAMO IGCC PLANT, SWEDEN

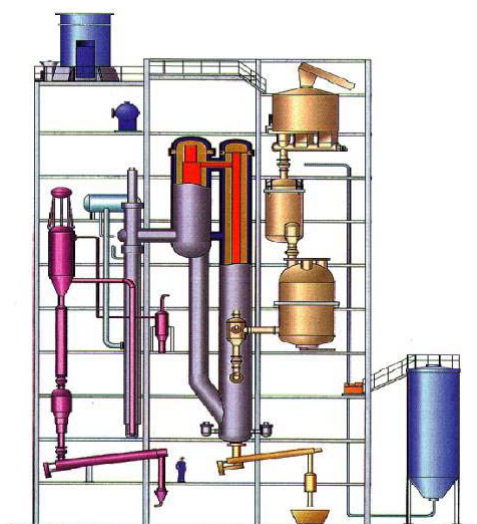
The Värnamo demonstration Integrated Gasification Combined Cycle (IGCC) plant (Figure 39, left hand side) was built by Sydkraft A.B. in 1991-1993 and was fully commissioned in 1995. It uses pressurised (at 22 bar) air-blown circulating fluidised bed gasification with 18 MW woody biomass fuel input (Figure 39, right hand side). The demonstration programme began in 1996 with power and heat generation, and was concluded in 2000. The next steps in the demonstration activities foresee conversion to oxygen-blown gasification (with tar cracker) for producing syngas and automotive fuels – initially DME and methanol, later hydrogen and F-T synthesis. Scaling-up the plant is also proposed. The start of the syngas production is envisaged for 2005, while the synthesis of F-T fuels is expected for 2007-2008 [1, 194, 243].

Figure 39

The IGCC plant at Värnamo, Sweden – outer appearance (left hand side) and diagram of the circulating fluidised bed gasification complex (right hand side)



Source: Adapted from [193]



Source: [243]

5.5. GÜSSING CHP PLANT, AUSTRIA

The CHP demonstration plant in Güssing / Austria (Figure 40), employing a steam-blown circulating fluidised bed gasifier and gas engine with 8 MW fuel input (mainly wood chips), was built in 2000-2001. The initial CHP programme was intended for evolution towards production of syngas from herbaceous-derived pyrolysis slurry for further processing into substitute natural gas, methanol and F-T liquids. The plant's design is relatively suitable for such a development, since steam gasification results in low contamination of tars and nitrogen in the product gas. However, some retrofitting is needed – additional gas cleaning facilities, tar cracker, F-T reactor. The plant's reconstruction had to be completed by the end of 2004 and first results were expected in spring 2005. However, some delays for various reasons were recently reported, so the pilot trials were postponed [2, 121, 186].

Figure 40
The CHP plant in Güssing, Austria



Source: [121]

At present the production of BTL fuels is at an experimental stage. Despite that BTL fuels are gaining an increasing interest, it would be extremely challenging to expect significant quantities of such fuels to reach the EU automotive market before 2010.

6. SECURITY AND DIVERSITY OF ENERGY SUPPLY

It is widely recognised that biomass contributes to the security and diversity of the EU energy supply. This is due to the difference between the reserves, production and supply patterns of biomass and those of fossil fuels. Bioenergy tends to be produced internally within the EU, while the majority of fossil fuels are imported (Figure 1) from a small number of countries (Figure 2). It can be assumed that part of biomass may be imported as final or half-finished products, but not as a feedstock, due to high transportation costs. Even in this case, there will be still a positive contribution to the security of supply, while the diversity of supply benefits may be, under certain conditions, slightly reduced. This is schematically depicted in Figure 41.

Figure 41
Probable impacts of bioenergy on the EU energy supply

EU energy supply	Product dependency	Product diversity
Dependency on suppliers	Oil	Bioenergy imports
Diversity of suppliers		Bioenergy business-as-usual

In more detail, the contribution of BTL products to the security and diversity of energy supply of the EU can be regarded within several specific contexts.

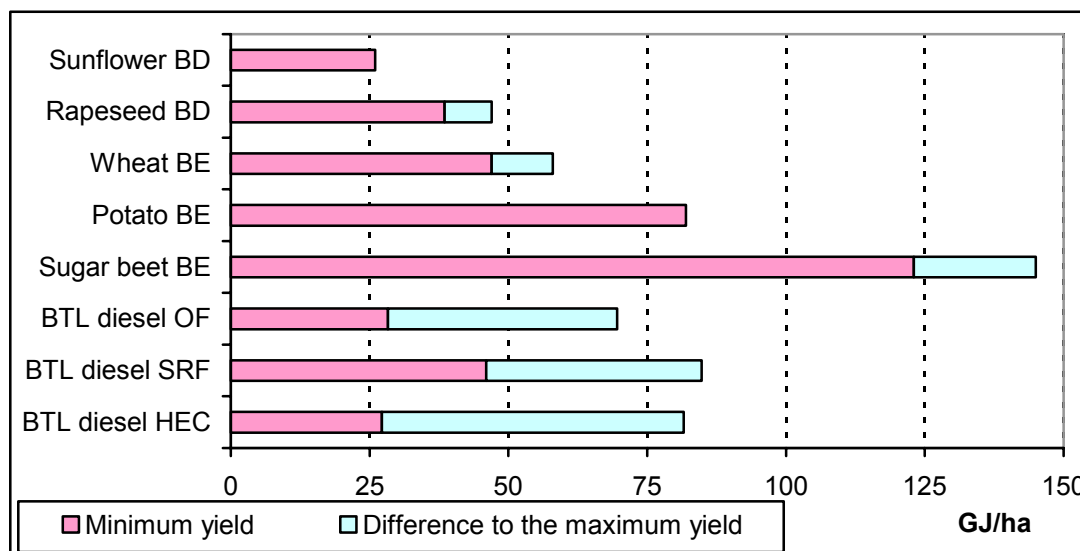
Compared to conventional biofuels, BTL fuels have a larger potential to replace traditional oil-based automotive fuels – petrol and diesel, owing to the following facts:

- ✓ At present the feasible land availability for woody and herbaceous biomass appears to be larger than that for agricultural feedstock. The cultivation of ligno-cellulosic material is less demanding in terms of soil quality, fertilisers, pesticides, etc., than the cultivation of agricultural feedstock. Hence, the competition on the land market between energy crops and food & feed agricultural crops is much softer. For these reasons, the cost of biomass raw material, which is a major if not the major component of the final biofuel cost, decreases. This implies a potentially lower final production cost of BTL fuels compared to that of conventional biofuels. Last, but not least, with the amendments in the Common Agricultural Policy of the EU, the support for energy crops has been restricted up to EUR 67.5 million per year (EUR 45 per hectare for a maximum guaranteed area of 1.5 million hectares⁵¹ [37]).
- ✓ The biofuel yield per hectare of BTL fuels is generally larger than that of conventional biofuels and especially of biodiesel, owing to a larger feedstock yield per hectare from woody and herbaceous biomass compared to that from agricultural crops [142, 154] – Figure 42. In this context, also as part of the reform of the Common Agriculture Policy, the cultivation of sugar beet – the agricultural crop with the largest biofuel yield per hectare

⁵¹ If a larger area is used for energy crops, the aid per hectare is reduced pro-rata. Furthermore, areas, which have been subject to an application for energy crops scheme, may not be counted as being set aside for the purposes of the set-aside requirement [37].

(Figure 42) – will not be supported under set-aside schemes [65]. Further steps, aiming at reducing the internal EU sugar beet production, are being proposed as well [70].

Figure 42
Feasible biofuel yield per hectare from various feedstocks and conversion routes



Legend:

BD – biodiesel

BE – bioethanol

OF – ordinary forestry

SRF – short-rotation forestry

HEC – herbaceous energy crops

Notes:

1) The wider difference between the minimum and the maximum yields for BTL diesel compared to conventional biofuel pathways is due to the higher uncertainties in BTL process efficiencies and feedstock yields per hectare.

2) The lack of variations in sunflower biodiesel and potato bioethanol comes from the fact that these pathways currently are not commercially available in the EU [142], thus the values indicate expected yields.

3) Assumed 60% BTL diesel yield from total BTL yield (Figure 32), without hydrocracking.

4) No straight production of methanol and DME from woody or herbaceous biomass has been thoroughly investigated so far, only the black liquor pathway has been evaluated. However, by analogue with the GTL synthesis from natural gas, it can be assumed that the methanol and DME energy yields per hectare should be higher than that of BTL diesel.

Source: Adapted, based on compilation of various data from [6, 14, 41, 145, 161, 169, 195, 247, Figure 12, Figure 24, Figure 31 and Figure 32]

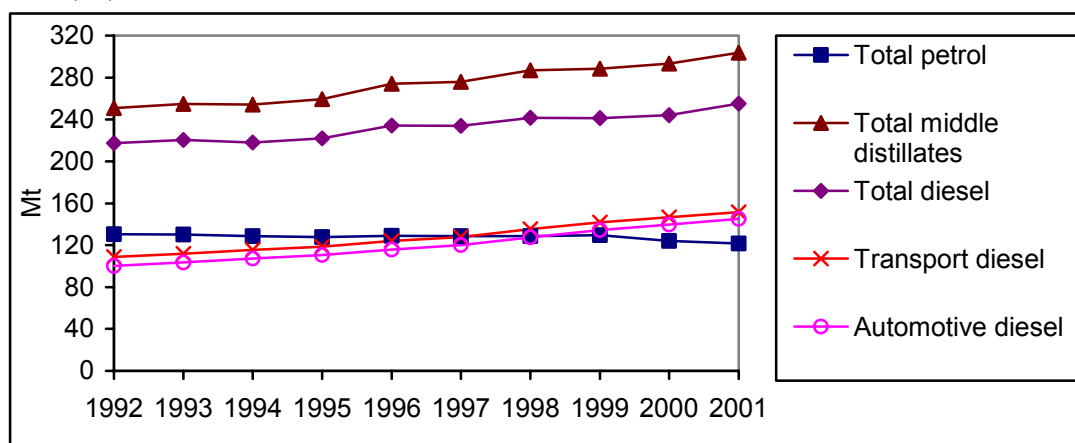
Referring to these reasons, the overall biofuel supply can be significantly increased and the difference between current and targeted growth rate in the biofuel production of the EU (Figure 7) could be reduced, if not totally eliminated.

Apart from the above advantages over conventional biofuels, GTL fuel production has another very important benefit compared to conventional oil refining, with particular relevance to the EU. As indicated in paragraph 4.1, the optimum oil refining output by fractions, obtained at minimum energy losses, polluting emissions and production costs, is spread amongst a number of products, is relatively constant and can vary within relatively narrow margins. The

refinery output can be optimised towards enlarging a certain fraction (e.g. diesel), but only to a little extent. Beyond this extent, any further expansion of this fraction, at the expense of another one (e.g. petrol), results in higher energy and GHG costs, and thus – monetary costs. In contrast, the optimum output by fractions from GTL synthesis is concentrated within the middle distillate fractions and it is more flexible – Figure 32.

Traditionally the EU consumes more middle distillates and especially diesel, rather than petrol – Figure 43. This is partly due to the fact that petrol has basically just one application – as an automotive fuel (more than 98%), while diesel has a number of applications. Transport and in particular road transport is a main, but not the only large middle distillates-consuming sector. Besides road transport, diesel fuel is used also in rail and sea transport, jet fuel (a mixture of kerosenes) is the prime fuel for air transport, while gasoil finds multiple applications as industrial fuel – Figure 43. For a number of factors, related mainly to road transport [147, 182], recently the demand for diesel and thus – for middle distillates in the EU has grown fast, at the expense of that for petrol – Figure 43.

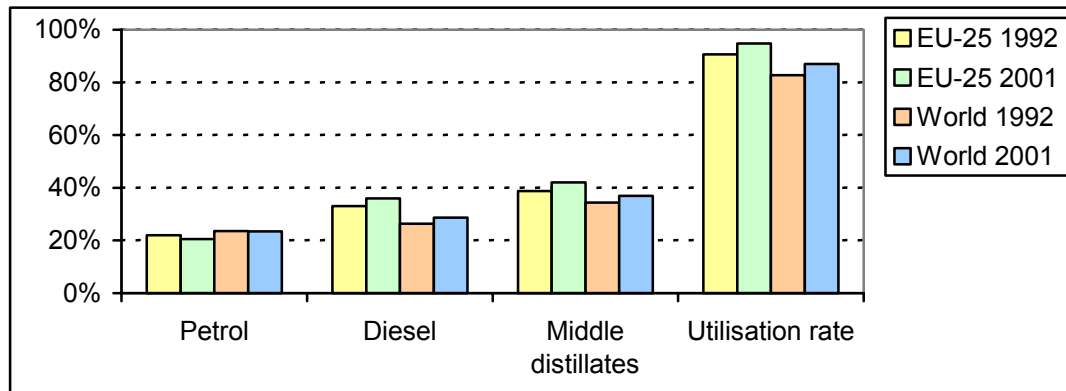
Figure 43
Total consumption of petrol, middle distillates (jet fuel, kerosene, diesel, gasoil) and diesel, diesel consumption in transport and automotive diesel consumption in EU-25 within 1992-2001, (Mt)



Source: Adapted from [50]

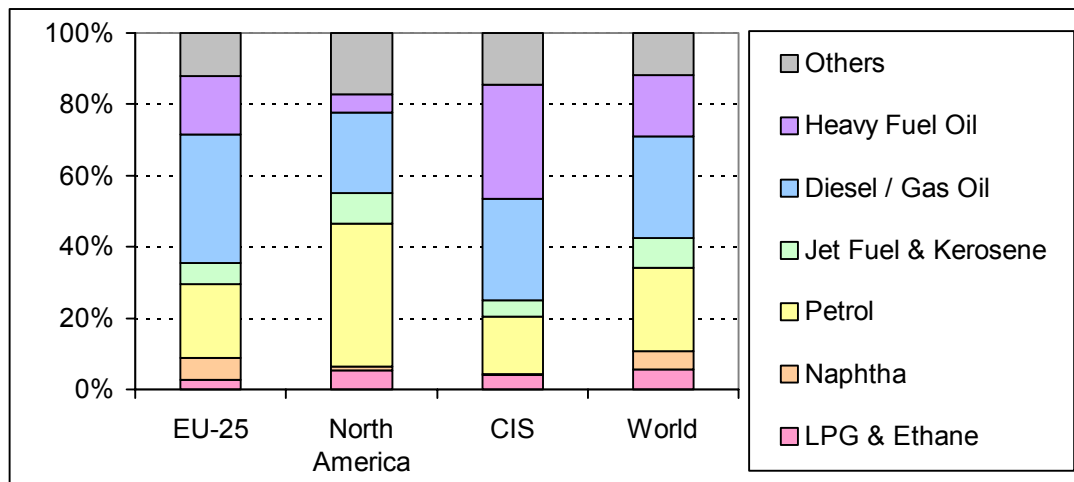
Trying to respond to this new market situation, the European refineries gradually increased diesel and middle distillates fractions, with parallel reduction of petrol yield, and improved the utilisation rate of refining capacities – Figure 44. As a result, the EU became the region with the largest diesel and middle distillate fraction in the world – Figure 45. Further extension of diesel and middle distillate fractions appears, however, not very likely. Figure 46 indicates that the difference between petrol and diesel energy and GHG production costs, respectively – monetary production costs and the economically feasible upper extent of this petrol-to-diesel conversion, is negligible, if any at all.

Figure 44
 Petrol and diesel refining fractions as shares of gross refinery output, and rate of utilisation of refining capacities in EU-25 and in the world in 1992 and 2001, (%)



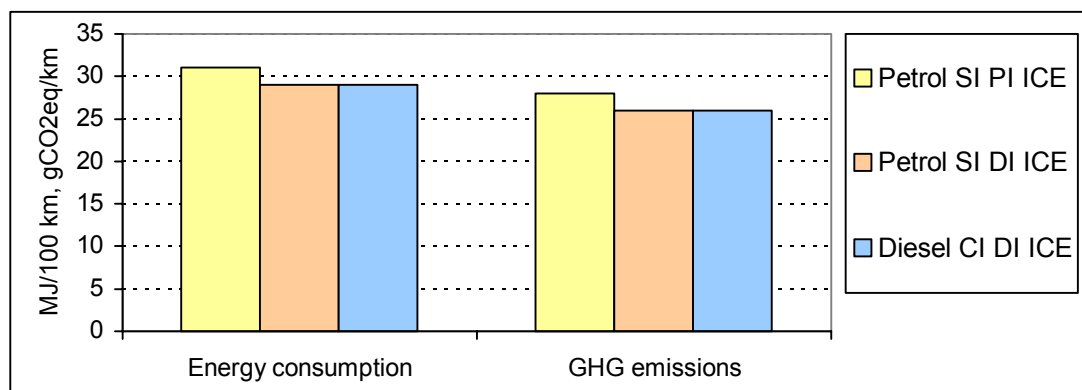
Source: Adapted from [50]

Figure 45
 Refinery output breakdown in EU-25, North America, Commonwealth of Independent States (CIS) and in the world in 2001, (%)



Source: Adapted from [50]

Figure 46
 Prevailing (2002) Well-To-Tank (WTT) energy requirements (MJ/100 km⁵²) and GHG emissions (gCO₂eq/km) for petrol (SI PI ICE and SI DI ICE) and diesel (CI DI ICE) in the EU

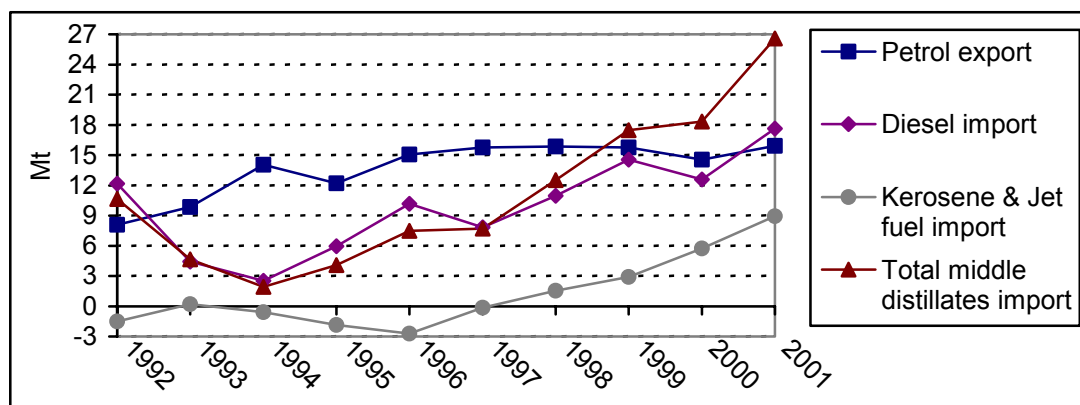


Sources: Adapted from [55]

⁵² WTT energy costs and GHG emissions as shares of final energy content of fuels are not available in [55]. A more complete discussion on energy consumption along fuel chains is proposed in chapter 7.

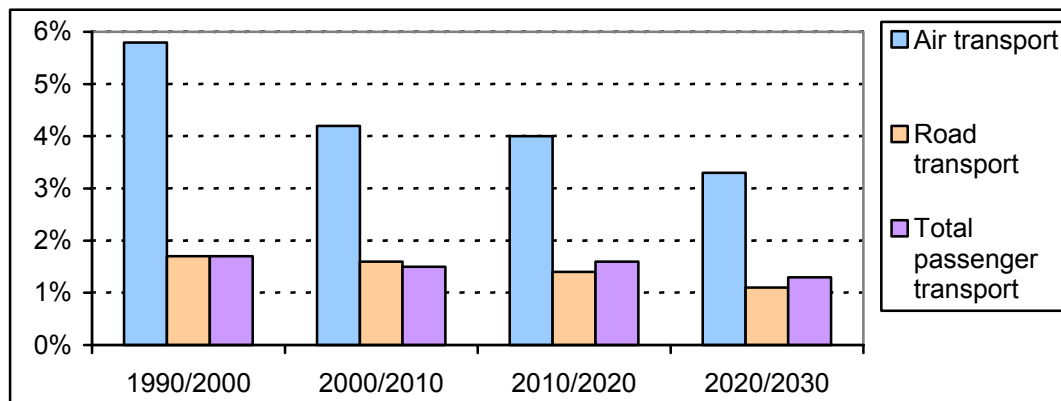
Hence, the growing diesel and middle distillates demand in the EU is covered via imports (Figure 47), mostly from the Commonwealth of Independent States (CIS). The total middle distillate imports are growing faster than those of diesel (Figure 47), due to the recent huge growth in air transport (the main consumer of kerosenes), whose growth moreover is expected to continue in the future – Figure 48. In parallel, petrol exports, mainly to the USA, are also performed, as even the reduced refining output of petrol still exceeds the internal demand in the EU – Figure 47.

Figure 47
Net export of petrol and net import of diesel, kerosene & jet fuel and total middle distillates from/to EU-25 within 1992-2001, (Mt)



Source: Adapted from [50]

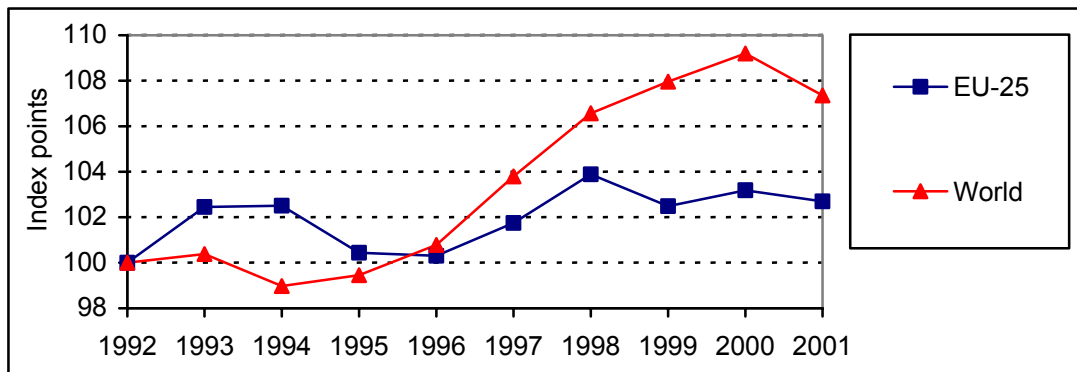
Figure 48
Retrospective (1990-2000) and projected (2000-2030) average annual growth in passenger transport – air, road and total – in EU-25, (%)



Source: Adapted from [75]

Increasing the supply of middle distillates through the construction of new refining capacities does not seem a workable solution for compensating imports, because it would mean a parallel growth in petrol, i.e. in petrol exports. Thus, the imbalance in the EU fuel foreign trade exchange will be worsened, with little or no impact on crude oil imports. Some indications for the low viability of this option is the negligible expansion in the EU refining capacities over the period 1992-2001 – totally with 0.3% only, compared to 0.8% world-wide [50], despite the stable diesel imports (Figure 49).

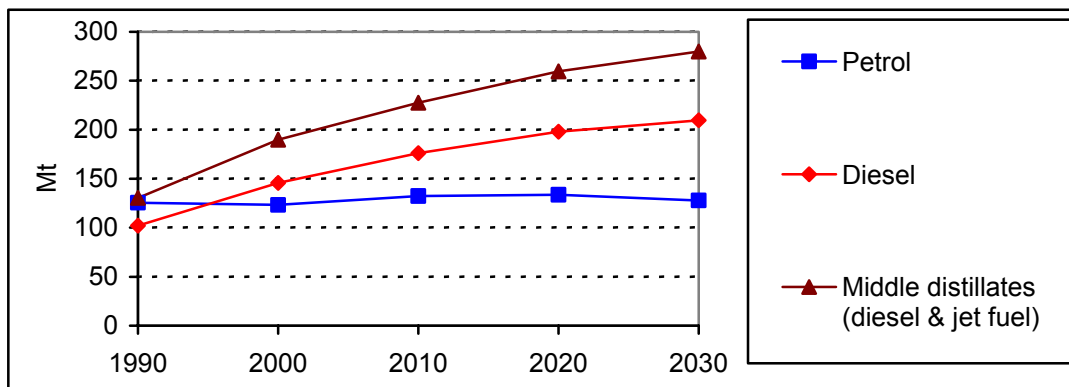
Figure 49
Growth index of oil refining capacities in EU-25 and in the world within 1992-2001 (Index points, 1992 = 100)



Source: Adapted from [50]

The above trends are not expected to change in the future either. Diesel and middle distillates consumption in transport will continue to grow in the EU, although at a lower rate than in the past. Petrol demand will stabilise around the 1990-2000 levels – Figure 50.

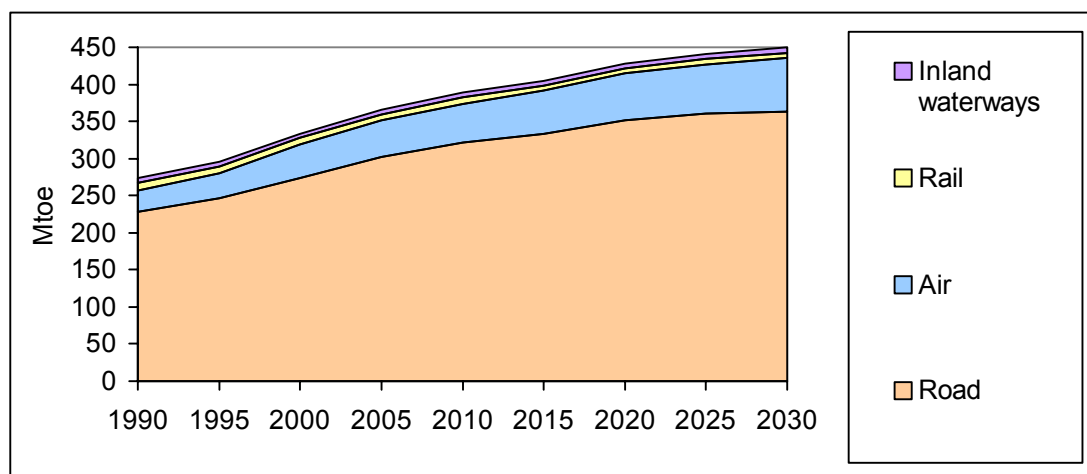
Figure 50
Retrospective (1990-2000) and projected (2010-2030) consumption of petrol, diesel and middle distillates in the transport sector of EU-25, (Mt)



Source: Adapted from [74, 75]

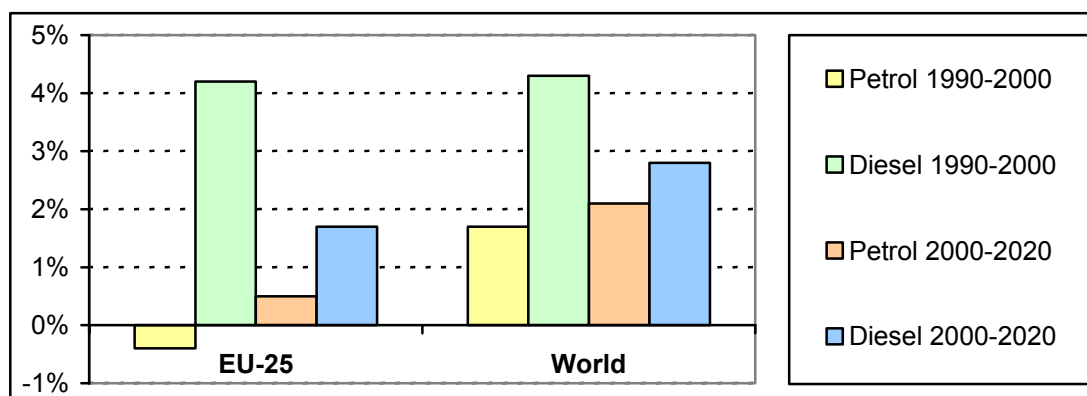
It is however important to stress two important elements of these projections. First of all, the growth in jet fuel demand will be faster than the growth in the automotive diesel. This will come from the continuing rapid increase in air traffic, making air transport the fastest growing transport mode in the EU – Figure 48. Consequently, the share of air transport in total energy demand of transport in the EU will enlarge noticeably – Figure 51. As a result, air transport will become an important concern in the EU in terms of a security and diversity of energy supply [168]. The second component, but not as a priority, is that the faster growth in diesel, compared to petrol, is not just a feature of the EU, but it is and it will be a world-wide trend [129, 132, 137, 270] – Figure 52.

Figure 51
Retrospective (1990-2000) and projected (2000-2030) transport energy consumption by modes of transport in EU-25, (Mtoe)



Source: Adapted from [75]

Figure 52
Retrospective (1990-2000) and projected (2000-2020) trends in the automotive petrol and diesel consumption in EU-25 and worldwide (average % increase per year)



Source: Adapted from [75, 222]

If there is room for a further increase of world diesel output, such a situation will not be of concern. However, upon comparison with the EU, where the feasible upper limit of the diesel fraction has been already (almost) reached (Figure 44 and Figure 45), the reserves for further increase of world diesel output do not seem very large – 3-4% at the maximum. The introduction of tougher fuel quality standards in many regions in the world (e.g. EU⁵³, USA) strengthens further the pressure on the refineries to supply sufficient quantities of clean diesel at a reasonable cost. Altogether, these facts increase the risk of the appearance of diesel deficits in the world [46, 210, 221, 241].

With regard to the above arguments, various estimates have recently been made concerning the feasible potential of BTL fuels to replace automotive fuels and in particular – diesel in the

⁵³ A more detailed discussion on the implications of the new fuel quality regulations is proposed in paragraph 8.2.

EU by 2010-2020. The following production & substitution figures and ranges have been projected:

- Without substantial changes in land use patterns, the feasible annual production of BTL diesel is ascertained at about 20.8 Mtoe, equal to 10.4% of the projected automotive diesel demand in EU-25 in 2010. 58% of this potential will come from agricultural surplus, 27% from crops grown on set-aside land and 15% from wood waste and residues. When changes in land use patterns are considered, the substitution potential of BTL fuels within 2010-2020 may reach 20% of all transport fuels, which is equal to more than 30% replacement rate of diesel in transport [6, 41, 142, 175, 185].
- The annual production of black liquor in Europe is about 10 Mtoe, which represents 70% of the annual black liquor production in the world. Roughly 20% of this black liquor can be employed for BTL synthesis – the remaining 80% goes for generating power and heat, most of which are consumed internally by the pulp and paper mills. Hence, the black liquor potential for BTL fuels comes up to about 1 Mtoe methanol or DME⁵⁴. The production potential is however strongly concentrated, depending on the distribution of chemical pulp and paper production across Europe. Sweden and Finland account for 2/3 of the overall potential (1/3 for each country), while the remaining 1/3 is spread across the rest of Europe [170].

For the purposes of the analysis, it would be useful to evaluate the potential contribution of BTL fuels to the security and diversity of energy supply of the EU in three core aspects:

- 1) What share of the projected demand for diesel and middle distillates (diesel and jet fuel) in transport of EU-25 in 2010 (hypothetical⁵⁵), 2020 and 2030 can be covered with BTL fuels, obtained from a certain share of total utilisable land⁵⁶ in EU-25?
- 2) What share of the likely imports of diesel and middle distillates (diesel and jet fuel) for transport application in 2010 (hypothetical), 2020 and 2030 can be covered with BTL fuels, obtained from a certain share of total utilisable land in EU-25?
- 3) How much land, as share of total utilisable land in EU-25, has to be reserved for BTL fuel production to cover the likely imports of diesel and middle distillates (diesel and jet fuel) for transport in EU-25 in 2010 (hypothetical), 2020 and 2030?

Figure 53 and Figure 54 summarise the answers to the first question, Figure 55 and Figure 56 present the answers to the second question, while Figure 57 and Figure 58 give the answers to the third question. Annex 2 briefs the background data for building these projections.

⁵⁴ At present methanol and DME are the products considered by the stakeholders. The production of F-T products is seen more as a back-up option.

⁵⁵ Since no large BTL fuel availability is feasibly expected by 2010.

⁵⁶ The notion "utilisable land", introduced for the purposes of this analysis, is explained in Annex 2.

Figure 53

Projected substitution rate of the likely diesel consumption for transport in EU-25 by 2010 (hypothetical), 2020 and 2030 with BTL diesel, if 10% of commercial forest land, 10% of arable land and 10% of both arable and commercial forest land in EU-25 are employed for producing feedstock for BTL diesel, (%)

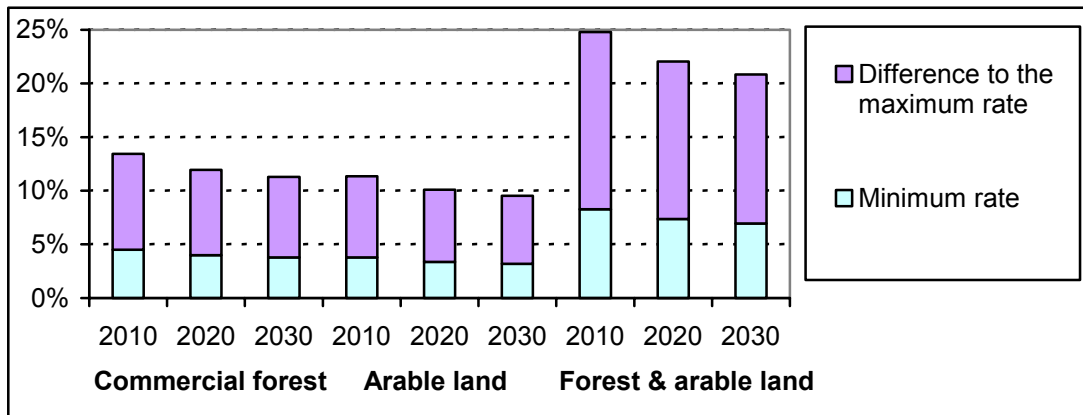
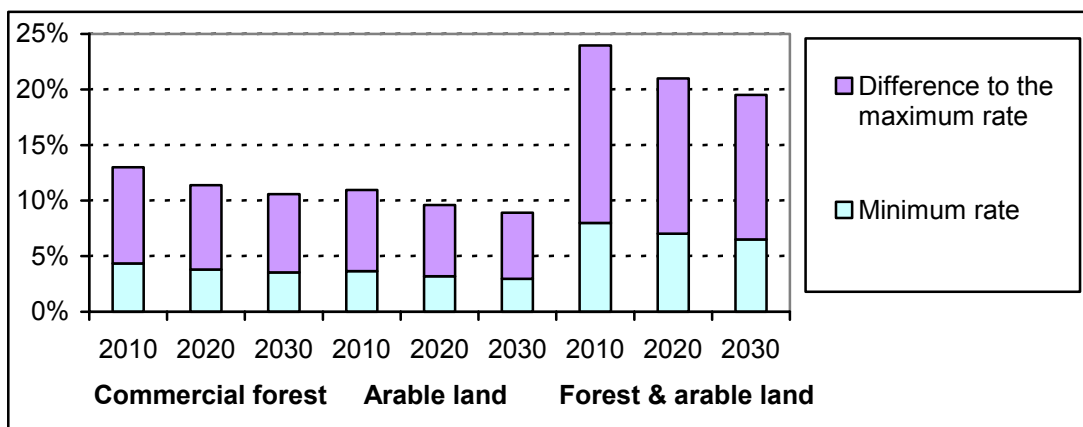


Figure 54

Projected substitution rate of the likely middle distillates consumption for transport in EU-25 by 2010 (hypothetical), 2020 and 2030 with BTL middle distillates, if 10% of commercial forest land, 10% of arable land and 10% of both arable and commercial forest land in EU-25 is employed for producing feedstock for BTL middle distillates, (%)



The following conclusions can be highlighted from Figure 53, Figure 54, Figure 55, Figure 56, Figure 57 and Figure 58:

- ✓ The BTL substitution rate for diesel only is higher than that for total middle distillates. This comes from the projected faster growth of air transport compared to that of road transport (Figure 48), i.e. in jet fuel consumption compared to that of automotive diesel (Figure 51).
- ✓ The BTL substitution rates gradually decrease, since the transport fuel consumption grows faster than the feasible supply of BTL fuels.
- ✓ The BTL substitution rate of commercial forest is larger than that of arable land, owing to the higher BTL yield per hectare (Figure 42). The forest-derived BTL fuel accounts for 54% of the cumulative (commercial forest & arable land) BTL fuel replacement.

Figure 55

Projected substitution rate of the likely net imports of diesel for transport in EU-25 by 2010 (hypothetical), 2020 and 2030 with BTL diesel, if 10% of commercial forest land, 10% of arable land and 10% of both arable and commercial forest land in EU-25 is employed for producing feedstock for BTL diesel, (%)

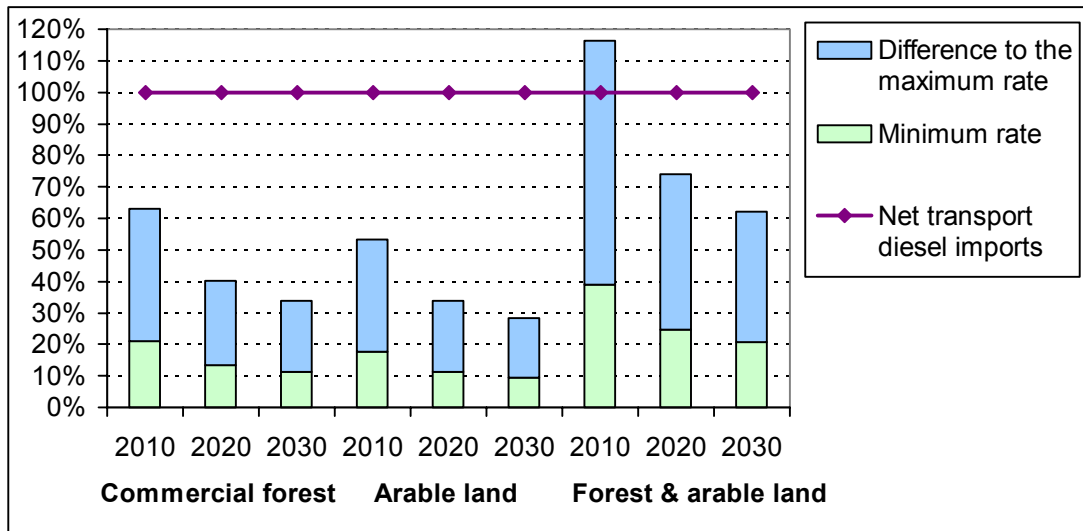
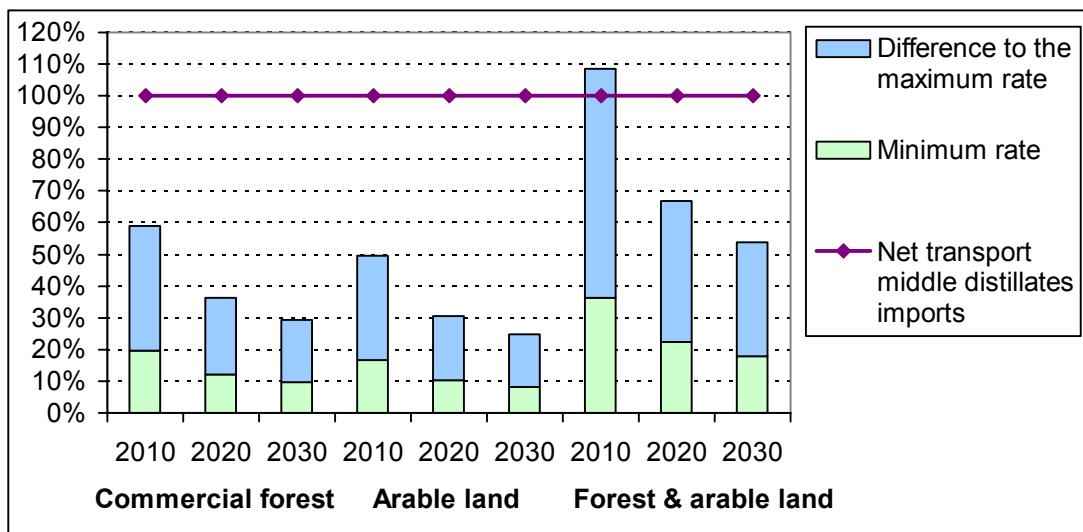


Figure 56

Projected substitution rate of the likely net imports of middle distillates for transport in EU-25 by 2010 (hypothetical), 2020 and 2030 with BTL middle distillates, if 10% of commercial forest land, 10% of arable land and 10% of both arable and commercial forest land in EU-25 is employed for producing feedstock for BTL middle distillates, (%)



- ✓ Using 20% of the utilisable land (10% of commercial forest land and 10% of arable land) for growing feedstock for BTL fuels could replace a significant part of transport diesel and middle distillate consumption in EU-25 by 2020 – 7%-22% (Figure 53) and 7-21% (Figure 54) respectively.
- ✓ Using 20% of the utilisable land (10% of commercial forest land and 10% of arable land) for growing feedstock for BTL fuels has the potential to cut to a large extent the diesel and middle distillate imports, driven by transport, to EU-25 by 2020 – between 1/4 and 3/4 (Figure 55) and between 1/4 and 2/3 (Figure 56) respectively.

Figure 57
Share of land needed for full substitution of net transport diesel imports in EU-25 by 2010 (hypothetical), 2020 and 2030 with BTL fuels (%)

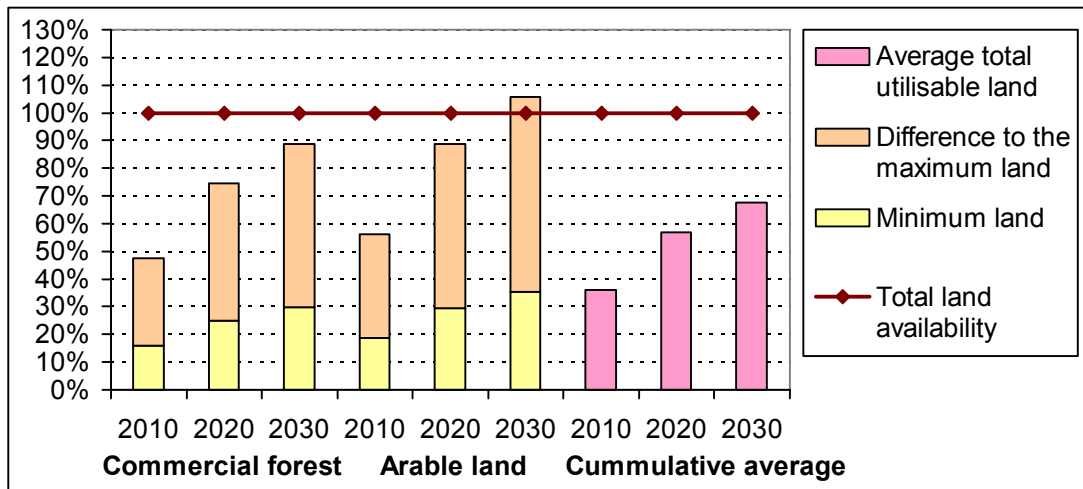
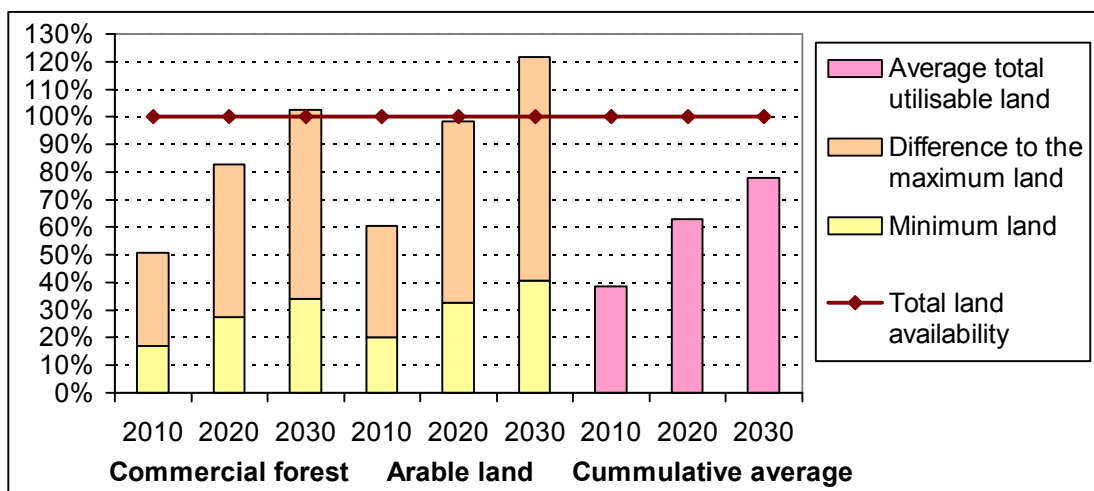


Figure 58
Share of land needed for full substitution of net transport middle distillate imports in EU-25 by 2010 (hypothetical), 2020 and 2030 with BTL fuels, (%)

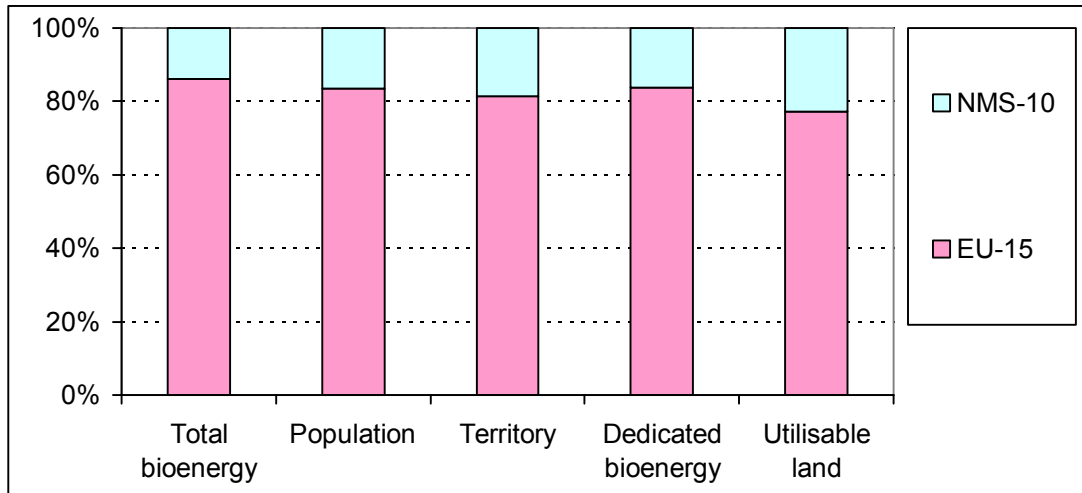


- ✓ The complete replacement of diesel and middle distillate imports for transport to EU-25 by 2020 would require more than half of the total utilisable land to be reserved to produce biomass for BTL production – 56% (Figure 57) and 63% (Figure 58) respectively. Considering other (non-energy) policy objectives and priorities, e.g. food and feed production, such scenarios would be extremely challenging for practical realisation.

When examining different substitution scenarios from Figure 53, Figure 54, Figure 55, Figure 56, Figure 57 and Figure 58, it is necessary also to identify the ways in which they can be achieved. This means to identify potential market niches & unexplored reserves for growing feedstock for BTL production in EU-25. In this context, it appears that NMS-10 have a significant unexploited biomass potential that can contribute to future large-scale BTL industry. Figure 59 indicates that currently the relative [compared to total population and

hence to population density (Figure 60) and gross land availability] bioenergy production in NMS-10 is lagging behind that in EU-15.

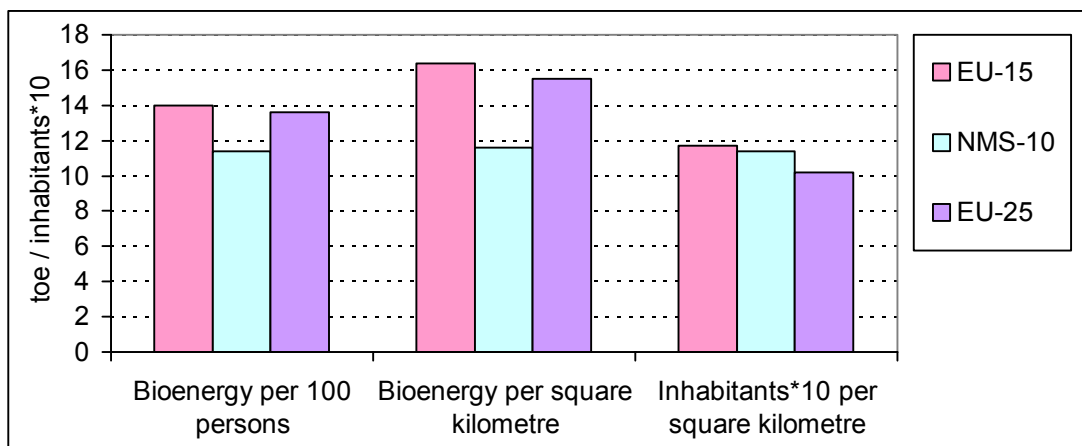
Figure 59
Percentage allocation between EU-15 and NMS-10 within EU-25 (EU-25 = 100%) of total bioenergy production, population, territory, dedicated bioenergy production (woody biomass and herbaceous energy crops⁵⁷) and utilisable land in 2001



Source: Adapted from [74, 84, 88]

The difference becomes even larger upon juxtaposing dedicated bioenergy production (based on growing woody and herbaceous crops) versus the availability of utilisable land – Figure 59.

Figure 60
Relative bioenergy application – “toe per 100 persons” and “toe per square kilometre” – and population densities (inhabitants*10 per square kilometre) in EU-15, NMS-10 and EU-25 in 2001⁵⁸



Source: Adapted from [74, 84, 88]

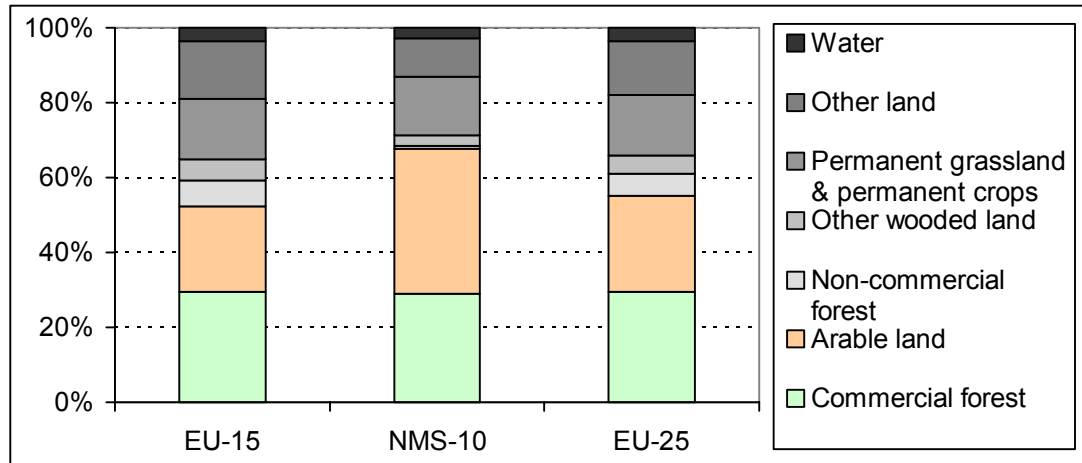
On equal terms, larger reserves to increase bioenergy production in NMS-10 could be associated with herbaceous energy crops, since the higher share of utilisable land in total

⁵⁷ The difference between total bioenergy and dedicated bioenergy is biogas and solid municipal waste, whose generation is not so strongly linked to population densities and land availability.

⁵⁸ The application of non-conventional measurement units “toe per 100 persons” and “inhabitants*10 (tens of inhabitants) per square kilometre” is applied in Figure 60 for easy-to-compare reasons.

land area of NMS-10, compared to EU-15, is due to the larger availability of arable land – Figure 61.

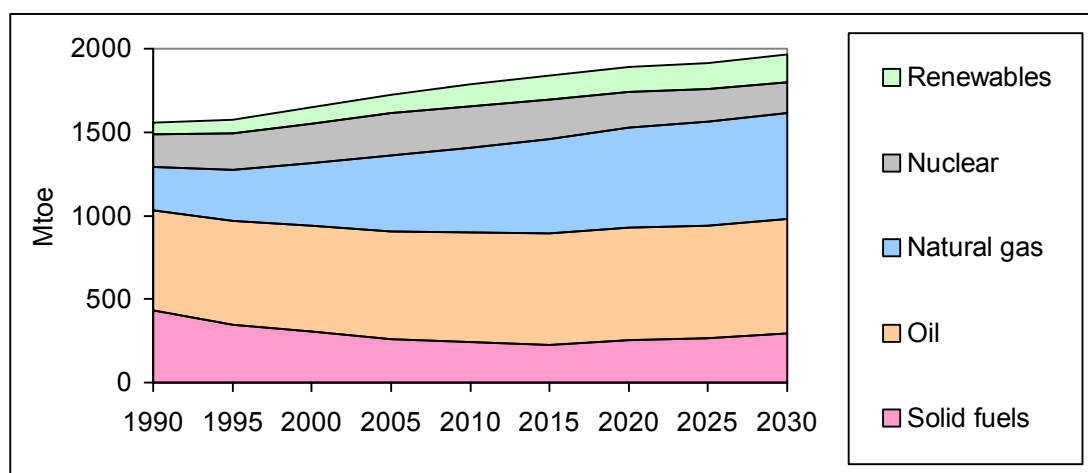
Figure 61
Breakdown of land in EU-15, NMS-10 and EU-25 in 2000, (%)



Source: Adapted from [83, 85, 86]

Besides transport, the development of bio-syngas production with further GTL synthesis of fuels and chemicals can have a significant positive impact on the overall security and diversity of energy supply of the EU. At present, more than 80% of synthesis gas both in the EU and in the world is produced from natural gas [249]. Natural gas is projected to be the fastest growing energy source in the EU – Figure 62. Since the remaining reserves of natural gas of EU-25 are low (Figure 63), the intensive growth in natural gas consumption will result in increased natural gas import dependence and thus – overall energy import dependence (Figure 1).

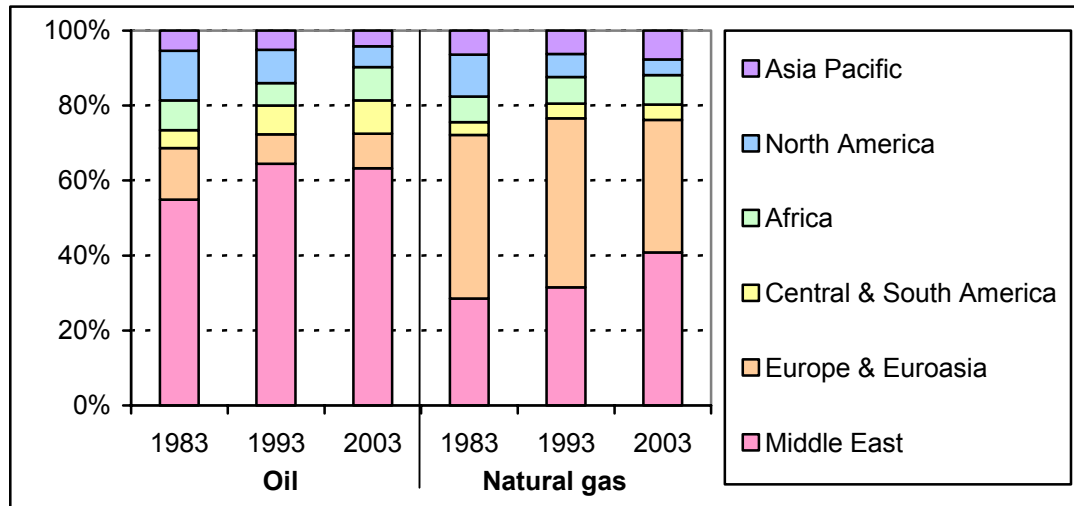
Figure 62
Retrospective (1990-2000) and projected (2000-2030) gross inland energy consumption by fuels in EU-25, (Mtoe)



Source: Adapted from [75]

In addition, the geo-political distribution of world reserves of natural gas and oil tends to follow similar patterns, since most new discoveries of natural gas take place in the Middle East – Figure 63.

Figure 63
Breakdown of oil and natural gas reserves by world regions in 1983, 1993 and 2003, (%)



Source: Adapted from [20]

Hence, the role of BTL technologies has to be regarded and evaluated based on a broader range of energy policy concerns.

Bioenergy clearly contributes to the security and diversity of energy supply of the EU, since its production and supply patterns differ from those of fossil fuels. BTL fuels have a greater potential to contribute to these policy objectives than conventional biofuels, owing to larger feasible land availability and higher biofuel yield per hectare. The technological specific of BTL processing to yield mostly middle distillates is of particular importance for the EU, which imports growing volumes of middle distillates, due to increasing demand by the transport sector. It appears that in the medium-term BTL fuels could compensate to a large extent the middle distillate imports for transport in the EU. This would have a significant contribution to the security and diversity of transport energy supply. A full substitution of the middle distillate imports for transport with BTL fuels appears however challenging, if possible at all, considering a broader range of policy priorities. Significant unexplored reserves to enlarge the biomass supply base and BTL production respectively seem to be available in NMS-10. The exploitation of the feasible reserves to increase the BTL output will incur further benefits for the security and diversity of energy supply by replacing syngas production, based on natural gas and thereby reducing natural gas imports.

7. ENERGY BALANCE

The calculation of energy consumption for transport fuels is normally performed via the so-called “Well-To-Wheel” (WTW) approach. The WTW methodology investigates the direct energy use along fuel chains (Figure 8) and consists of two parts. The first part – Well-To-Tank (WTT), investigates the stage from the extraction of feedstocks until the delivery of fuels to the vehicle tank. The second part – Tank-To-Wheel (TTW), assesses the performance of fuels in the engine. Consequently, the WTW analysis integrates the WTT and TTW parts.

A summary of findings about the energy use along different BTL pathways, adapted from several recent WTW studies, is presented in Annex 4. For comparative reasons, the figures in Annex 4 are relative, juxtaposed to the respective conventional (oil-based) powertrains. For completeness, Annex 4 also contains values of energy consumption for other fuel chains, based on oil, natural gas, coal and biomass. The criteria, applied for selecting WTW studies and fuel chains are given in Annex 3. In order to facilitate reading and understanding of Annex 4, the following visual effects are introduced:

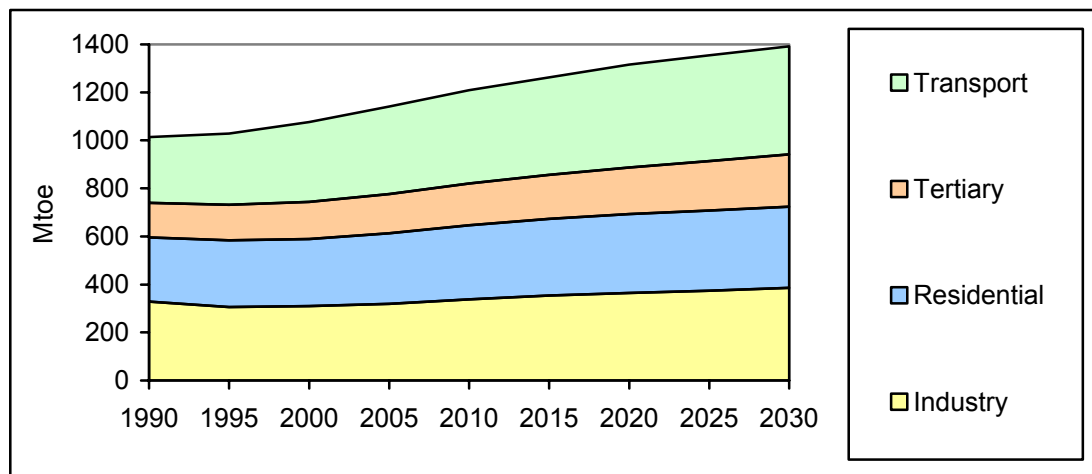
- The rows, which contain values for BTL fuels, have a yellowish background.
- The rows, which contain values for other biofuels, have a greyish background.
- Values, which exceed by more than 5% the corresponding baseline, are given in red.
- Values, which are lower by more than 5% from the corresponding baseline, are in blue.
- Values, which differ by less than +/-5% from the corresponding baseline (assumed as a negligible variation in real conditions), are given in green.

A quick look at Annex 4 indicates that red values prevail in yellow boxes, i.e. BTL fuels typically have larger energy consumption than the respective oil-derived baselines. This is not surprising, since unlike BTL processing, oil refining is a mature, well-proven and optimised over a number of years technology. On top of that, oil refining involves a smaller number of energy transformations, compared to BTL processing, i.e. the energy losses are lower⁵⁹.

Again not astonishing, BTL processing is more energy intensive than natural gas-based fuel chains, including similar GTL fuels. As already stated, this is due to the fewer transformations needed to obtain syngas (CO and H₂) from natural gas compared to biomass, since natural gas virtually consists of carbon and hydrogen only – Figure 12. Hence, from a pure energy efficiency point of view, the application of BTL fuels for transport does not make much sense because it will increase further the energy demand of transport and thus, the total final energy consumption of the EU – Figure 64.

⁵⁹ See Figure 8 and the related explanatory paragraph.

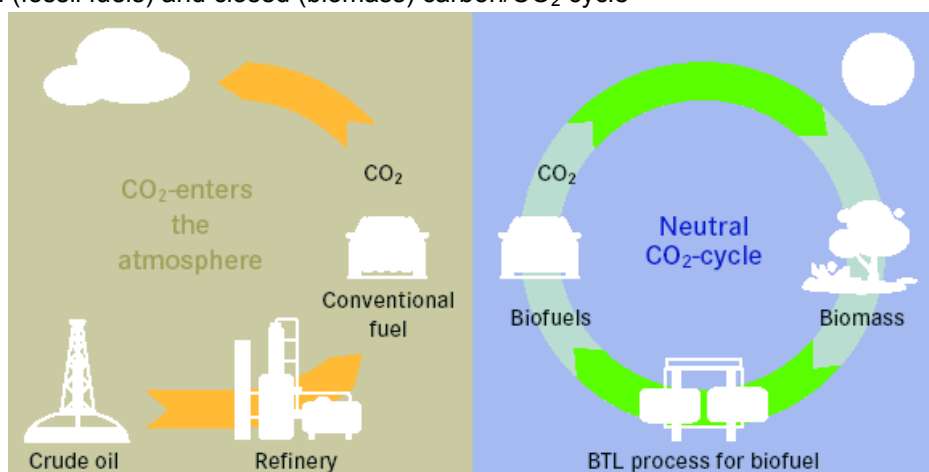
Figure 64
Retrospective (1990-2000) and projected (2010-2030) final energy consumption by sectors in EU-25, (Mtoe)



Source: Adapted from [75]

Nonetheless, when considering a broader range of policy objectives, the use of BTL fuels for transport is worthwhile, even at the expense of such increased overall energy consumption. This is due to the fact that unlike oil and natural gas, which are coming largely from import – Figure 1, biomass is produced within a sustainable carbon cycle. There, the CO₂, released during biofuel combustion, is later on absorbed by the new generation of plants, which need it for their growth – Figure 65. Hence, the more oil and natural gas-derived fuels are replaced by BTL fuels, the lower the energy import dependence.

Figure 65
Broken (fossil fuels) and closed (biomass) carbon/CO₂ cycle

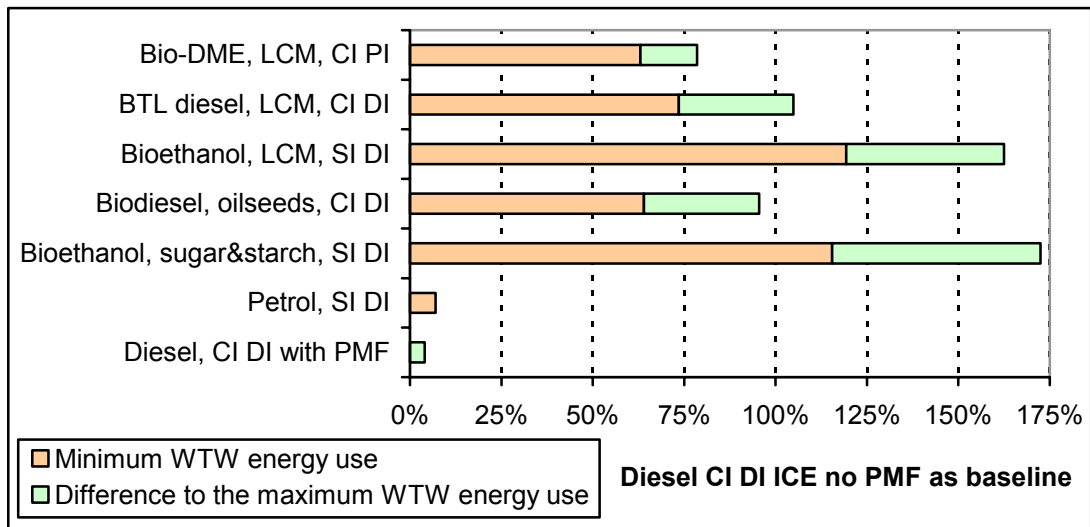


Source: [41]

The importance of BTL fuels becomes more obvious upon their comparison with conventional biofuels – bioethanol from sugar-containing and starch crops, as well as from ligno-cellulosic material and biodiesel from oilseeds. Based on the data from Annex 4, Figure 66 and Figure 67 present the projected by 2010 relative WTW energy performance of different biofuels in ICE and FC, compared to corresponding oil-derived fuels as baseline.

Figure 66

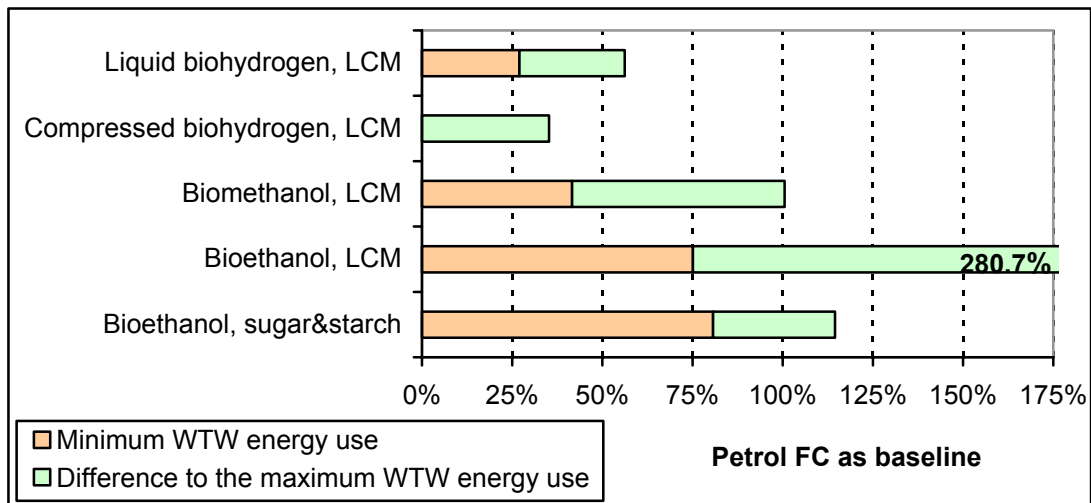
Prospective (by 2010) relative WTW figures for energy use in ICE for various oil and biomass energy pathways, compared to diesel in CI DI ICE without particulate matter filter (PMF) as baseline, (% from the baseline)⁶⁰



Source: Adapted from Annex 4

Figure 67

Prospective (by 2010) relative WTW figures for energy use in FC for various biomass energy pathways, compared to petrol in PC as baseline, (% from the baseline)



Source: Adapted from Annex 4

Figure 66 and Figure 67 indicate that all bioethanol pathways are more energy intensive than the BTL fuel chains. This is due to the more complicated cultivation of agricultural feedstock compared to ligno-cellulosic material, e.g. higher consumption of fertilisers and pesticides, whose production is highly energy consuming; more labour-intensive, etc. In addition, bioethanol pathways have a larger extent of variations in energy efficiency, i.e. higher uncertainty, which indicates a high dependence on feedstock routes and on the utilisation of by-products.

⁶⁰ The direct injection (DI) option does not bring significant energy efficiency benefits when gaseous fuels are burnt, hence it is more appropriate from a cost-benefit point of view DME vehicles to be equipped with conventional and cheaper port injection (PI) system [224].

Biodiesel performs somewhere between BTL DME (slightly worse, due to larger variation) and BTL diesel (slightly better) – Figure 66. However, the modest energy efficiency advantages of biodiesel over BTL diesel are offset by the significantly lower feasible availability of biodiesel, due to the cultivation specifics of oilseeds, which have long crop-rotation period (5-8 years), and the much lower biofuel yield per hectare – Figure 42.

In particular with regard to the FC applications, it should be stressed that under most optimistic estimates compressed biohydrogen demonstrates similar to oil-derived petrol WTW performance – Figure 67.

Another conclusion, which comes from Figure 66 and Figure 67, is that the minimisation of WTW variations (expressed by the “difference to the maximum WTW energy use” bar) could significantly improve the overall energy efficiency of BTL fuels. Such a minimisation can be achieved primarily via optimising the utilisation of by-products from BTL processing – steam, various hydrocarbon chemicals, etc. In this context, Annex 4 indicates the prevailing lack of detailed WTW estimates for BTL naphtha. Since BTL naphtha accounts for a large share in total BTL yield (Figure 32), its potential useful utilisation as a chemical feedstock even today and/or as an hydrogen carrier for FC in the longer term, could improve significantly the energy and cost-benefit performance of BTL plants.

BTL fuels are more energy-intensive than conventional diesel and petrol, and natural gas-based fuels. Nevertheless, due to different production patterns of fossil (oil and natural gas) and biomass fuels, the application of BTL fuels at higher gross energy cost can be justified by security and diversity of energy supply benefits. On the other hand, BTL fuels are generally less energy-demanding than conventional biofuels (bioethanol and biodiesel), produced from agricultural feedstock.

8. ENVIRONMENTAL PERFORMANCE

The pollution released to the atmosphere by transport can be classified in two main groups. The first group comprises pollution with global impact – the GHG, causing climate changes. As mentioned in chapter 1, the major GHG is carbon dioxide (CO₂). Other important GHG are methane (CH₄) and nitrous oxide (N₂O). The second group consists of pollution with regional impact, affecting local air-quality. The main representatives of this group are carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂), various organic compounds and particulate matters (PM).

8.1. GREENHOUSE GAS EMISSIONS

Similar to the energy use, GHG emissions are typically measured on WTW basis. Hence, the methodological principles of WTW, given in the beginning of chapter 7, are fully applicable to GHG emissions as well. A summary of findings about GHG emissions along different BTL pathways, adapted from several recent WTW studies, is presented in Annex 5. Similar to the way of presenting the data on the WTW energy use:

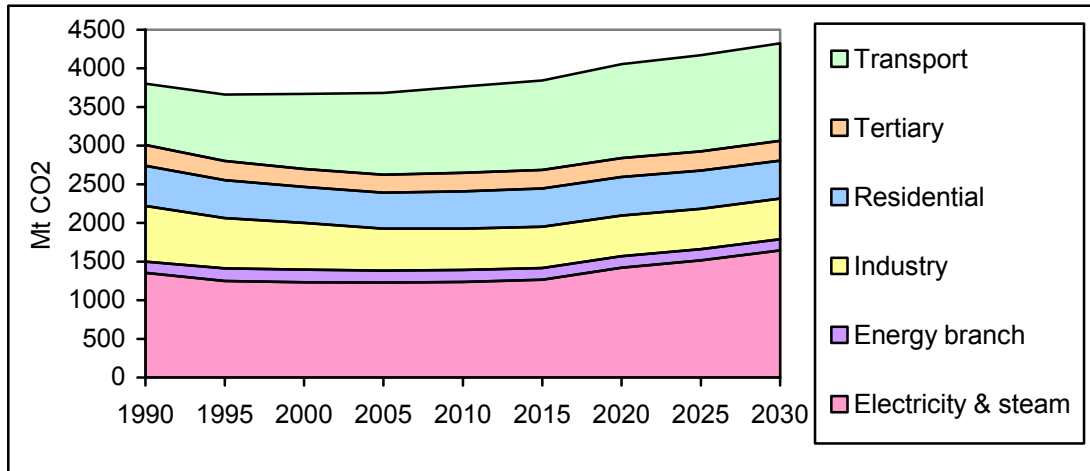
- The figures in Annex 5 are relative, juxtaposed to the respective conventional (oil-based) powertrains.
- Annex 5 contains also values of GHG emissions for other fuel chains, based on oil, natural gas, coal and biomass.
- The criteria, applied for selecting WTW studies and fuel chains are stated in Annex 3.
- The rows in Annex 5, which contain values for BTL fuels, have a yellowish background.
- The rows in Annex 5 that contain values for other biofuels, have a greyish background.
- The values in Annex 5, which exceed by more than 5% the corresponding baseline, are given in red.
- The values in Annex 5, which are lower by more than 5% from the corresponding baseline, are given in blue.
- The values in Annex 5, which differ by less than +/-5% from the corresponding baseline (assumed as negligible variation in real conditions), are given in green.

CO₂ emissions are generally proportional to fuel consumption⁶¹. Considering the results from Annex 4, Figure 66 and Figure 67, this would mean that burning biofuels and in particular – BTL fuels, would result in higher gross GHG emissions, compared to conventional fuels (diesel and petrol). However, owing to the closed cycle of biomass production (Figure 65), the net CO₂ emissions from biomass combustion are significantly lower than the net CO₂ emissions from fossil fuel combustion. By earning large CO₂ benefits over fossil fuels, biofuels

⁶¹ The CO₂ emissions from fuel combustion are crucial for the overall CO₂ balance, since the TTW CO₂ emissions account for about 85% of all WTW CO₂ emissions. The TTW CO₂ emissions are proportional to carbon content of fuels. Hence, higher fuel consumption or combustion of fuels with larger carbon chains results in higher TTW and respectively – WTW CO₂ emissions.

can improve significantly the CO₂ and respectively – the GHG performance of the EU transport sector and of the EU in general – Figure 68.

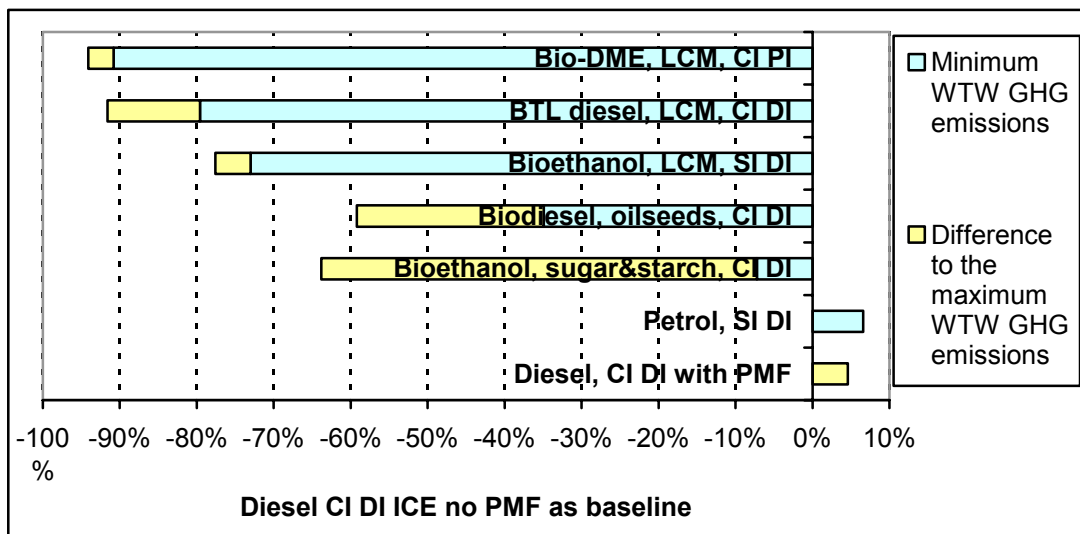
Figure 68
Retrospective (1990-2000) and projected (2000-2030) CO₂ emissions by sectors in EU-25, (Mt of CO₂)



Source: Adapted from [75]

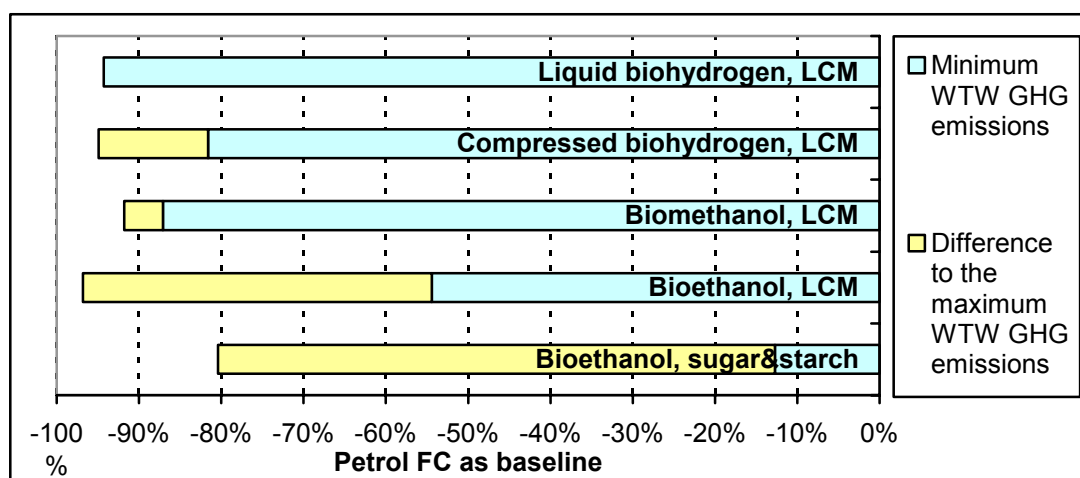
The above conclusion is confirmed by the predominance of blue values in yellow and grey boxes of Annex 5. Similar to the approach from chapter 7, it would be appropriate to compare BTL fuels with conventional biofuels – bioethanol from sugar-containing and starch crops, as well as from ligno-cellulosic material, and biodiesel from oilseeds. Based on the data from Annex 5, Figure 69 and Figure 70 present the projected by 2010 relative WTW GHG of different biofuels in ICE and FC, compared to corresponding oil-derived fuels as baseline.

Figure 69
Prospective (by 2010) relative WTW figures for GHG emissions from ICE for various oil and biomass energy pathways, compared to diesel in CI DI ICE without particulate matter filter (PMF) as baseline, (% from the baseline)



Source: Adapted from Annex 5

Figure 70
Prospective (by 2010) relative WTW figures for GHG emissions from FC for various biomass energy pathways, compared to petrol in FC as baseline, (% from the baseline)



Source: Adapted from Annex 5

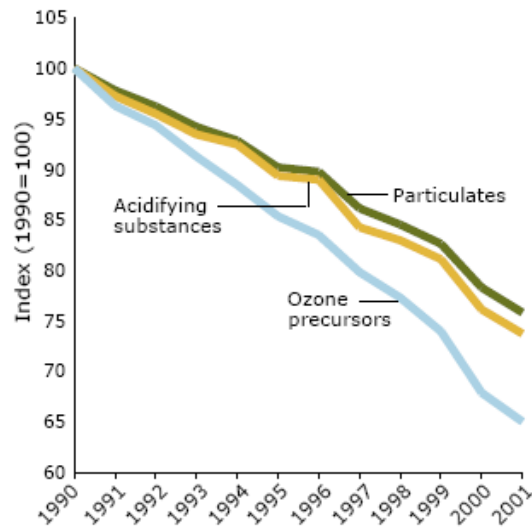
The main conclusion from Figure 69 and Figure 70 is that BTL fuels have the potential to earn the largest CO₂ & GHG savings amongst all biofuels for transport. Due to more intensive cultivation, biofuels from agricultural feedstock ensure lower CO₂ cutback than BTL fuels. In addition, the extent of CO₂ reductions from agriculture-based biofuels is heavily dependent on the feedstock cultivation pathways and on the utilisation of by-products from the biofuel production. Only bioethanol from ligno-cellulosic material is comparable to BTL fuels in terms of CO₂ & GHG reduction performance. Nevertheless, the ligno-cellulosic ethanol differs from BTL fuels with a larger extent of uncertainty, due to a higher site-dependence (Figure 69 and Figure 70).

8.2. LOCAL-POLLUTING EMISSIONS

The emissions of local pollutants are only relevant to fuel application in internal combustion engines, since FC do not emit such pollutants.

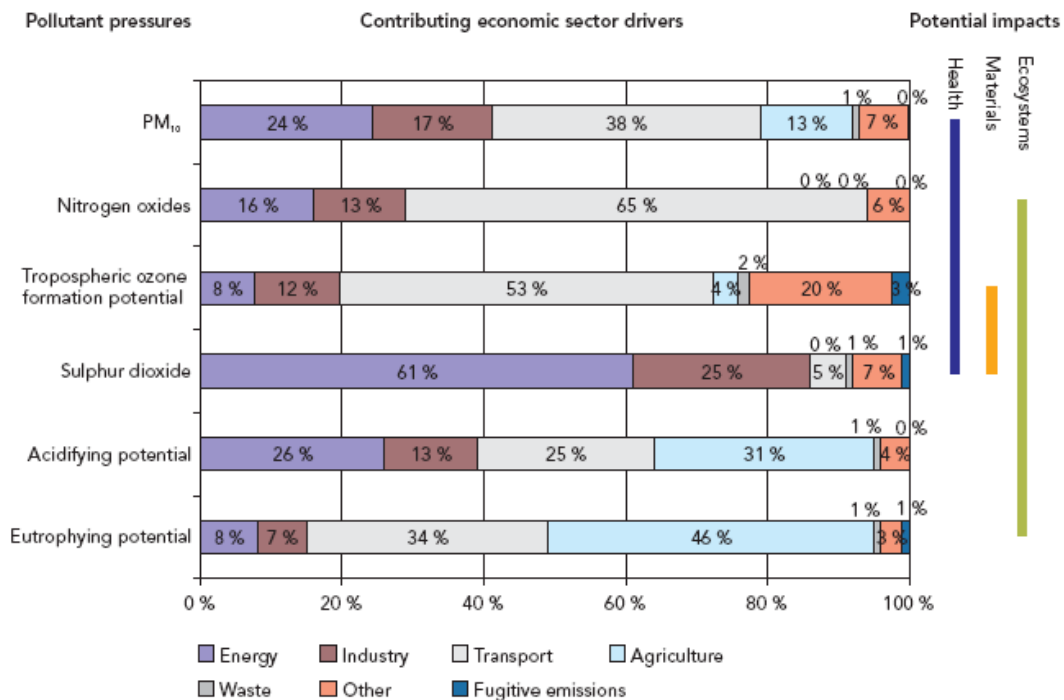
Within the period 1990-2001 the EU achieved substantial reduction in the emissions of local pollutants from all sectors: -63.6% in SO₂, -40.2% in CO, -29.4% in Non-Methane Volatile Organic Compounds (NMVOC) and -25.8 % in NO_x [95]. This large cutback was achieved primarily by fuel switching from coal to natural gas, triggered by stricter emission regulations and control. The emissions of local pollutants from transport were also reduced substantially – Figure 71, owing exclusively to stricter emission regulations (Annex 6, [77, 99]) with basically no impact of fuel switching. Nonetheless, amongst the sectors of industry, transport remains a key emitter of local pollutants, especially of NO_x and fine particulate matter (PM₁₀) – Figure 72 [90, 92, 93]. Thus, the potential for further reduction of transport-derived local pollutants has to be explored. Because of the nature and impact of local pollutants, this is particularly important for densely populated urban areas.

Figure 71
 Index of local polluting emissions from transport in Europe⁶² within 1990-2001, (Index points, 1990 = 100)



Legend:
 Acidifying substances – SO_x, NO_x, NH₃
 Ozone precursors – NO_x, NMVOCs
 Particulates – PM₁₀
 Source: Adapted from [97]

Figure 72
 Shares of different sectors in selected local-polluting emissions in EU-15 in 1999



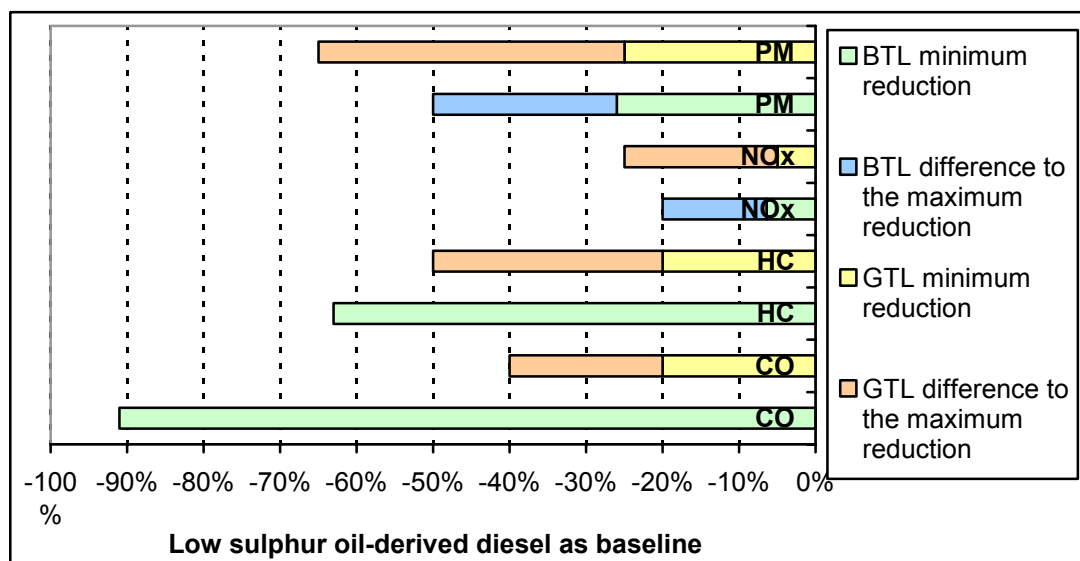
Source: Adapted from [90]

In terms of local-polluting emissions, BTL diesel performs better than the low-sulphur oil-derived diesel (sulphur content less than 10 ppm), owing to better fuel and combustion properties – virtually sulphur free, higher cetane number, lower density, etc. – Figure 73.

⁶² The 31 EEA member countries – EU-25 plus Bulgaria, Iceland, Liechtenstein, Norway, Romania and Turkey

Figure 73

Relative reduction of the emissions of local pollutants from BTL and GTL diesel, compared to low-sulphur oil-derived diesel, (%)



Source: Adapted from [14, 21, 24, 41, 149, 175, 176, 178, 189, 191, 219, 233, 288, 300]

BTL diesel shows also lower local-polluting emissions compared to biodiesel based on transesterification⁶³. Another important fact for BTL diesel is that the reduction is over-linear when BTL/GTL diesel is blended with conventional diesel⁶⁴ [119, 189]. Nonetheless, so far few data about the engine performance of BTL diesel are available. More experimental work is therefore needed to reduce the degree of uncertainty, shown in Figure 73 [233].

The emissions of SO₂ are not explicitly given in Figure 73, since all BTL fuels are virtually sulphur free, due to the low content of sulphur in biomass and the mandatory very low sulphur contamination in syngas, required by the fuel synthesis. The advantages of BTL diesel versus oil-derived diesel in this aspect will however tend to become negligible in the future, considering the gradual reduction of sulphur content in the latter [49, 99].

The over-linear reduction of local polluting emissions with BTL fuel blends could become a major incentive for the promotion of BTL fuels in the EU. Besides the efforts to reduce GHG emissions, the EU is aiming also at decreasing the emissions with impact on local air quality. The new emission standard EURO 4, which started gradually to replace the previous EURO 3 standard as from the beginning of 2005, imposes lower limits for a set of local pollutants – Annex 6. The reduction of nitrogen oxide (NOx) emissions from diesel engines is normally accompanied by an increase in particulate matters (PM) emissions and fuel consumption. Due to the NOx/PM trade-off, some after-treatment technologies might be needed – lean de-NOx catalysts or particulate matters filters (PMF). The automotive industry believes that the recent improvements in diesel technology will allow the new diesel passenger cars from the

⁶³ Biodiesel from oilseeds tends to show higher NOx emissions than oil-derived diesel.

⁶⁴ The extent of reduction is larger than the blending share.

lowest class (1) from Annex 6, run on conventional oil-derived diesel, to meet simultaneously the EURO 4 limits for NO_x and PM without additional equipment, e.g. PMF [35]. If this cannot be achieved in practice, the introduction of PMF will be necessary. The alternative solution is to utilise cleaner fuels, e.g. BTL fuel blends.

The introduction of tougher emission regulations is taking place not only in Europe, but also in other regions, e.g. the new TIER 2 standard in the USA. TIER 2 and EURO 4 are not directly comparable, as they look at different types of pollutants, however the combined impact of both regulations will be an increase in the demand for cleaner fuels [46, 210, 221]. Meeting the stricter environmental regulations appears to be generally more difficult and more costly for diesel than for petrol. This is partly due to the fact that the proper performance of a number of the new sophisticated improvements in the diesel technology requires cleaner fuel (especially with low sulphur content⁶⁵) with strictly determined and maintained specifications [46]. With growing global demand for diesel (Figure 52), sufficient availability of such clean diesel can become challenging [46, 241]. Hence, ensuring alternative supply of clean diesel via other routes, e.g. like the BTL one, could become extremely attractive for refineries and car manufacturers.

Due to little experience with DME, very few data are available so far about its local pollution saving potential. It is suggested that DME can ensure large (up to 90%) reductions in NO_x and PM. The lack of such NO_x/PM trade-off for DME makes it basically the optimum fuel choice for CI ICE from the point of view of the emissions of local pollutants [10, 49, 141, 269]. Similar to BTL diesel, no SO₂ emissions from DME are observed either.

Finally, an important point has to be made. The above-described environmental advantages of BTL fuels over conventional fuels are based on a proper engine performance. Modern engines are complex and sophisticated systems, which require very fine tuning⁶⁶. They need strictly-defined and maintained fuel properties to ensure low energy consumption and emissions. When an engine, designed for a conventional fuel, is run without any adjustments on an alternative fuel that has better qualities than the conventional fuel, this may not always lead to a better energy and environmental performance of the engine. Hence, the introduction of BTL automotive fuels should always take into account the specifics of the interactions within the sophisticated “fuel & engine” systems.

8.3. OTHER ENVIRONMENTAL CONCERNS

⁶⁵ As from 2005 the limits for sulphur content of petrol and diesel in the EU are 50 ppm, while the application of only sulphur-free fuels (sulphur content below 10 ppm) as from 2009 has been imposed [99]. The new U.S. emission limits for 2007-2010 are set up based on the assumption that exhaust after-treatment for NO_x and PM will be available and that sulphur in diesel will be capped at 15 ppm starting middle of 2006, in order not to contaminate the exhaust treatment devices [46].

⁶⁶ More about modern engine design, characteristics and performance can be found in [35, 57, 223].

Besides the direct emissions from fuel combustion, there are also other environmental issues with BTL fuels. These are especially concerns about the impacts of the intensive cultivation of energy crops on biodiversity, landscape, water and soil protection, etc., e.g.:

- As mentioned in paragraphs 2.1.2 and 2.3.1, poplar and willow need large amounts of water, which might result in groundwater depletion. Red canary grass is very invasive of wetlands and is not a suitable alternative to arable crops on high grades of agricultural land.
- Growing short-rotation forestry on a large-scale would cause significant and rapid visual landscape changes, since SRF is tall and grows fast. There will be also further impacts, ensuing from the complex logistics system for collection and transportation of all this wood to the processing plants [6, 169].
- Straw is widely employed for non-energy purposes and the impacts of its potential large-scale use for BTL production on farming patterns are not yet fully examined [169].
- It is often suggested that potential shortages of internal biomass supply in the EU can be compensated with imports from tropical countries (e.g. Brazil), which possess abundant feedstock resources. Nevertheless, this would in fact represent an export of externalities, associated with intensive bioenergy production, to other regions. The respective impacts on the sustainability of tropical flora are almost unknown at present [169].
- It is sometimes assumed that growing GMO crops strictly for energy purposes could boost the development of bioenergy by increasing the supply base and reducing costs. However, the wider (beyond laboratory experiments) spread of GMO is currently subject of strong debates. Eventual cultivation of GMO crops for biofuels might create opposition to bioenergy in the society [169]. It might also be somewhat difficult to keep track of the strict utilisation of GMO crops only for bioenergy purposes, but not e.g. for food use.

A great deal of the above environmental issues is still under-investigated and needs further assessments [49, 87, 101, 109, 207, 246].

Owing to the CO₂ recycling, the net GHG emissions of BTL fuels are substantially lower than those of conventional diesel and petrol and of all natural gas-based fuels. BTL fuels also offer GHG savings over conventional biofuels (bioethanol and biodiesel), produced from agricultural feedstock. Hence, BTL fuels appear as the most promising option to cut the CO₂ emissions from transport.

Since BTL diesel and DME offer significant decrease in local-polluting emissions compared to conventional diesel, this makes them very attractive in urban areas, where local air quality is a particular concern. Thanks to synergies, the reduction in the emissions of local pollutants from BTL diesel is over-linear, i.e. even small blending share of BTL diesel in conventional diesel results in significant emission reduction.

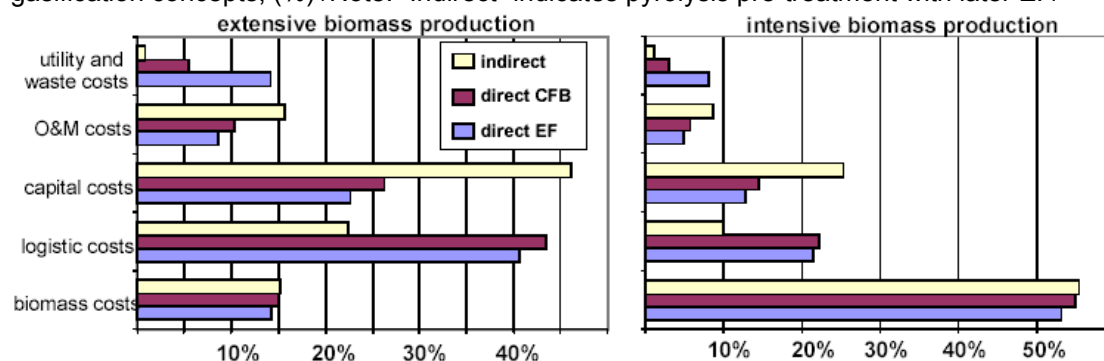
9. COST ANALYSIS

In principle, the identification of costs of production and application of BTL fuels should follow the approach that has been used to evaluate energy consumption and GHG emissions along fuel chains. It is however extremely difficult to make such cost estimates at present, due to the initial stage of production and application of BTL fuels. Hence, any cost estimates along BTL fuel chains would contain a very high degree of uncertainty. The following analysis comprises therefore only those components of BTL fuel chains, which can be identified currently with a reasonable degree of certainty.

The first major component in the total production costs of BTL fuels is the cost of the feedstock. Figure 74 indicates that the feedstock cost has a crucial impact on the breakdown of biosyngas production costs, ranging from about 15% to more than 50% of total biosyngas costs depending on whether cheap or expensive biomass is used. As a result, the final production cost of biosyngas from cheap biomass is roughly two times lower than that of biosyngas obtained from expensive biomass – Figure 75.

Figure 74

Breakdown of biosyngas production costs for extensive biomass production (feedstock cost EUR 0.6/GJ) and intensive biomass production (feedstock cost 4.0 EUR/GJ) for different gasification concepts, (%) /Note: "Indirect" indicates pyrolysis pre-treatment with later EF/



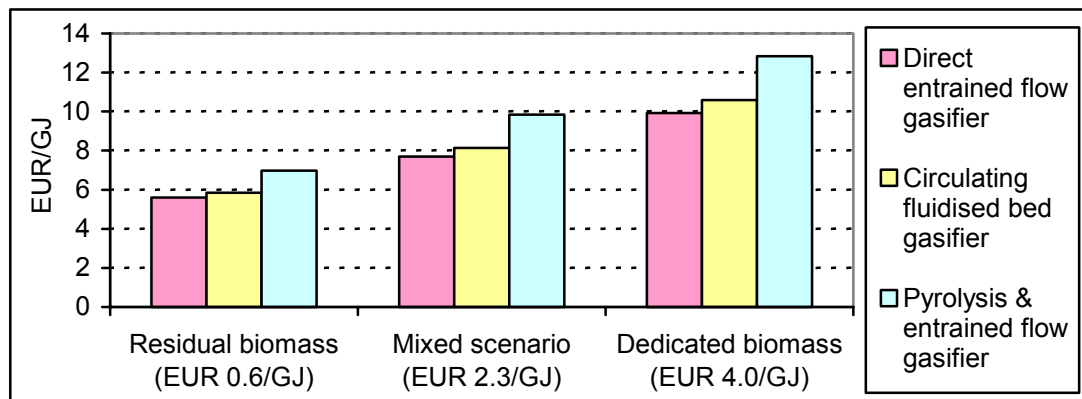
Source: Adapted from [26]

On the other hand, the dependence of production cost of BTL fuels on the feedstock cost is less pronounced than that of conventional biofuels. Besides that the economics of large BTL plants is still supposed to be heavily dependent on the feedstock cost (40-50%), in the case of conventional biofuels this dependence is even greater, exceeding 80%. Furthermore, the economics of the production of conventional biofuels depends to a larger extent on the revenue from by-products than the economics of BTL fuels [154].

Owing to the large share of feedstock costs in total biosyngas production costs, as well as to the more sophisticated syngas production route from biomass compared to e.g. natural gas, the biosyngas production costs account for the largest part in total BTL production costs. The

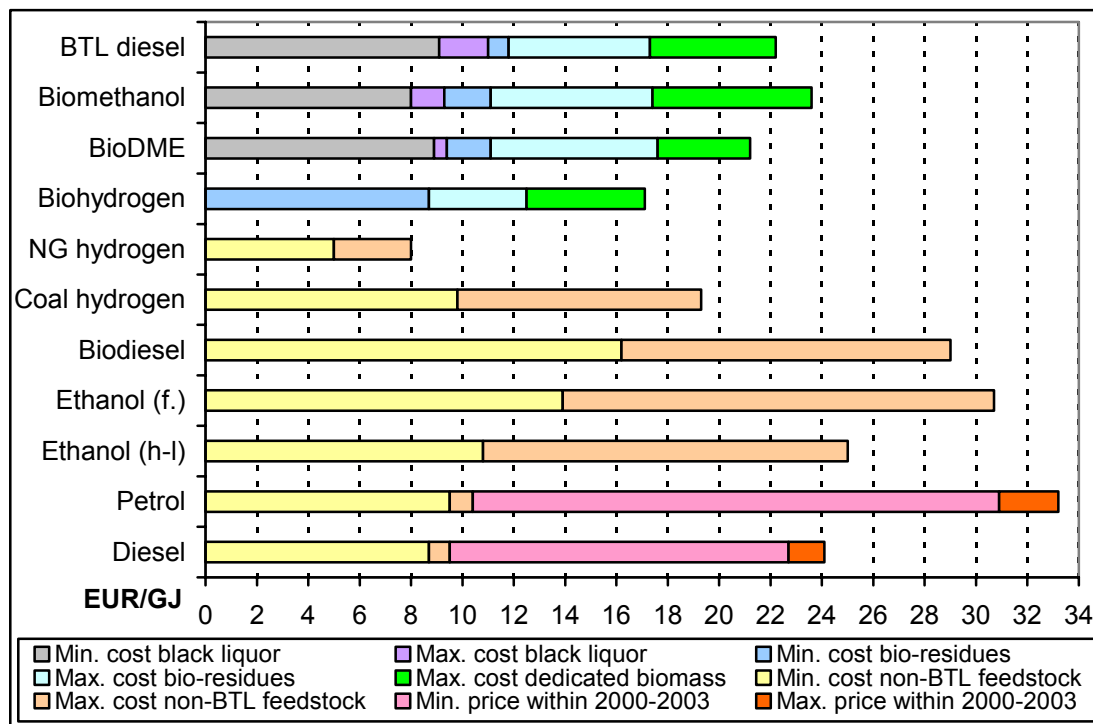
comparison between Figure 75 and Figure 76 indicates that the biosyngas production costs account for 50-75% of total BTL production costs [1, 16, 116, 141, 205, 229].

Figure 75
Estimates for biosyngas production costs via different gasification concepts, depending on the feedstock costs (EUR/GJ)



Source: Adapted from [26]

Figure 76
Production costs of BTL fuels, conventional biofuels and selected fossil fuels for application in ICE⁶⁷ and average (2000-2003) price (with taxes) of petrol and diesel in the EU, (EUR/GJ⁶⁸)



Note: BTL naphtha is assumed to have the cost breakdown of BTL diesel

Legend: NG – natural gas; (f.) – fermentation; (h-l) – hydrolysis;

Source: Adapted from [1, 6, 14, 19, 49, 76, 115, 135, 140, 142, 152, 161, 165, 169, 170, 178, 183, 195, 196, 229, 237, 243, 245, 250]

⁶⁷ Calculations of fuel costs for FC applications are not proposed, since they would contain an extremely large extent of uncertainty. Besides the differences in direct fuel costs, the variation range will be further enhanced by the cost uncertainty of the FC technology, including the specific cost surcharge for each hydrogen carrier (low/high temperature reforming) and by the hydrogen production pathway (partial oxidation / steam reforming and the share of fuel hydrogen in the latter case – Equation 6 to Equation 9 in Annex 1).

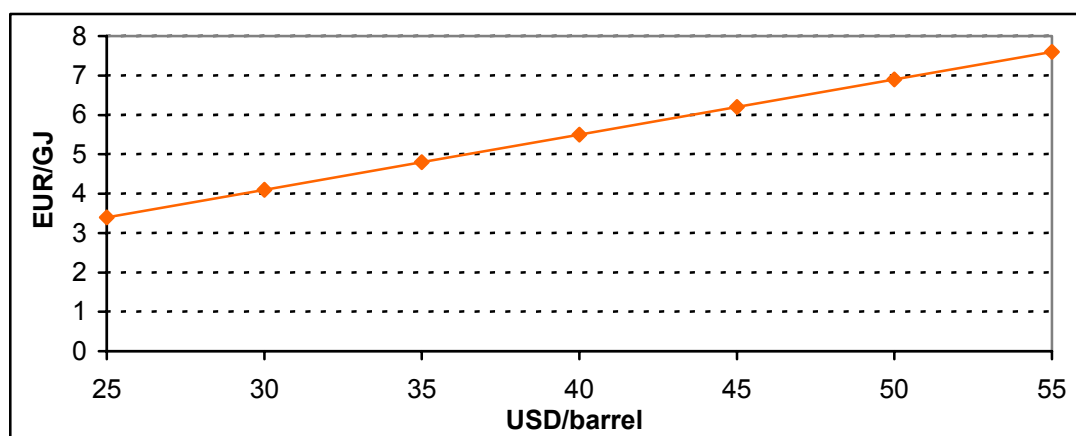
⁶⁸ For every horizontal bar the cost contribution from a particular feedstock starts from "0".

Besides the feedstock costs, this large share of syngas costs in total production costs of BTL processing comes also from high capital costs. Similar to total production costs, the share of direct capital costs, associated with biosyngas generation, accounts for 50-75% of all direct⁶⁹ capital costs in BTL plants [116, 205].

With regard to the relative cost positioning of BTL fuels, both internally (amongst each other) and versus other fuels, Figure 76 shows that in most cases BTL fuels are approximately 2-3 times more expensive to manufacture than conventional oil-derived petrol and diesel. BTL fuels are cost competitive to petrol and diesel only when they are produced from very low cost residual feedstocks – black liquor or cheap woody and/or herbaceous residues and waste. In all other cases BTL fuels need preferential tax incentives to be competitive to petrol and diesel on the EU automotive fuel market. The large cost variations for BTL fuels are also due to the immature status of BTL technologies, which consequently implies large differences in the design and efficiencies of various BTL pathways. Hence, besides the direct feedstock cost differences, the lower cost ends in Figure 76 indicate greater optimisation of fuel chains – improved supply and handling logistics, economies of scale, deeper integration of processes, etc. Nevertheless, even with such progress in technologies, BTL fuels will remain more costly than petrol and diesel at least in the foreseeable future, due to the following reasons:

- The cost per energy unit of biomass feedstock is lower than that of oil – respectively 0.6-4.0 EUR/GJ [16, 18, 19, 26, 116, 154, 229, 237] versus 3.4-7.6 EUR/GJ for oil price range 25-55 USD/barrel⁷⁰ – Figure 77. However, a weight unit of biomass contains about two times less energy than a weight unit of oil – 16-23 MJ/kg (Figure 12) versus 41.8 MJ/kg. Hence, the logistics costs (handling, storage, transportation) per energy unit of biomass are twice higher than those of oil.

Figure 77
Cost of oil feedstock in EUR/GJ, depending on the price of oil in USD/barrel



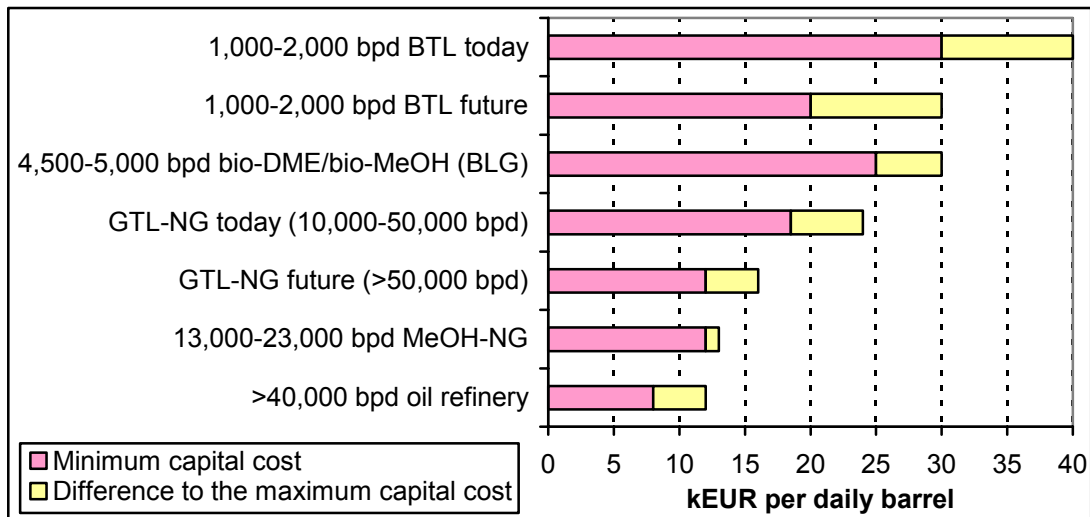
⁶⁹ For the purposes of the analysis, the direct capital cost include feedstock pre-treatment, oxygen plant and gas purification facilities, biosyngas generation, GTL synthesis and product upgrade.

⁷⁰ The EUR/USD conversion factor is taken at 1.25 for all re-calculations in this work.

- Biomass resource is far more dispersed than that of oil, since it depends on the land availability and land productivity. Conversely, crude oil is inherent with extremely large single accumulations, which allow huge economies of scale and cost-efficient exploitation for years. Combined with the lower energy density, this means that biomass is inherent with much higher logistics costs than oil and the feasible extent of enlarging BTL plants (and thereby earning economies of scale) is much lower than that of oil refineries.
- BTL pathways to automotive fuels are much more technologically sophisticated and thus, more expensive than oil refining. Under optimistic estimates, the direct capital cost of a hypothetical large-scale BTL refinery with an economically feasible output of 1,000-2,000 daily barrels would cost at least 3 times more than a conventional oil refinery of 20 to 40 times larger economically feasible output – Figure 78. In the future, owing to integration, economies of numbers, economies of scale, learning curve, etc., the cost difference between BTL plants and oil refineries might go down to a factor of 2. The direct capital costs of bio-DME and biomethanol plants are supposed to be slightly lower than those of BTL plants, due to higher conversion efficiencies and economies of scale, when the production is integrated with pulp and paper production. Nonetheless, all these values will still remain above the direct capital costs of GTL plants using natural gas. In any case, both GTL and BTL direct capital costs will stay well above the direct capital costs of oil refineries and modern large methanol complexes based on natural gas – Figure 78.

Figure 78

Rough estimates of direct capital costs of BTL plants, GTL plants running on natural gas and oil refineries with different output capacity (in barrels per day /bpd/), (kEUR per daily barrel)



Source: Adapted from [1, 6, 16, 18, 19, 26, 34, 103, 106, 108, 122, 141, 158, 183, 233, 245, 252, 269, 287, 290]

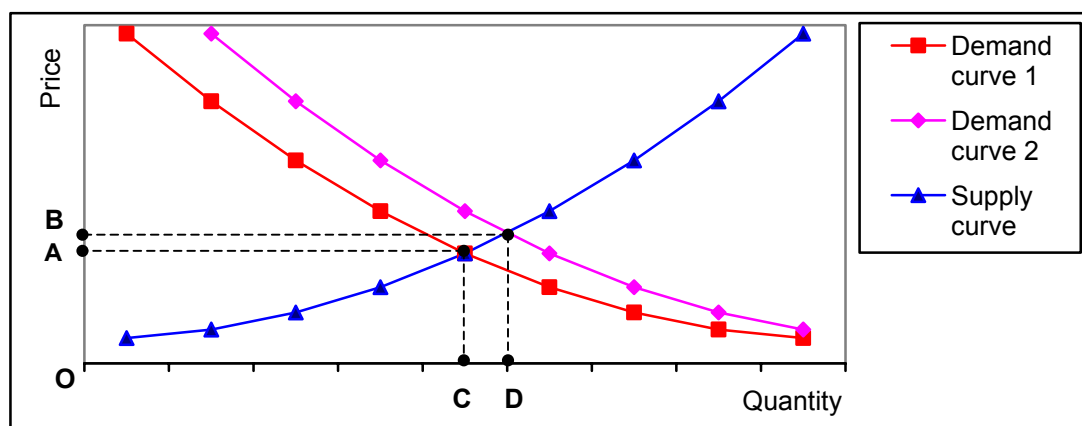
Despite the above facts, there are anyhow some potential for improvement, which can be exploited for further reduction of BTL production costs. The key element in all these reserves

is “optimisation” – optimisation of feedstock costs, handling costs, processing costs and product revenues.

Feedstock costs can be reduced via a more complete utilisation of the internally (within the EU) available cheap biomass material and/or via bringing cheap feedstock from abroad (e.g. from tropical countries), and via optimising handling and transportation costs. Obviously, it is more cost-efficient to manufacture BTL products from cheap feedstock (e.g. wood residues and waste) rather than from expensive one (e.g. short-rotation forestry) – Figure 76. The “small” problem in this case is that all bioenergy users follow the same logic, i.e. they always prefer first to use cheap biomass and then expensive. Hence, strong competition is observed amongst different players in the bioenergy field for access to cheap bio-feedstock. This competition may not always favour either the optimum utilisation of the cheap biomass resource, or the development of bioenergy as a whole. In this context, the recent large growth in bioenergy in the EU has come indeed mainly from a more complete use of the available “cheap” bio-resource. The efforts to improve production technologies for “expensive” bio-material and thus to reduce its costs, recently have lagged behind the growth in the “cheap” feedstock application. As a result, increasing and even maintaining the recent expansion trends in biomass application in the EU might become more challenging, due to a gradual depletion of the “cheap” bio-resource and the ensuing need for switching to “expensive” feedstock [7, 69, 177, 203].

The prevailing classification of “cheap” and “expensive” feedstock refers exclusively to production costs, but not to price mechanisms. Such a partial viewpoint disregards the economic fundamentals of price formulation, resulting from the interactions between demand and supply. From an economic point of view, “cheap” goods (OA in Figure 79) are those, which are either over-supplied, or which have little utility within a specific context – OC in Figure 79.

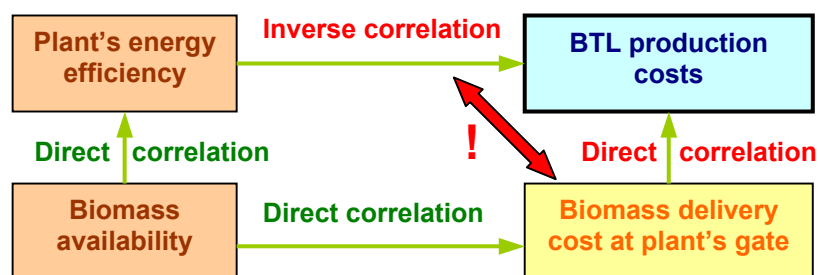
Figure 79
General economics correlations between supply, demand and prices



However, on equal terms if the demand for such goods grows (from OC to OD in Figure 79), owing to the appearance of new customers and/or new applications, the market price of those goods will also increase (from OA to OB in Figure 79) and they might not be “cheap” any longer. Hence, it is not correct to perceive the “cheap” and “expensive” categories statically, i.e. to assume that currently “cheap” biomass feedstock will remain cheap forever.

BTL production costs can be also reduced by realising economies of scale, i.e. manufacturing BTL fuels in large centralised plants [5]. The benefits in terms of spared capital costs, increased energy efficiency and respectively – reduced production costs of such large BTL plants are obvious. Such big plants need also large amounts of biomass feedstock, whose cost-efficient delivery to the plant’s gate is however problematic, due to the low energy density of biomass and its dispersed availability – Figure 80. Hence, the optimum of BTL production costs depends on several factors, which have to be considered simultaneously.

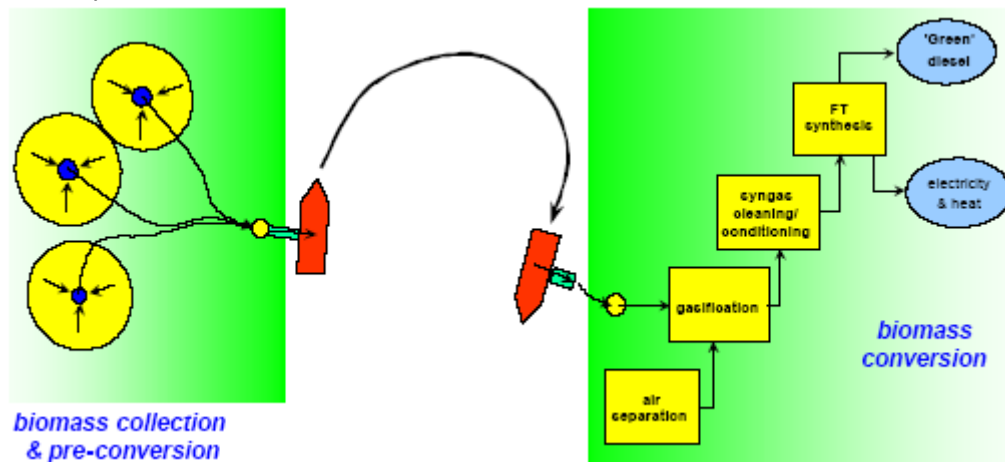
Figure 80
Direct correlation between biomass availability and BTL production costs through biomass delivery cost at the plant gate and inverse correlation between biomass availability and BTL production costs through plant’s energy efficiency



The optimisation of biomass transportation, storage and handling costs is the main feasible way of overcoming to a certain extent this cost trade-off. Owing to the largest average cargo carrying capacity per vehicle amongst transport modes, waterborne transport is the cheapest and hence, the most convenient mode of transport for moving mass cargoes⁷¹ such as biomass. Thus, by locating BTL plants in/near sea or river ports (Figure 81), the transportation costs can be significantly reduced. The delivery cost of biomass feedstock at the gate of the BTL plant can be reduced further via increasing biomass energy density. Biomass could be collected in relatively small pre-treatment plants and then pyrolysed (Figure 25) at the same location. Then, the obtained pyrolysis oil, which has much higher energy density than virgin biomass (Figure 27 and Figure 12), can be brought to a large centralised BTL plant. The transportation costs per energy unit of biomass would therefore decrease substantially. Summing up, the waterborne transportation of pre-treated (pyrolysed) biomass to large centralised BTL plants located in or nearby sea or river ports, appears to be the BTL logistics option with the lowest transportation, storage and handling costs – Figure 81 [17, 120].

⁷¹ In general, mass cargoes have relatively low product value, are transported in large volumes and the share of transport costs in their final delivery cost is high.

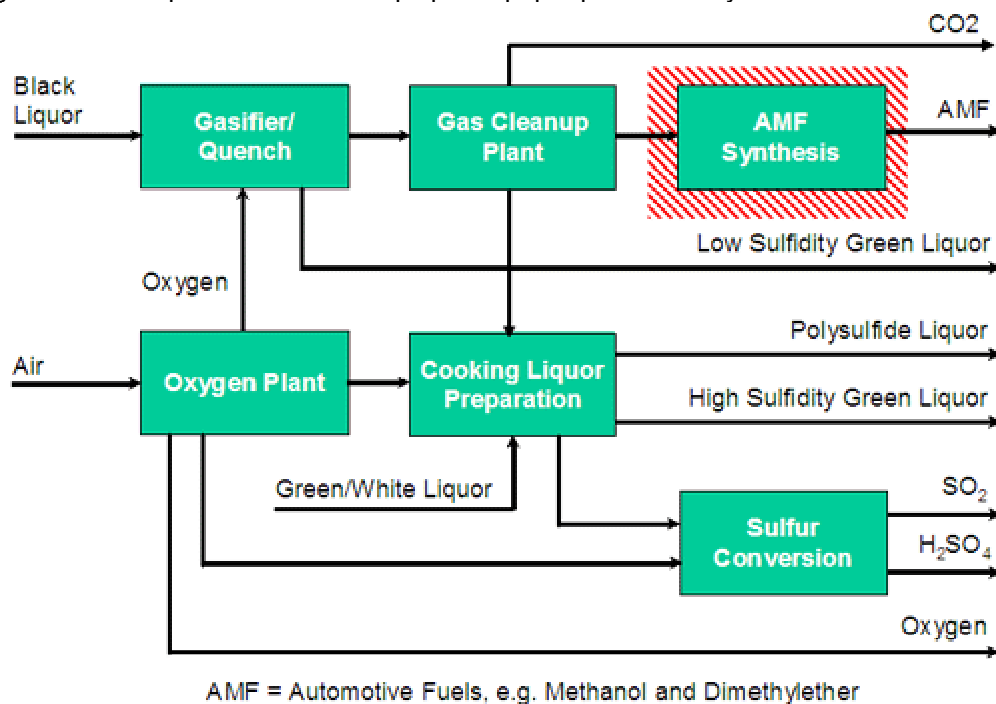
Figure 81
Schematic presentation of optimised logistics system for feedstock supply to a large centralised BTL plant via distributed biomass collection and pre-treatment with later water-borne transportation



Source: [19]

Besides economies of scale, the capital costs of BTL plants can be reduced via synergies with other processes. As commented in paragraph 5.2, the large-scale production of methanol and DME from black liquor – a residual production from pulp and paper mills, is under investigation. Such design of BTL plants would ensure not only higher overall efficiency of the combined pulp/paper & BTL manufacturing, but it would also earn synergy benefits for both production lines, owing to complex integration of processes – Figure 82 – [170].

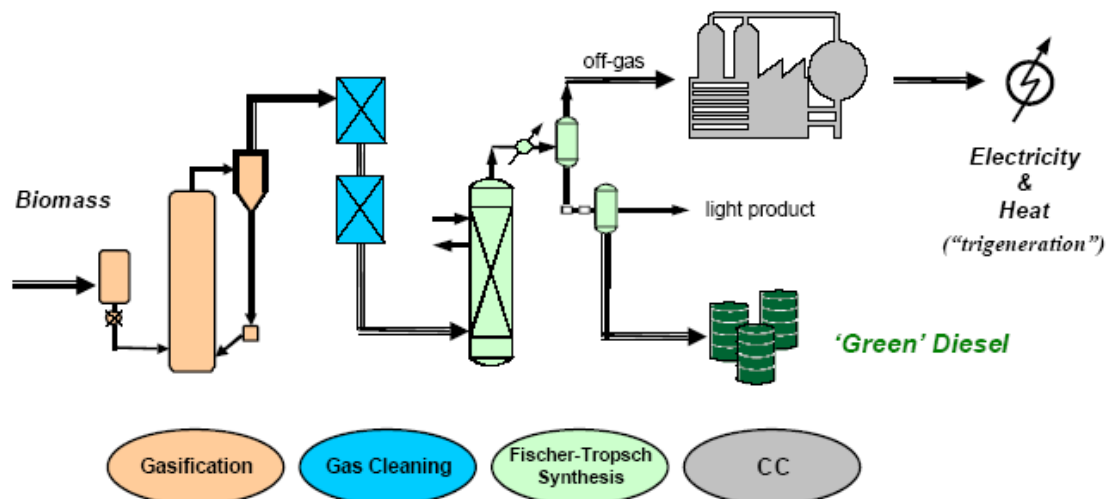
Figure 82
Integration of BTL production into the pulp and paper production cycle



Source: [253]

Another way of earning synergy benefits and thus, increasing the overall energy efficiency of BTL plants and reducing their production costs, is product integration. As indicated by Figure 32, the F-T synthesis, similar to oil refining, results in a range of products. Obviously, the market realisation of as many as possible of these products would reduce the total F-T production costs pro-rata. Besides the direct products out of F-T synthesis, the F-T (and BTL) production costs can be decreased further by finding markets for the heat, obtained as by-product from the synthesis reactions. As discussed in Annex 1, the synthesis of almost all BTL products results in the generation of significant amounts of steam. This steam can be employed either for electricity generation, or for heat generation, or for both (“tri-generation” of fuels, power and heat – Figure 83) [1, 5, 18, 135, 229].

Figure 83
Integrated concept of combined generation of BTL fuels, electricity and heat (trigeneration)



Legend: “CC” – combined cycle
Source: [19]

On equal terms, the “tri-generation” concept would ensure the largest energy efficiency and cost benefits. The realisation of the “tri-generation” concept however requires the availability of sufficient and stable heat demand nearby the BTL plant, because of the high transmission losses for steam [148].

Besides the direct costs of production, the automotive application of methanol, DME and hydrogen is associated with additional costs, related to infrastructure and vehicle on-board equipment, for example:

- An existing petrol or diesel tank at a refuelling station can be retrofitted to handle methanol for \$20,000-32,000. The capital costs of adding a methanol storage and dispensers to an existing petrol station are higher – \$55,000-100,000⁷² [3, 21, 47, 277].
- Since the automotive application of DME is still at an experimental stage, no data are basically available for the infrastructure and vehicle on-board equipment cost surcharge

⁷² The lower figure is for above-ground tank, the higher – for underground tank

for this fuel. Nevertheless, since DME has similar to LPG handling requirements, it could be assumed that the costs for DME would be similar to those for LPG. The typical conversion cost for petrol vehicles to petrol-LPG bi-fuel⁷³ vehicles is EUR 1,000-2,500 for passenger cars and light-duty vehicles [82, 296], \$4,000-5,000 for medium-duty vehicles and more than \$15,000 for buses and heavy-duty vehicles [25, 296]. The cost of small LPG stations ranges within \$25,000-40,000, while the annual maintenance costs are modest – around \$1,000 [22, 25, 82].

- Because of a number of technical and technological complexities, the cost of current hydrogen filling stations is about \$2-3 million [25, 277]. An expansion of hydrogen use would create more refuelling points, which could bring down the cost of filling stations to the range of large compressed natural gas (CNG) stations – EUR 0.5-1.0 million. Besides the refuelling infrastructure cost surcharge, the cost difference between hydrogen-powered vehicles and their conventional analogues enlarges, owing to the FC surcharge. The combined impact of high fuel distribution and powertrain costs implies a cost of about \$1 million for a FC bus on hydrogen that is roughly 3 times higher than the cost of its diesel counterpart [128].

Referring to the above facts, the calculation of the overall application costs of BTL fuels is a complex issue, which appears to need further and careful investigation.

For a number of reasons – immature technologies, more sophisticated transformation process etc. BTL fuels tend to be 2-3 times more expensive than conventional oil-derived automotive fuels. This difference could be narrowed in the future, owing to economies of numbers, economies of scale, learning curve, synergies, etc. The key components of BTL production costs, which respectively should be targeted first for optimisation, are feedstock costs and direct capital costs, as well as logistics costs. Nevertheless, preferential tax incentives for BTL fuels will be needed in any case to make them competitive to conventional oil-derived fuels.

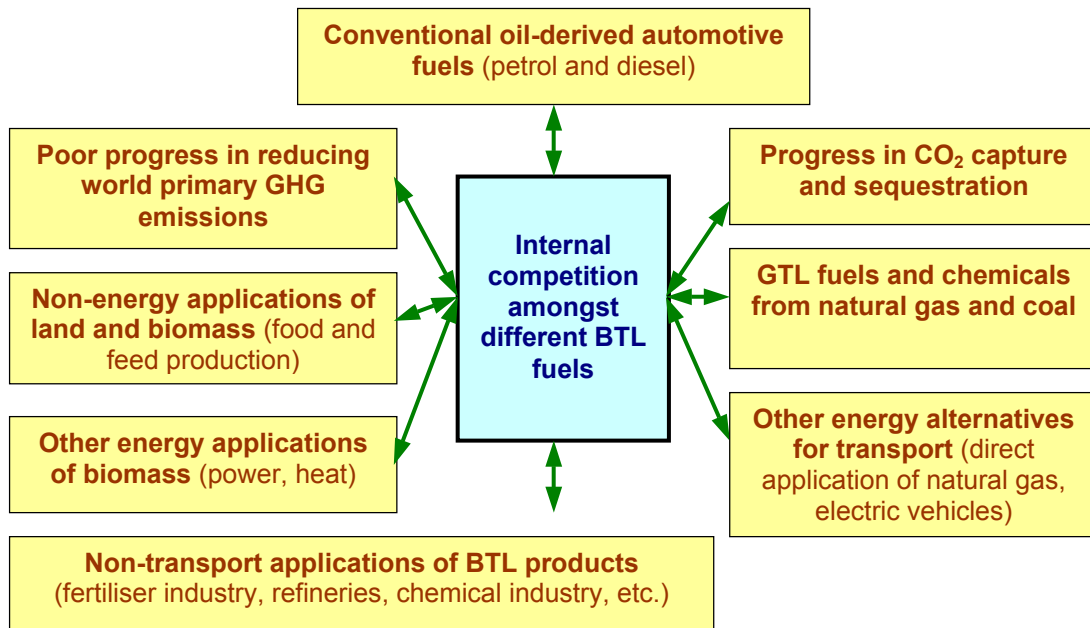
⁷³ Flexible vehicles, which can run either on petrol or on LPG.

10. MARKET ASPECTS

Based on the analysis, performed in the previous chapters, this last chapter is aiming at identifying the optimum ways in which BTL fuels could enter the market in the EU and then could enhance their market share.

As shown in Figure 84, the market for BTL fuels is inter-related and competes with other energy and non-energy markets.

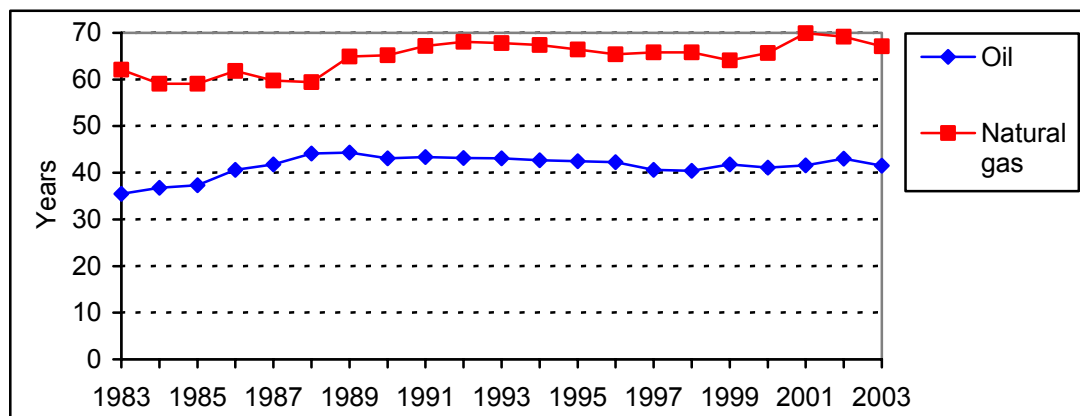
Figure 84
Competitors and factors that can hinder market penetration of BTL fuels



The first and very strong competition for BTL fuels comes from the side of oil-derived petrol and diesel – the dominant automotive fuels nowadays. Oil refining is a well-proven, developed over a number of years, highly-efficient technology, which earns great economies of scale. The room for further perfections in this technology is not yet fully explored. The qualities of petrol and diesel, along with the efficiency of oil processing, improve continuously. The sufficient availability of oil in the foreseeable future – Figure 85 and the lack of any alternative energy source & conversion technology with similar efficiency and cost-benefit parameters, give the oil refining industry additional incentives to invest in further improvements of this technology. Conversely, BTL technologies are still at a development stage, having far lower conversion efficiencies, respectively – much higher production costs than oil refining. In order to be competitive to oil derivatives, BTL products need preferential tax incentives. The market position of BTL fuels is further complicated by the fact that the majority of the existing fuel tax regulations across Europe are drawn up notably with regard to the characteristics and properties of oil-derived fuels [5]. Hence, in many occasions the taxation frameworks do not

reflect fully the specifics and advantages of BTL fuels⁷⁴. Consequently, BTL technologies for motor fuels are not attractive from a business investment point of view, at least in the near to medium future.

Figure 85
World reserves-to-production (R/P) ratio⁷⁵ for oil and natural gas within 1983-2003, (years)



Source: Adapted from [20]

An accelerated development of CO₂ capture and sequestration technologies might improve the GHG performance of oil-derived fuels and thereby strengthen their positions on the fuel market. As a result, the competitiveness of BTL fuels versus oil-based fuels will be reduced. Currently, the CO₂ capture and sequestration technologies are still at a research and development stage, hence the cost of CO₂ abatement is quite high – \$100-300 per tonne of CO₂ [8, 133, 228]. Nevertheless, it is believed that this cost range could be brought down to a much lower level that will make feasible their large-scale application [206].

BTL fuels heavily compete also with GTL fuels from other feedstocks – natural gas and coal. Besides being also more costly than oil refining, GTL production from natural gas and coal has a much longer history than that of BTL fuels, representing indeed the predecessor of BTL. Thus, unlike BTL, GTL from natural gas and coal is a commercially available technology, which reached already a certain level of maturity – current world GTL output capacity accounts for more than 43,000 bpd⁷⁶. Recently the interest in GTL production of fuels and chemicals grew fast, along with the growing demand for cleaner transport fuels. As a result, a number of new GTL projects based on natural gas and to a lesser extent – on coal, are at different stage of development. The output of single GTL plants under consideration reaches already 100,000 bpd, which is comparable with oil refineries. Even larger GTL plants with 200,000 bpd output are under investigation. Despite that various technical and technological

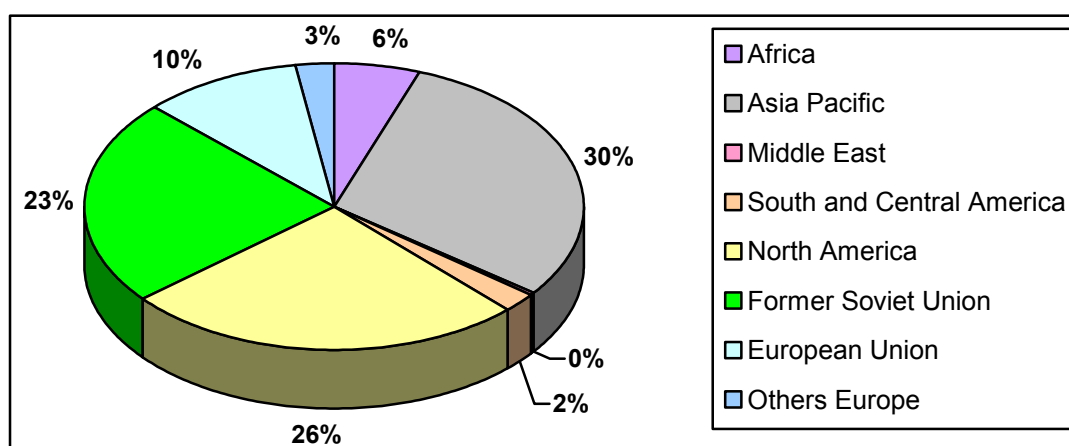
⁷⁴ For instance, the excise duty on transport fuels is typically charged per litre. Compared to oil diesel, BTL diesel has higher energy content per kilogramme, but lower energy content per litre, owing to its lower specific gravity. Hence, on equal terms an energy unit of BTL diesel is taxed at a higher rate than an energy unit of oil diesel.

⁷⁵ The R/P ratio represents the length of time (in years), obtained when the reserves at the end of the year are divided by the production in that year. The quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known reservoirs under existing economic and operating conditions, are taken as reserves in the R/P ratio calculation [20]

⁷⁶ Major plants: PetroSA's (former Moss gas) in South Africa – 30,000 bpd and Shell Bintulu in Malaysia – 12,500 bpd.

problems with these large plants are likely to appear in the beginning of their exploitation (the same consideration applies also to the first commercial BTL plants), this accelerated progress in GTL technologies is expected to bring world GTL output capacity to more than 600,000 bpd by 2010-2012 [103, 233, 244, 255, 264, 281, 284, 287, 288, 308]. However, the large-scale GTL production of transport fuels from natural gas might not contribute much to the diversity of energy supply, since most new discoveries of natural gas take place in the Middle East (Figure 63). However, with regard to GTL production based on coal, such argument cannot be raised, since the distribution of world coal reserves differs from that of crude oil – Figure 86, juxtaposed to Figure 2.

Figure 86
Breakdown of proved coal reserves by regions in the world at the end of 2003, (%)



Source: Adapted from [20]

Hence, an eventual accelerated development of GTL production of transport fuels from coal, in combination with breakthroughs and CO₂ capture and sequestration technologies [103, 162, 235, 236], could have a substantial braking impact on the progress in BTL technologies in the near to medium term.

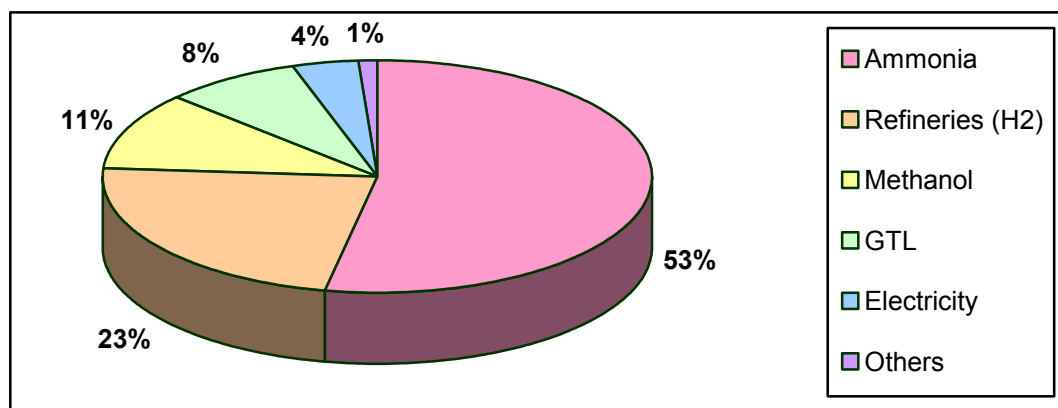
Besides the alternative production of GTL fuels from natural gas and coal, BTL fuels compete also with other energy alternatives for transport. Conventional biofuels do not appear strong opponents, since their feasible production potential is lower, while their production costs are similar to or even higher than those of BTL fuels (Figure 76). The direct applications of natural gas, however, can potentially be a real rival of BTL fuels. Despite being also a relatively “young” automotive energy alternative, natural gas has reached already a certain stage of maturity. At present, there are approximately 2 million vehicles in the world, which run on natural gas, the largest fleet being in Argentina – 750,000 vehicles. In Europe, Italy is the clear leader in promoting natural gas as an automotive fuel (90% of total natural gas fleet in the EU), with 400,000 vehicles and 340 filling stations [263, 268]. Although being a fossil fuel, natural gas burns cleaner than oil-derived fuels. Furthermore, the application of natural gas contributes to the security of energy supply. The reason is that natural gas production and

market patterns do not follow exactly those of oil [146], moreover that its reserves are projected to last longer than the reserves of oil – Figure 85. For these motives, similar to biofuels, the promotion of natural gas as an automotive fuel is also under investigation at EU level [64].

Next to natural gas, the grid-dependent electric vehicles (metro, trams and trolleys) are an extremely convenient transport solution for the main passenger flow routes in densely-populated urban areas. It is true that the infrastructure investments for certain grid-dependent transport technologies are large. Nonetheless, this can be compensated via the higher energy efficiency and environmental gains of centralised electricity production, even compared to the production of BTL fuels. These environmental benefits are basically “zero” local polluting emissions at the place of fuel consumption, very low noise levels and significantly reduced GHG emissions, if CO₂ capture and sequestration (for fossil fuels) or renewable energy sources (wind, biomass) are applied.

The production of BTL fuels competes also with other potential, non-energy applications of BTL products. Currently, more than half of world syngas production goes for ammonia manufacturing, while another quarter is used in the refineries as hydrogen – Figure 87.

Figure 87
Current breakdown of world synthesis gas market by applications

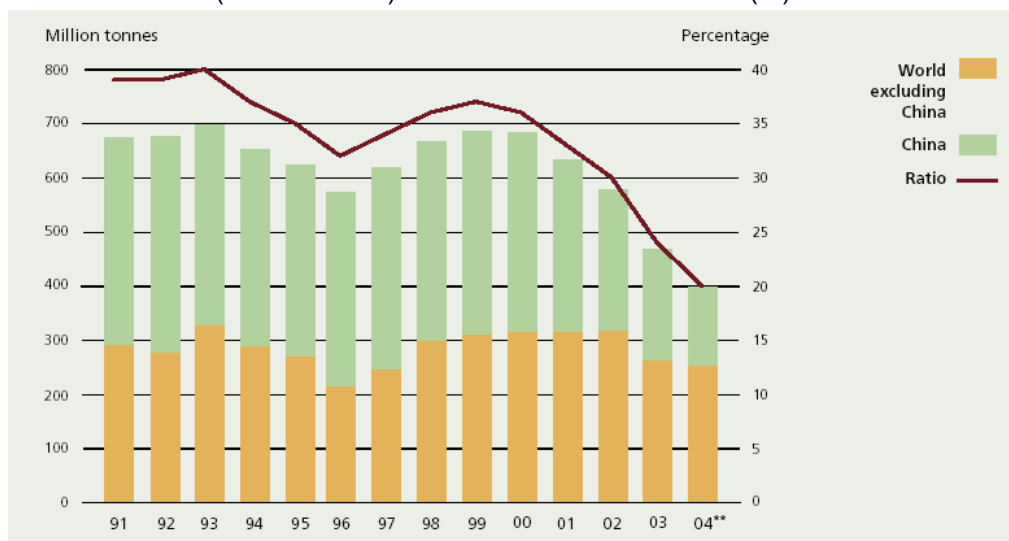


Source: Adapted from [238]

The demand for ammonia is driven mainly by the nitrogen fertiliser industry. Conversely, the market of nitrogen fertilisers depends on food markets, primarily – on cereal markets. When the supply base of cereals is tight, leading to raise in cereal prices, the demand for and prices of nitrogen fertilisers also increase. Recently, both world absolute and relative (as stocks-to-consumption ratio) cereal stocks were steadily going down, reaching historically low levels – Figure 88. This low level of world cereal stocks is projected to last at least till 2011-2013 and even further reductions are also possible. This will be due to a number of factors, mainly the continuous growth of world population, resulting in respective growth in world demand for cereals. Such a situation might create incentives to increase cereals production, which

consequently would increase the demand for and prices of nitrogen fertilisers [71, 107, 173, 257, 265, 274]. As a result, even a larger part of world syngas production might start going for manufacturing fertilisers, which would hinder further the development of GTL and BTL production of transport fuels.

Figure 88
World cereals stocks (million tonnes) and stocks-to-utilisation ratio (%) within 1991-2004

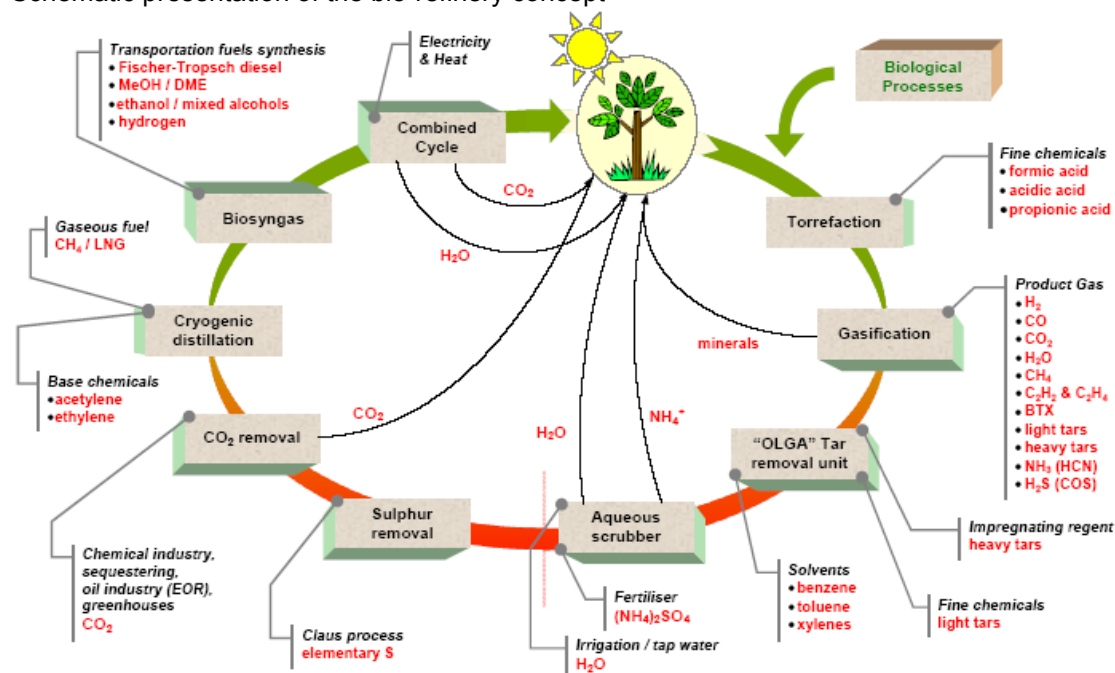


Source: [107]

The demand for hydrogen from refineries is driven indeed by the increasing world demand for specific fuels out of oil refining, mostly – diesel (Figure 52) and total middle distillates. The projected further growth in global demand for middle distillates will increase further the needs of hydrocracking, resulting in a pressure from the side of the refining sector on the syngas industry and market to supply larger quantities of hydrogen. The GTL and BTL production of transport fuels might not be therefore a competitive alternative on the future syngas market. In general, all GTL and BTL transport fuels need a kind of preferential tax incentives in order to be competitive to oil derivatives. Hence, on equal terms selling hydrogen straight to the refineries might be a more profitable option for the syngas producers in the near to medium term than manufacturing and selling profitably GTL and BTL transport fuels.

As stated in paragraph 4.2, methanol is one of the most widely used chemicals in the world [229]. Apart from the construction industry, the organic chemical industry is another main consumer of methanol, using it as a semi-finished material for producing plastics, e.g. ethylene, propylene. The demand for both ethylene and propylene is expected to undergo a significant growth by 2015 – from 90 Mt currently to more than 160 Mt for ethylene and from 50 Mt to more than 105 Mt for propylene [104, 105]. As a result, the bio-refinery concept for combined simultaneous manufacturing of various products (fuels, chemicals, plastics, etc. – Figure 89) is expected to gain a growing popularity worldwide [5, 125, 229].

Figure 89
Schematic presentation of the bio-refinery concept



Source: [13]

BTL technologies face also a strong competition from other energy applications of biomass – the generation of power and heat. Similar to the transport sector, a target for 22.1% electricity generation from renewable energy sources has been set up for the EU⁷⁷ [98]. Being the major renewable energy source, bioenergy is supposed to give the largest contribution to this renewable energy target. Recently, the promotion of renewable heating and cooling especially from biomass attracted particular attention, since both sectors were seen as key factors for the delayed progress towards achieving the 12% renewable energy target in gross inland energy consumption of the EU by 2010 [5, 61, 68, 166, 167].

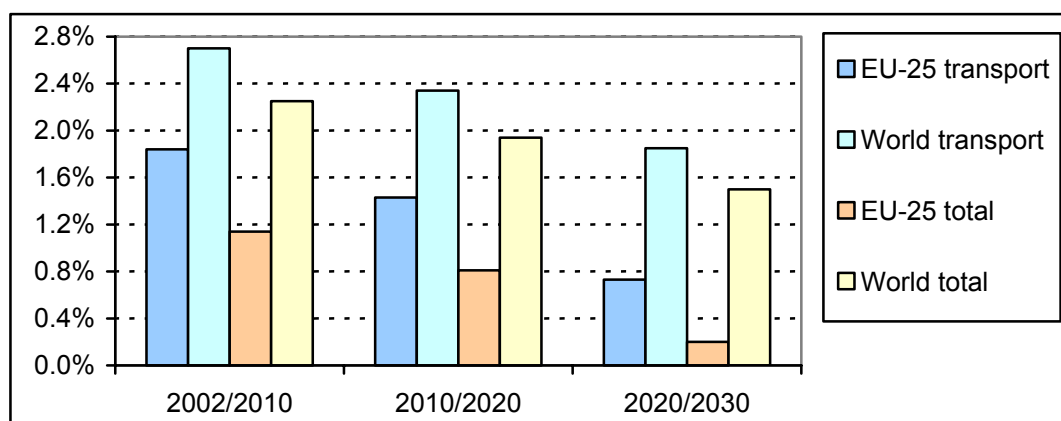
Besides these alternative bioenergy uses, BTL production of fuels heavily competes with other, non-energy applications of biomass. It is widely agreed upon that land availability is the core factor that limits the biomass potential. However, the available land can find a number of applications. The Common Agriculture Policy (CAP) secures the food supply of the EU – a core element in the EU strategy for sustainable development. Hence, a substantial part of the available land is by definition reserved for this purpose. In this context, the CAP regulations ensure also a reasonable profit for farmers [65, 66, 67, 261]. The non-food and non-energy land production (e.g. flowers, pharmaceutical plants, wood for construction, etc.) normally has higher value than bioenergy production and thus, it is more competitive on the land market. Bioenergy interacts also with other socio-economic factors – land use, visual changes of landscape, impacts on biodiversity, etc. Thus, biomass and bioenergy should be always

⁷⁷ Down to 21% for EU-25, due to lower national targets negotiated by the NMS-10.

considered within a broader framework of policy objectives and priorities [5, 109, 124, 136, 144, 155, 169, 172, 220, 249].

In addition, the development of BTL technologies could be significantly hampered and even stopped by poor progress in the primary reduction of world GHG emissions⁷⁸. The large GHG savings of BTL fuels are a main reason for their promotion. In exchange, these GHG benefits result in greater fuel expenditure, due to the higher cost of BTL fuels compared to conventional fuels. Unlike local-pollutants, the impact of GHG is not localised by areas, but it affects global climate. If the reduction of GHG in one part of the world is accompanied by a larger increase of GHG emissions in another part of the world, the net global GHG balance will be still negative. Unfortunately, the baseline projections foresee exactly such a perspective – both transport and total GHG emissions will grow much faster in the world than in the EU – Figure 90. If no progress in reducing GHG emissions at world level is achieved, the incentives for developing BTL fuels in the EU and respectively – paying that higher cost, might be seriously weakened [211, 212].

Figure 90
Projected annual increase in CO₂ emissions from transport and in total in EU-25 and in the world within 2002-2030, (%)



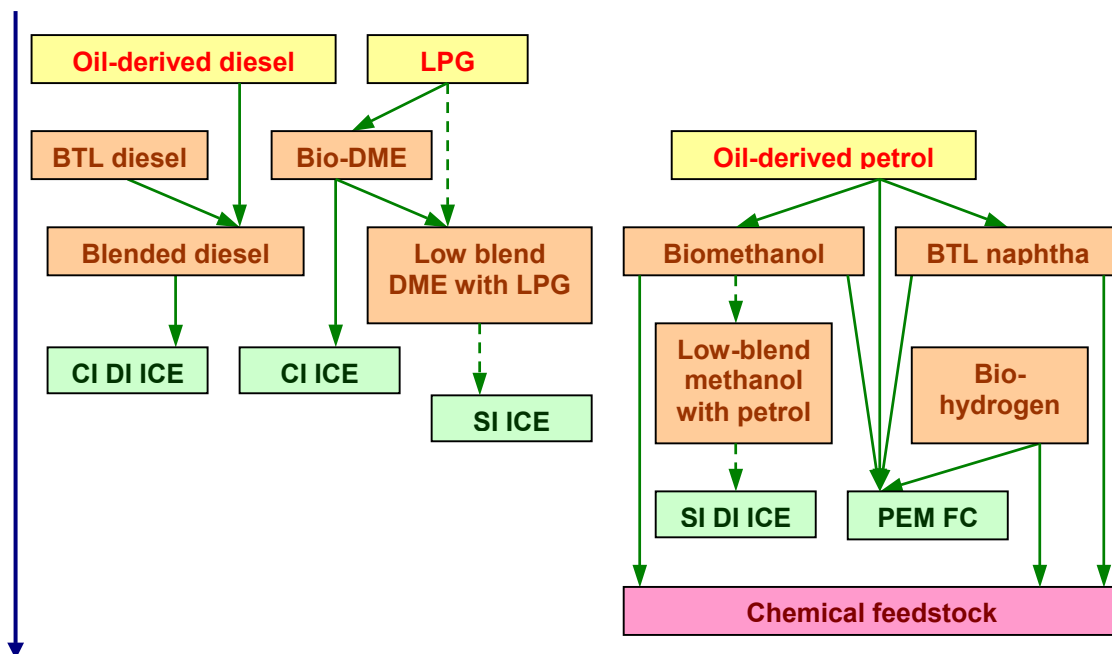
Source: Adapted from [138]

Finally, besides the above external rivals, BTL fuels are in mutual competition with each other, indeed for the use of the prospective availability of bio-syngas. This internal competition ensues partly from different national approaches, e.g. at present biomethanol and DME are considered predominantly in Sweden, while BTL diesel is investigated mainly in Germany. However, this competition comes also from the trade-offs amongst performance characteristics of various BTL fuels in terms of energy efficiency, environmental performance and costs, identified in the previous chapters.

Based on the above reasons, several evolutionary pathways for market penetration of BTL fuels in the EU are proposed in Figure 91.

⁷⁸ Without CO₂ capture and sequestration.

Figure 91
Possible evolutionary pathways for market penetration of BTL fuels



Amongst all BTL fuels, BTL diesel is the only one, which can enter the automotive fuel market even today without any additional infrastructure or vehicle costs. BTL diesel will benefit from its full compatibility with oil-derived diesel and CI DI ICE technology, as well as with the existing fuel handling and distribution infrastructure. Considering the high cost of BTL diesel and the over-linear reduction in local polluting emissions from BTL diesel / oil diesel blends, it will be more appropriate to blend BTL diesel with oil diesel than to use it in pure form. With regard to the reduction of local pollutants, the introduction of such blended fuel may first take place in densely-populated urban areas, e.g. for public transport.

The penetration of bioDME can be facilitated in regions, where an LPG infrastructure already exists. Hence, the use of DME will be promising on niche markets, where LPG is already known as an automotive fuel – either in the form of LPG/DME blends for SI ICE (eventually!), or as a pure fuel for CI ICE. Similar to BTL diesel, another alternative for DME is densely-populated urban areas, where a substantial and concentrated fuel demand exists, which will reduce the investments for building dedicated DME distribution infrastructure. The excellent performance of DME with regard to local-polluting emissions (the lack of NOx/PM trade-off) will give further incentives for promoting its utilisation in urban areas. However, unlike BTL diesel, DME does not appear to have the potential to develop from a niche fuel to a widespread fuel even in the longer term, notably due to these infrastructure constraints. This does not mean that DME could not get a large share on specific (regional) markets.

As an introductory step, methanol might be blended in very low concentrations with petrol, if fuel quality standards allow such blending and if there is no public opposition to such blends. Nevertheless, in the short-term biomethanol can find a safer automotive use via replacing

fossil methanol in biodiesel production from oilseeds. In such a way biodiesel will become a 100% renewable fuel, which will have a certain, however modest impact on the security and diversity of energy supply of the EU via a slight reduction in natural gas imports. Enhancing the utilisation of biomethanol as a chemical feedstock, either again by substituting fossil methanol, or by covering new demand, might have a much larger reduction impact on natural gas imports in the near to medium term. This is also valid for BTL naphtha, which represents a higher quality chemical feedstock than oil-derived naphtha and thus, has the potential to replace it to a great extent.

Considering the time needed to improve FC technologies, the use of naphtha and methanol as hydrogen carriers for FC can be regarded as a medium term option. Naphtha and methanol can benefit from the already existing distribution infrastructure for petrol, which can be adjusted at no or relatively small cost. In such a way naphtha and methanol can be used as transition steps towards the potential direct automotive use of hydrogen in FC.

Besides the mutual competition amongst different BTL fuels, their automotive application faces strong competition from conventional oil-derived fuels, GTL fuels from natural gas and coal, direct use of natural gas as a motor fuel and electricity-powered vehicles. Beyond the transport sector, BTL fuels compete with other non-energy applications of BTL semi-finished materials and end products, with other energy applications of the available biomass resource and with non-energy uses of land and biomass. The progress in CO₂ capture and sequestration technologies, as well as a poor progress in the primary reduction of GHG emissions worldwide may also prevent the development of BTL technologies. Hence, the selection of potentially promising market niches for BTL fuels should take into account a number of inter-related factors and trade-offs in pursuing a sustainable energy system. The optimum positioning of different BTL fuels – BTL diesel, DME, methanol, BTL naphtha and hydrogen – has to be performed on a case-by-case basis.

11. CONCLUSIONS

Based on the analysis in the previous chapters, the following conclusions can be drawn about the production and application of BTL fuels in the EU by 2010 and beyond:

- ✓ BTL technologies represent thermal transformation of woody or herbaceous biomass via gasification techniques and synthesis reactions into a range of liquid and gaseous fuels and chemical feedstocks. The BTL fuels with potential automotive application are BTL naphtha, BTL diesel, methanol, di-methyl-ether (DME) and hydrogen.
- ✓ Obtaining high-quality synthesis gas from biomass for further transformation into fuels appears to be the crucial step in the BTL fuel chains, which step needs the largest amount of further research and development work.
- ✓ At present, the production and utilisation of BTL fuels is at an experimental stage. It is not feasible to expect significant contribution from BTL fuels to the automotive fuel supply by 2010.
- ✓ BTL fuels have the potential to add to the security and diversity of energy supply of the EU beyond 2010. This contribution will be larger than that of conventional bioethanol and biodiesel from agricultural feedstock, owing to larger land availability for BTL feedstock and higher biofuel yield per hectare. The larger share of middle distillate yield in BTL synthesis compared to that in oil refining is a particular advantage with regard to the trends in the transport fuel consumption in the EU.
- ✓ The application of BTL fuels results in higher gross energy consumption than that of oil-based petrol and diesel. The net energy consumption of BTL fuels is however lower than that of oil-derived petrol and diesel, owing to the closed carbon / CO₂ cycle of biomass. The energy use of BTL fuel chains is also lower than that of conventional bioethanol and biodiesel.
- ✓ The application of BTL fuels earns large GHG savings over that of oil-based petrol and diesel, owing to the closed carbon / CO₂ cycle of biomass. It ensures also GHG benefits over the use of conventional bioethanol and biodiesel.
- ✓ BTL fuels ensure great reductions in local-polluting emissions compared to oil-derived petrol and diesel. The emissions of local pollutants from BTL fuels are also lower than those from conventional bioethanol and biodiesel.
- ✓ The production costs of BTL fuels are 2-3 times higher than those of oil-derived petrol and diesel. Owing to progress in technologies and process optimisation, this difference can be narrowed. However, preferential tax incentives will be still needed for BTL fuels to be competitive to oil-based petrol and diesel on the automotive fuel market. Nevertheless, BTL fuels have the potential to become cheaper than conventional bioethanol and biodiesel.
- ✓ Besides being in a mutual competition amongst each other, the production and application of BTL fuels heavily competes with oil-derived and other alternative energy

solutions for transport, as well as with other energy and non-energy applications of BTL and gas-to-liquid products, land and biomass. Hence, the selection of promising market niches for BTL fuels should take into account a number of inter-related factors.

- ✓ Amongst all BTL fuels, BTL diesel is the only one that is ready to the market even today, preferably blended with oil-derived diesel.
- ✓ In the medium-term DME can be a promising substitute on niche markets of diesel and to a lesser extent – of petrol when blended with LPG. The compatibility of DME and LPG handling can facilitate its market penetration.
- ✓ Methanol does not appear as a promising fuel for internal combustion engine anylonger. However, in the medium to long-term methanol, together with BTL naphtha, might be used as hydrogen carriers for fuel cells, paving the way towards direct use of bio-hydrogen. These three BTL products find also a number of non-transport and non-energy uses.

Summarising the above conclusions, Figure 92 presents the relative ranking of BTL fuels compared to fossil fuels with regard to security and diversity of energy supply, energy efficiency, GHG emissions, local polluting emissions and costs.

Figure 92

Relative ranking of BTL fuels vice-versa fossil fuels with regard to security and diversity of energy supply, energy efficiency, GHG emissions, local polluting emissions and costs

	F-T naphtha	F-T diesel	Methanol	DME	Hydrogen
Security & diversity of supply	++	++	++	++	++
Energy efficiency	-- / -	-- / -	-- / -	-- / -	- / 0
GHG emissions	++	++	++	++	++
Local-polluting emissions	++	++	++	++	++
Costs	-- / -	-- / -	-- / -	-- / -	-- / -

Legend: (++) Significant benefits; (+) Moderate benefits /none/; (0) No impact / similar performance; (-) Moderate penalties; (--) Significant penalties;

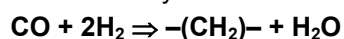
12. ANNEXES

ANNEX 1

Technology brief of GTL synthesis⁷⁹

The common expression of the production of GTL (F-T) fuels and chemicals from synthesis gas is presented in Equation 1

Equation 1: Generalised presentation of F-T synthesis

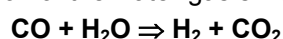


Since the reaction from Equation 1 is exothermic, significant amounts of steam are released – 20-25% of total chemical energy [19, 130, 183, 223, 229]. The beneficial utilisation of this steam for power and/or heat generation can improve significantly the overall energy efficiency of GTL processing.

The type and the breakdown of products from F-T synthesis depend on the applied temperatures, pressure and catalysts. Petrol and olefins are mainly obtained at 330-350°C (high-temperature GTL synthesis), using iron (Fe) catalysts. At 180-240°C (low-temperature GTL synthesis), pressure 10-60 bar and with the employment of cobalt (Co) catalysts, mostly middle distillates and waxes are produced [16, 18, 19, 43, 139, 140, 183, 229, 233, 252, 288]. The breakdown of fractions can be controlled to a certain extent, concentrating the yield predominantly within the range C5-C20 [252].

As it can be seen from Equation 1, optimum GTL yield is achieved at 2:1 proportion between H₂ and CO in the synthesis gas, since each mole of carbon monoxide reacts with 2 moles of hydrogen. As indicated from Figure 19, the H₂/CO ratio in the synthesis gas from biomass is much lower, due to the large oxygen content of biomass (Figure 12). Hence, the H₂/CO ratio has to be adjusted. This is achieved via the so-called water-gas shift (WGS) reaction, where the excess amount of CO is further reacted with steam to form hydrogen (and carbon dioxide as a by-product) [16, 19, 183] – Equation 2.

Equation 2: Generalised presentation of the water-gas shift (WGS) reaction



Similar to GTL synthesis (Equation 1), the WGS reaction is exothermic and steam credits can be also exploited. In addition, the WGS reaction gives the opportunity to reduce GHG emissions from BTL fuels (see Annex 5), since the resulting carbon dioxide could be captured and sequestered.

⁷⁹ The major challenge in the production of BTL fuels is the production of syngas with sufficient cleanliness, i.e. as high as possible content of carbon monoxide and hydrogen. The syntheses of various fuels are generally well-known, mature and thoroughly described technologies [5]. Hence, the description of GTL synthesis is performed only to the extent of the necessary minimum.

The WGS reaction is different for high-temperature and for low-temperature GTL synthesis. Iron catalysts, used in high-temperature F-T synthesis, show significant WGS activity and the H₂/CO ratio is adjusted in the synthesis reactor. In the case of cobalt catalysts, employed in low-temperature GTL synthesis, the H₂/CO ratio has to be adjusted beforehand [18].

Figure 19 and Equation 2 indicate that roughly between 40% and 70% of the hydrogen that is employed in GTL processing based on syngas from biomass comes in fact from the water via the WGS reaction. Hence, sufficient quantities of water at BTL plants have to be secured.

Besides the right proportion between hydrogen and carbon monoxide, the cleanliness of syngas is the second major preliminary condition for efficient GTL synthesis. F-T catalysts, especially the cobalt ones, are very sensitive even to small amounts of impurities [19, 139, 170]. Hence, before being fed to the F-T reactor, the syngas has to be properly cleaned from all impurities, which can affect the efficient performance of catalysts. The main syngas impurities and their tolerance level are presented in Figure 93.

Figure 93
Main syngas impurities and tolerances for F-T and methanol synthesis

Impurities tolerance	Sulphur	Halides	Nitrogen
F-T synthesis	1.00-0.02 ppm	10 ppb	10 ppm vol. NH ₃ 0.2 ppm vol. NO _x 10 ppb HCN
Methanol synthesis	<0.5 ppm vol. (<0.1 preferred)	0.001 ppm vol.	n.a.

Source: [26, 229]

Over the years the F-T synthesis underwent a significant development. Various generations of commercially-operated F-T reactors are shown in Figure 94.

Methanol synthesis generally requires higher pressure than F-T synthesis – 50-350 bar [130, 229]. Currently the low-pressure (at 50-100 bar) methanol synthesis at 220-280°C, employing copper oxide (CuO) or zinc oxide (ZnO) catalysts is the favourite option [45, 120, 115, 141, 170, 229]. Since copper catalysts are very sensitive to site-blocking poisons such as sulphur, the gas-phase sulphur concentration has to be kept very low – Figure 93. The reaction (Equation 3) is highly exothermic and generates significant amount of steam.

Equation 3: Generalised presentation of methanol production from syngas

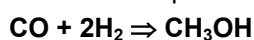
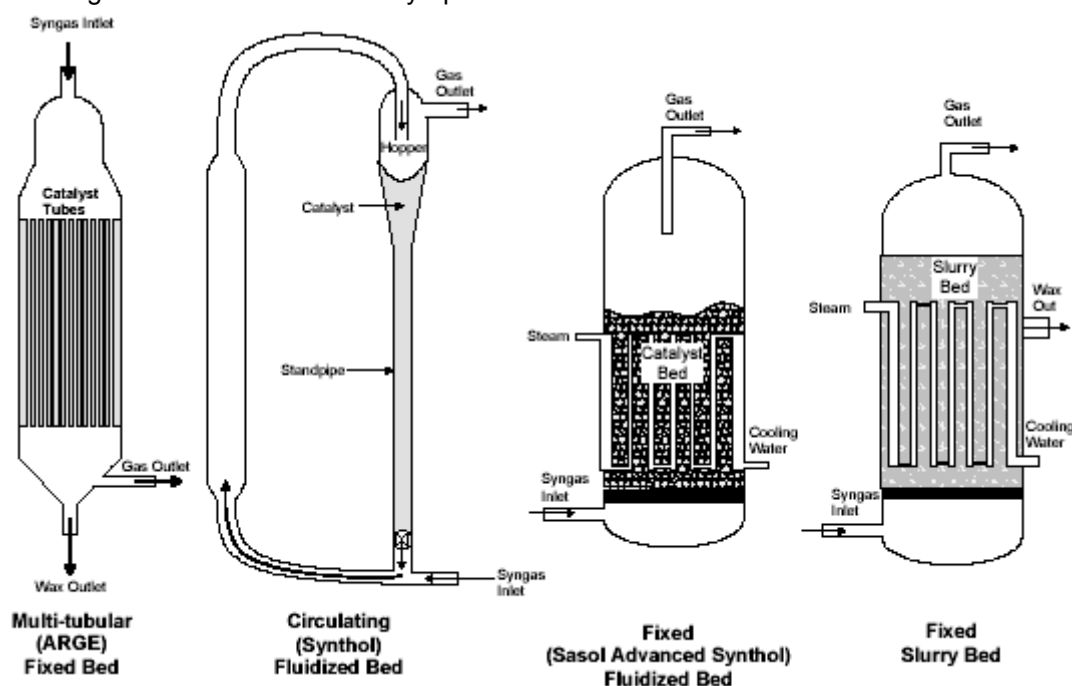


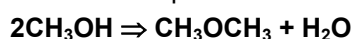
Figure 94
Various generations of commercially-operated F-T reactors



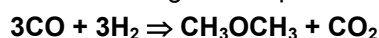
Source: [229]

DME is obtained either via methanol de-hydration (conventional route – Equation 4), or via direct synthesis (a novel route – Equation 5). The second option is more energy efficient and thus the preferred one, since it involves just one process instead of two – methanol synthesis (Equation 3) preceding methanol de-hydration. The direct DME synthesis typically requires pressure of 60-70 bar and temperatures of 210-300°C. Again, similar to methanol synthesis, the reaction is highly exothermic, generating ≈40 bar steam [1, 141, 170, 171, 229].

Equation 4: Generalised presentation of DME production via methanol de-hydration [280]



Equation 5: Generalised presentation of straight DME production from synthesis gas

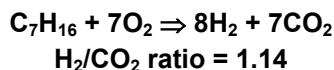


In principle, ethanol could also be obtained via GTL synthesis. Nevertheless, from a practical point of view this does not make much a sense, because the conversion efficiency is far lower than those of the alternative ethanol routes via neat fermentation or via hydrolysis with later fermentation. In addition, the fermentation routes still indicate significant unexplored potential, unlike e.g. biodiesel production from oil extraction and trans-esterification. The GTL pathway for ethanol is therefore not considered as a feasible alternative in the foreseeable future [229].

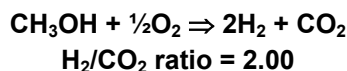
The direct pathway to hydrogen from synthesis gas is the WGS reaction – Equation 2. The usually considered indirect pathways via partial oxidation or steam reforming, which involve

hydrogen intermediate carriers – BTL naphtha and biomethanol, are presented in Equation 6 to Equation 9.

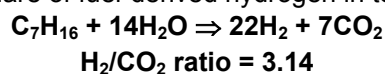
Equation 6: Generalised presentation of indirect hydrogen production from naphtha⁸⁰ via partial oxidation and H₂/CO₂ ratio



Equation 7: Generalised presentation of indirect hydrogen production from methanol partial oxidation and H₂/CO₂ ratio

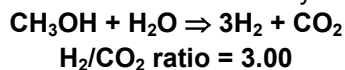


Equation 8: Generalised presentation of indirect hydrogen production from naphtha via steam reforming, H₂/CO₂ ratio and share of fuel-derived hydrogen in total hydrogen yield



Share of fuel-derived hydrogen in total hydrogen yield = 36.4%

Equation 9: Generalised presentation of indirect hydrogen production from methanol via steam reforming, H₂/CO₂ ratio and share of fuel-derived hydrogen in total hydrogen yield



Share of fuel-derived hydrogen in total hydrogen yield = 66.7%

As it can be seen from Equation 6 to Equation 9, the structure of hydrogen yield depends on the employed feedstock and on the reforming agent. In all cases a mole of higher hydrocarbon (naphtha) gives a higher absolute yield of hydrogen. However, in the case of partial oxidation this is achieved at the expense of larger CO₂ emissions, respectively – lower H₂/CO₂ yield. In the case of steam reforming, 2/3 of the hydrogen yield from higher hydrocarbons comes in fact from the steam (water). In principle, this is an advantage, since the cost (price) of water is generally much lower, even negligible compared to that of naphtha. On the other hand, relying so heavily on water-derived hydrogen could be a significant disadvantage for any potential automotive applications. The storage of such large quantities of water aboard the vehicles most probably would be an important problem, in view of the significantly reduced passengers and cargo-carrying capacity.

⁸⁰ The length of the naphtha carbon chain is taken on average from the data from Figure 31.

ANNEX 2

Background data for calculating BTL potentials in EU-25

The notion “utilisable land” introduced for the purposes of the analysis incorporates the commercially exploitable forest (commercial forest) and the arable land:

- Forest is defined as land with tree crown cover (or equivalent stocking level) of more than 10% and area of more than 0.5 ha. The trees should be able to reach a minimum height of 5 m at maturity in situ. It may consist either of closed forest formations where trees of various storeys and undergrowth cover a high proportion of the ground; or of open forest formations with a continuous vegetation cover in which tree crown cover exceeds 10%. Young natural stands and all plantations established for forestry purposes which have yet to reach a crown density of 10% or a tree height of 5 m are included under forest, as they are areas normally forming part of the forest area which are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest. The commercially exploitable forest is a forest where any legal, economic, or specific environmental restrictions do not have a significant impact on the supply of wood. This includes areas where, although there are no such restrictions, harvesting is not taking place, e.g. areas included in long-term utilisation plans or intentions. Apart from the commercial forest, there is also non-commercial forest, where legal, economic or specific environmental restrictions prevent any significant supply of wood. The last type of woody surface is the so-called other wood land, which is a land either with a tree crown cover (or equivalent stocking level) of 5-10% of trees able to reach a height of 5 m at maturity in situ; or a crown cover (or equivalent stocking level) of more than 10% of trees not able to reach a height of 5 m at maturity in situ (e.g. dwarf or stunted trees) and shrub or bush cover [85].
- Arable land comprises the land worked regularly, generally under a system of crop rotation. In case of combined cropping of a given parcel, the main area is split pro-rata between the crops concerned [86].

The projections for the automotive diesel and middle distillates demand within 2010-2030 are taken from [75]. The assumed internal production for transport purposes is calculated as follows:

- The production in 2000 from [50] is extrapolated with a growth coefficient 0.3%, which was the average annual growth of the EU refining capacities over 1992-2001.
- The breakdown of oil refining fractions is taken from Figure 45, since it is assumed that no further increase in the diesel and middle distillate fractions is economically feasible in the EU, referring to Figure 46.
- 60% of diesel production is assumed to go for transport purposes, which was roughly the share of transport in total diesel consumption by 2001, according to [50].

- 90% of the total kerosene & jet fuel production is assumed to go for transport purposes, which was roughly the share of transport in total kerosene & jet fuel consumption by 2001, according to [50].

In the next stage, by having the prospective automotive demand and the internal supply of diesel and middle distillates for transport, the net imports of diesel and total middle distillates, driven by transport, are derived.

The BTL yields are derived based on Figure 24, Figure 32 and Figure 42. More specifically:

- The moisture content of feedstocks is taken at 15%. The gross wood and herbaceous yields are reduced pro-rata.
- The share of diesel in total GTL yield is assumed at 60%. No hydrocracking is considered, since it increases production costs.
- The share of jet fuel is assumed as 15%. No hydrocracking is considered either.
- Unlike oil refining, the whole BTL yield of middle distillates is assumed to go for transport application.

ANNEX 3

Criteria for selecting WTW studies and limitations in the WTW comparative analysis

The following preliminary conditions and limitations are considered in the comparative WTW analysis:

- Since BTL fuels are still at an experimental stage, only prospective fuel & engine chains are investigated. The time horizon of the studies found is 2010 (2012 for [48]). Predictions with a sufficient extent of certainty in longer time horizon, e.g. by 2020, were not found.
- WTW studies with practical orientation are used only. Purely theoretical and academic research works are not referred.
- Only WTW studies, where at least one BTL fuel is examined both absolutely and relative to other conventional (oil-based) and alternative (GTL from natural gas or coal, or conventional biofuels) fuel pathways, are considered. WTW studies, which do not examine BTL fuels, are not included, due to possible substantial differences in the preliminary conditions.
- The efficiency comparisons are performed for equivalent fuel & engine technologies, where possible. The impossibility in some cases comes from the different stage of development of technologies, i.e. BTL processing is a new, immature technology, while oil refining is a well-proven technology.
- Advanced SI DI ICE and CI DI ICE are examined, as well as their hybrid configurations. The FC technology is also included in the analysis for selected fuels. The hybrid FC option is not considered, since hybridisation offers modest additional efficiency benefits to FC, if any at all. The combination of FC stack with hybrid equipment aboard the vehicle seems little feasible, since it would account for an impractically large share of the carrying capacity of the vehicle. The additional weight might even fully offset the efficiency benefits from FC hybridisation.
- The hydrogen routes include two basic variants – direct production (centralised or onsite production of hydrogen from natural gas or biomass) or on-board reforming from selected appropriate fuels and feedstocks (petrol, naphtha, methanol and ethanol). Centralised hydrogen production from finished products (e.g. methanol), all hydrolysis pathways based on electricity and on-board reforming of gaseous fuels (e.g. DME) are not considered, due to low energy and GHG efficiency, and low economic feasibility.

ANNEX 4

Summary of findings about WTW energy use for various fuel & engine pathways, adapted from recent WTW studies (% differences from the corresponding baselines). The actual baseline figures (in MJ/km) are given in brackets, where available

Fuel ↓	Feedstock ↓	Study → Base fuel → ↓ Engine →	EUCAR-CONCAWE-JRC [55]			GM-LBST [111]			Ecotraffic (2001) [48]		
			Petrol SI DI ICE	Diesel CI DI ICE	Petrol FC	Petrol SI DI ICE	Diesel CI DI ICE	Petrol FC	Petrol SI DI ICE	Diesel CI DI ICE	Petrol FC
Petrol	Oil	SI DI ICE	(2.14)	7.0	15.7	(2.45)	11.9	18.4	Baseline	25.0	18.4
Petrol	Oil	SI DI ICE-H	-13.1	-7.0	0.5	-21.6	-12.3	-7.2	-19.4	0.8	-4.5
Diesel	Oil	CI DI ICE	-6.5/-2.8	(2.00)	8.1/12.4	-10.6	(2.19)	5.8	-20.0	Baseline	-5.3
Diesel	Oil	CI DI ICE-H	-23.4	-18.0	-11.4	-24.9	-16.0	-11.1	-33.6	-17.1	-21.4
CNG	Natural gas	SI PI ICE	0.9/17.3	8.0/25.5	16.8/35.7	1.2/29.8	13.2/45.2	19.8/53.6	-4.3	19.6	13.3
LNG	Natural gas	SI PI ICE	14.0/17.8	22.0/26.0	31.9/36.2	13.1	26.5	33.8	-2.6	21.7	15.3
F-T diesel	Natural gas	CI DI ICE	-	-	-	34.3/37.1	50.2/53.4	58.9/62.3	27.9	59.8	51.4
F-T diesel	Natural gas	CI DI ICE-H	-	-	-	11.4/14.7	24.7/28.3	31.9/35.7	6.0	32.6	25.6
F-T diesel	Ligno-cellulose	CI DI ICE	76.2/83.6	88.5/96.5	103.8/112.4	55.1/74.7	73.5/95.4	83.6/106.8	63.9	104.9	94.1
F-T diesel	Ligno-cellulose	CI DI ICE-H	44.4/51.4	54.5/62.0	67.0/75.1	30.2/46.9	45.7/64.4	54.1/73.9	36.1	70.1	61.1
Biodiesel	Oilseeds	CI DI ICE	53.3/82.7	64.0/95.5	77.3/111.4	-	-	-	-	-	-
Biodiesel	Oilseeds	CI DI ICE-H	25.2/50.5	34.0/61.0	44.9/74.1	-	-	-	-	-	-
Bioethanol	Sugar & starch	SI DI ICE	101.4/154.7	115.5/172.5	133.0/194.6	-	-	-	-	-	-
Bioethanol	Sugar & starch	SI DI ICE-H	74.3/121.0	86.5/136.5	101.6/155.7	-	-	-	-	-	-
Bioethanol	Ligno-cellulose	SI DI ICE	145.3	162.5	183.8	-	-	-	75.4	119.3	107.7
Bioethanol	Ligno-cellulose	SI DI ICE-H	113.1	128.0	146.5	-	-	-	41.4	76.8	67.5
DME	Natural gas	CI ICE	22.9/43.0	31.5/53.0	42.2/65.4	-	-	-	0.5	25.4	18.8
DME	Ligno-cellulose	CI ICE	66.4/66.8	78.0/78.5	92.4/93.0	-	-	-	30.4	63.0	54.4
Petrol	Oil	FC	-13.6	-7.5	(1.85)	-15.5	-5.5	(2.07)	-15.5	5.6	Baseline
Naphtha	Oil	FC	-15.9	-10.0	-2.7	-19.6	-10.0	-4.8	-	-	-
F-T Naphtha	Natural gas	FC	-	-	-	23.7/26.1	38.4/41.1	46.4/49.3	-	-	-
Bioethanol	Sugar & starch	FC	-	-	-	52.7/81.2	70.8/102.7	80.7/114.5	-	-	-
Bioethanol	Ligno-cellulose	FC	-	-	-	94.7/221.6	117.8/259.8	130.4/280.7	47.9	84.9	75.1
Methanol	Natural gas	FC	11.2/27.6	19.0/36.5	28.6/47.6	6.1/9.4	18.7/22.4	25.6/29.5	-7.0	16.3	10.1
Methanol	Natural gas	DMFC-H	-	-	-	-	-	-	6.6	33.3	26.2
Methanol	Coal	FC	34.6	44.0	55.7	-	-	-	-	-	-
Methanol	Ligno-cellulose	FC	43.0	53.0	65.4	26.5/79.2	41.6/100.5	49.8/112.1	22.5	53.2	45.1
Methanol	Ligno-cellulose	DMFC-H	-	-	-	-	-	-	40.4	75.6	66.3
CGH2	Natural gas	FC	-25.7/0.9	-20.5/8.0	-14.1/16.8	-26.9/-11.8	-18.3/-1.4	-13.5/4.3	-10.6	11.7	5.8
CGH2	Coal	FC	-4.7	2.0	10.3	-	-	-	-	-	-
CGH2	Ligno-cellulose	FC	-13.6/-1.4	-7.5/5.5	0.0/14.1	-13.9/0.8	-3.7/12.8	1.9/19.3	14.2	42.7	35.2
LGH2	Natural gas	FC	-5.6/7.0	1.0/14.5	9.2/23.8	-2.9/18.8	8.7/32.9	15.0/40.6	26.7	58.4	50.1
LGH2	Ligno-cellulose	FC	9.8	17.5	27.0	-	-	-	31.9	64.9	56.2

ANNEX 5

Summary of findings about WTW emissions of GHG for various fuel & engine pathways, adapted from recent WTW studies (% differences from the corresponding baselines). The actual baseline figures (in grCO₂eq./km) are given in brackets, where available

Fuel ↓	Feedstock ↓	Study Base fuel → ↓ Engine →	EUCAR-CONCAWE-JRC [55]			GM-LBST [111]			NETL [157]
			Petrol SI DI ICE	Diesel CI DI ICE	Petrol FC	Petrol SI DI ICE	Diesel CI DI ICE	Petrol FC	Diesel CI DI ICE
Petrol	Oil	SI DI ICE	(162)	6.6	15.7	(188)	13.3	19.0	-
Petrol	Oil	SI DI ICE-H	-13.0	-7.2	0.7	-20.7	-10.2	-5.7	-
Diesel	Oil	CI DI ICE	-6.2/-1.9	(152)	8.6/13.6	-11.7	(166)	5.1	(316)
Diesel	Oil	CI DI ICE-H	-22.8/-19.1	-17.8/-13.8	-10.7/-6.4	-25.5	-15.7	-11.4	-
CNG	Natural gas	SI PI ICE	-21.6/-4.9	-16.4/1.3	-9.3/10.0	-21.3/3.7	-10.8/17.5	-6.3/23.4	-
LNG	Natural gas	SI PI ICE	-8.0/-7.4	-2.0/-1.3	6.4/7.1	-10.6	1.2	6.3	-
F-T diesel	Natural gas	CI DI ICE	-	-	-	5.3/8.0	19.3/22.3	25.3/28.5	4.9/28.1
F-T diesel	Natural gas	CI DI ICE-H	-	-	-	-11.7/-10.6	0.0/1.2	5.1/6.3	-
F-T diesel	Coal	CI DI ICE	-	-	-	-	-	-	60.3/89.0
F-T diesel	Ligno-cellulose	CI DI ICE	-90.7/-87.7	-90.1/-86.8	-89.3/-85.7	-92.6/-85.1	-91.6/-83.1	-91.1/-82.3	-79.6
F-T diesel	Ligno-cellulose	CI DI ICE-H	-92.6/-89.5	-92.1/-88.8	-91.4/-87.9	-93.6/-87.2	-92.8/-85.5	-92.4/-84.8	-
Biodiesel	Oilseeds	CI DI ICE	-61.7/-38.9	-59.2/-34.9	-55.7/-29.3	-	-	-	-
Biodiesel	Oilseeds	CI DI ICE-H	-68.5/-50.0	-66.4/-46.7	-63.6/-42.1	-	-	-	-
Bioethanol	Sugar & starch	SI DI ICE	-66.0/-13.0	-63.8/-7.2	-60.7/0.7	-	-	-	-
Bioethanol	Sugar & starch	SI DI ICE-H	-70.4/-24.1	-68.4/-19.1	-65.7/-12.1	-	-	-	-
Bioethanol	Ligno-cellulose	SI DI ICE	-79.0/-74.7	-77.6/-73.0	-75.7/-70.7	-	-	-	-
Bioethanol	Ligno-cellulose	SI DI ICE-H	-81.5/-77.8	-80.3/-76.3	-78.6/-74.3	-	-	-	-
DME	Natural gas	CI ICE	-4.9/15.4	1.3/23.0	10.0/33.6	-	-	-	-
DME	Ligno-cellulose	CI ICE	-94.4/-91.4	-94.1/-90.8	-93.6/-90.0	-	-	-	-
Petrol	Oil	FC	-13.6	-7.9	(140)	-16.0	-4.8	(158)	-
Naphtha	Oil	FC	-17.9	-12.5	-5.0	-19.1	-8.4	-3.8	-
F-T Naphtha	Natural gas	FC	-	-	-	-3.7/-3.2	9.0/9.6	14.6/15.2	-
Bioethanol	Sugar & starch	FC	-	-	-	-26.6/-83.5	-16.9/-81.3	-12.7/-80.4	-
Bioethanol	Ligno-cellulose	FC	-	-	-	-61.7/-97.3	-56.6/-97.0	-54.4/-96.8	-
Methanol	Natural gas	FC	-10.5/6.2	-4.6/13.2	3.6/22.9	-19.1/-14.9	-8.4/-3.6	-3.8/1.3	-
Methanol	Coal	FC	80.9	92.8	109.3	-	-	-	-
Methanol	Ligno-cellulose	FC	-91.4/-88.9	-90.8/-88.2	-90.0/-87.1	-93.1/-91.0	-92.2/-89.8	-91.8/-89.2	-
CGH2	Natural gas	FC	-42.6/-22.2	-38.8/-17.1	-33.6/-10.0	-46.8/-34.0	-39.8/-25.3	-36.7/-21.5	-
CGH2	Coal	FC	11.1	18.4	28.6	-	-	-	-
CGH2	Ligno-cellulose	FC	-93.8/-91.4	-93.4/-90.8	-92.9/-90.0	-95.7/-84.6	-95.2/-82.5	-94.9/-81.6	-
LGH2	Natural gas	FC	-25.9/-16.7	-21.1/-11.2	-14.3/-3.6	-26.2/-8.5	-16.9/3.6	-12.7/8.9	-
LGH2	Ligno-cellulose	FC	-95.1	-94.7	-94.3	-	-	-	-

ANNEX 6

EURO 3 and EURO 4 emission standards for passenger cars (PC) and light-duty vehicles (LDV), (g/km)

	Vehicles / Pollutants	CO	THC	NOx	HC+NOx	PM
E	PC and LDV – petrol, (1)	2.30	0.20	0.15	-	-
U	PC and LDV – diesel, (1)	0.64	-	0.50	0.56	0.05
R	LDV – petrol, (2)	4.17	0.25	0.18	-	-
O	LDV – diesel, (2)	0.80	-	0.65	0.72	0.07
	LDV – petrol, (3)	5.22	0.29	0.21	-	-
3	LDV – diesel, (3)	0.95	-	0.78	0.86	0.10
E	PC and LDV – petrol, (1)	1.00	0.10	0.08	-	-
U	PC and LDV – diesel, (1)	0.50	-	0.25	0.30	0.025
R	LDV – petrol, (2)	1.81	0.13	0.10	-	-
O	LDV – diesel, (2)	0.63	-	0.33	0.39	0.040
	LDV – petrol, (3)	2.27	0.16	0.11	-	-
4	LDV – diesel, (3)	0.74	-	0.39	0.46	0.060

Legend: (1) – vehicle weight below 1,305 kg;

(2) – vehicle weight 1,305-1,760 kg;

(3) – vehicle weight more than 1,760 kg;

CO – carbon monoxide

THC – total hydrocarbons

NOx – nitrogen oxide

HC – hydrocarbons

PM – particulate matters

Source: Adapted from [77]

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