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RENEW

Renewable fuels for advanced powertrains

Integrated Project

Sustainable energy systems

***WP 5.4 Technical Assessment
Scientific report***

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Abstract

This document presents the results of work in work package 4. As the work package itself, this document is divided into two sections:

- Section 1: “Suitability for Internal Combustion Engines” (Task 5.4.1)
- Section 2: Technical Assessment (Task 5.4.2)

The results achieved in those two sections are described by the respective partners in the following chapters.

The work in task 5.4.1 (which is described in section 1) was carried out by the automobile partners Volkswagen AG, Daimler Chrysler AG and Volvo Technology. The results of task 5.4.2 (described in section 2) were elaborated by the technical experts Institute for Energy and Environment, Zentrum für Sonnenenergie und Wasserstoffforschung, Volkswagen AG, Paul Scherer Institut who were supported by experts from (Total, EdF, BP).

SECTION 1

SUITABILITY FOR INTERNAL COMBUSTION ENGINES

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Content

Abstract	3
Content	5
1 Introduction.....	7
1.1 List of investigated fuels	9
1.2 Analysis of properties	10
2 Material tests	16
2.1 Elastomer material	17
2.2 Metal coated material	20
3 Emissions and consumptions	24
3.1 Test results of engines equipped with Unit injectors.....	24
3.2 Investigation of influence of Cetan No.....	27
3.3 Test results of engines equipped with Common rail injection systems.....	29
3.4 Summary of the passenger car tests.....	31
3.5 Test results of future advanced combustion engines (HCCI)	32
3.6 Test Results of commercial-vehicle engines with DME fuel	38
3.7 Considerations on biomethane and ethanol	38
4 Cold start behaviour	40
4.1 Experiments	40
4.2 Emission test results	42
4.3 Starting phase consideration	45
5 Safety and toxicity aspects	52
5.1 Introduction	52
5.2 Toxicity	52
5.2.1 Summary of the toxicity for the different fuels	52
5.2.2 Need for further work	53
5.3 Environmental	53
5.3.1 Emission to water and ground.....	53
5.3.2 Emission to the air.....	53
5.4 Safety.....	53
5.4.1 Physical properties for the fuels	53
5.4.2 Summary of safety aspects.....	54
5.5 Summary and conclusions	54
6 Impact on payload	56
6.1 Energy density.....	56

6.2	Payload	58
6.3	Cruising range	58

0 Introduction

In the RENEW project a variety of liquid and gaseous fuels produced from biomass has been examined. These fuels are produced by different processes, which are with the exception of the enzymatic production route for ethanol (ABENGOA, SP 4, WP 4.1), all based on a thermochemical conversion of the biomass to syngas, followed by a synthesis step to produce the final fuel. For most of the processes a life cycle analysis has been made (ESU SP 5, WP 5.2) from which energy efficiency, emissions and environmental impacts for the different processes are available.

In addition to the production application aspects are of paramount importance. Although all of the fuels examined in the RENEW project are suitable for vehicle application, each of the fuels has distinct advantages and disadvantages. All fuels are primarily restricted to either spark ignited or compression ignited engines but some of the fuels however seems to be suitable also for future advanced combustion processes like CCS, HCCI and CAI.

Fuel Type	Spark ignition	Compression ignition	Advanced Combustion
Fischer Tropsch Diesel	–	x	(x)
Fischer Tropsch Naphtha	–	(x)	x
DME	–	x	(x)
Ethanol	x	–	–
Methane	x	–	–

Table 1: Fuel Types in Renew

One of the important criteria for an assessment as automotive fuel is the **potential to reduce emissions and fuel consumption**. As this potential depends also on engine technology and especially on the exhaust gas aftertreatment technology a differentiation between older technologies, which represent most of the current vehicle fleet, and modern state of the art vehicles is reasonable.

The fuels should provide the same good **driveability** behaviour than modern conventional fuel. This has to hold also for extreme climate like **low and hot temperatures** and high altitudes.

The fuels should be **compatible with materials**, typically used in engines and tank systems. They must not cause corrosion or abrasion.

Some of the fuels (Methane and DME) are not liquid at standard condition. **Storage density** of gaseous fuels are generally lower. This causes lower **cruising ranges** or lower **payloads**. Gaseous fuels need a dedicated **distribution infrastructure**. Blending with conventional liquid fuels is not possible. Although a bivalent operation of NG and gasoline is possible and because of the restricted range of dedicated NG vehicle most common, the emission benefits of NG can be best realized in dedicated NG vehicles. Even though it would be technically possible to have bivalent operation of DME together with conventional diesel fuel it is most relevant to have dedicated DME-fuelled engines. This is due to the relatively complex and expensive injection system of diesel engines.

Environment and safety aspects are important especially in case of accidents. The **toxicity** of the fuels is an important criteria at normal or accidental exposure.

Table 2 gives an overview over the considered evaluation criteria

- Emission reduction potential
- Fuel consumption reduction potential
- Suitability with modern aftertreatment technologies
- Suitability for advanced combustion processes
- Drivability
 - Cold start, cold weather behaviour
 - Hot weather behaviour
 - Deposit formation, sludge formation
- Compatibility with materials
 - Compatibility with polymer materials
 - Corrosion behaviour
 - Lubricity and wear
- Storage properties
 - Energy density
 - Payload
 - Cruising range
- Infrastructure aspects
 - Suitable for blends with conventional fuels
 - Additional infrastructure necessary
- Dedicated vehicles necessary or reasonable
- Environmental and safety aspects
 - Biodegradability
 - Flammability, risk of explosion
- Toxicity

Not all of the RENEW fuels have been tested with engine and vehicle tests.

The focus in the RENEW project was on liquid diesel fuels produced by the Fischer-Tropsch process. Only UET was able to provide the necessary amounts of fuel for engine tests. The **UET FT-diesel** is produced in fixed bed tubular reactors with a commercial Cobalt catalyst. Most of the UET fuels tested were straight run FT diesel. UET and CERTH also produced Diesel by hydrocracking of the waxy fraction of the FT-product and delivered this fuel separately.

Both the straight run diesel and the hydrocracked diesel are not supposed to be the final fuel for a completely integrated BTL facility. Nevertheless these fuels are representative for the current state of art BTL technology. A comparison with commercial GTL fuels showed that the engine and vehicle test results (New European Driving Cycle, NEDC-tests) of UET-BTL were quite similar.

Production of DME is not a part of SP3 and therefore commercial DME, blended with different amount of methanol and water, which are the most important contaminates, have been used in the Volvo study.

AICIA and Abengoa produced **ethanol** via an enzymatic route and via a gasification/synthesis route. Engine or vehicle test of Ethanol was not planned in the RENEW project.

PSI produced **methane** from syngas. The distribution of decentralised produced bio - methane will be done by feeding it to the local natural gas grid. No direct fuelling of natural gas vehicles is intended. Hence engine or vehicle test of bio methane was not planned in the RENEW project.

To asset also ethanol and methane results from in-house experience for these fuels were supplemented. It is assumed that the fuel quality of the processes developed in the RENEW project will in the end not differ much from the current ethanol or natural gas standards.

0.1 List of investigated fuels

The following table summarizes the fuels investigated within Renew and a list of performed tests with the corresponding fuel sample.

Fuel	Producer	Analysis of properties	Material tests	Engine tests	Cold start
BTL P2 low FBP	UET	x	x	x	
BTL P4 high FBP	UET	x	x	x	
BTL P7	UET	x	x	x	x
BTL P10	UET	x	x	x	x
BTL P11	UET	x	x	x	
BTL Hydrocracked	UET	x		x	
BtL Hydrocracked	Certh/NICE	x		x	
BTL P5 Naphta	UET	x	x	x	
BTL P6 Naphta	UET	x	x	x	
BTL with different Specs	CUTEK	x		Insufficient amount	
BTL with different Specs	TUV	x		Insufficient amount	
DME	External producer	X	-	X	-
Bio Ethanol	AICIA			No engine tests were planned in theRENEW project	
Bio Methan	PSI			No engine tests were planned in theRENEW project	

Table 2: Overview of fuels and tests investigated in Renew

0.2 Analysis of properties

The chemical analysis for the different Fischer-Tropsch fuels produced in the RENEW project was done by the ITN. ITN reported the results in four Reports, in which deliverables D1.13.1.1 ... D1.13.1.3 cover the results for fuels from SP1, mainly UET fuels, and D 2.6.6 covers fuels from SP2, mainly from TU Vienna.

A compilation of all fuel data in a standardized form can be found in an excel fuel database. The detailed reports from ITN and the data base can be downloaded from the RENEW web site. An overview of the various fuels and suppliers gives table Table 3.

Sample	Type of fuel	Producer	Remarks	Analysed by
P1	FT-Fuel	UET		ITN
P2	FT-Fuel	UET	Tested in 2004 by DC = low FBP sample	ITN
P4	FT-Fuel	UET	Tested in 2004 by DC = high FBP sample	ITN
P3	FT-Fuel	UET	Kerosene High	ITN
P5	FT-Fuel	UET	Naphta for Regienov	ITN
P6	FT-Fuel	UET	Naphta for Regienov	ITN
P7	FT-Fuel	UET	Kerosene High	ITN
P8	FT-Fuel	UET	Kerosene High	ITN
P9	FT-Fuel	UET	HC-Diesel wide range	ITN
P10	FT-Fuel	UET	Kerosene	ITN
P11	FT-Fuel	UET	Diesel	ITN
P12	FT-Fuel	UET	Naphta for Regienov	ITN
P13	FT-Fuel	UET	Diesel	ITN
P14	FT-Fuel hydrocracked	CERTH	Kerosen high, Hydrocracked by CERTH	ITN
P15	FT-Fuel hydrocracked	CERTH	Naphta, Hydrocracked by CERTH	ITN
P16	FT-Fuel hydrocracked	UET	Kerosen high, Hydrocracked by UET	ITN
P17	FT-Fuel hydrocracked	CERTH	Diesel, Hydrocracked by CERTH	ITN
P18	FT-Fuel hydrocracked	UET	Naphta, Hydrocracked by UET	ITN
P19	50% FT-Fuel hydrocracked	UET	Naphta, Hydrocracked by UET, blended with UET straight run naphta 50%	ITN
P20	FT-Fuel	UET	Diesel , Additive testing	ITN
FT-30/250	FT-Fuel	TU Viena	Diesel	ITN
FT-30/280	FT-Fuel	TU Viena	Diesel	ITN
FT015	FT-Fuel	TU Viena	Kerosene high	ITN
FT-022	FT-Fuel	TU Viena	Diesel	ITN
FT-025	FT-Fuel	TU Viena	Diesel	ITN
FT-026	FT-Fuel	TU Viena	Diesel	ITN
DF 200-360	FT-Fuel	TU Viena	Diesel	ITN
FT-Prod Cutec	FT-Fuel	CUTEC	Diesel	ITN

Table 3: Overview of fuels and their suppliers

ITN tested the fuels according the international standardized test procedures, which were developed for conventional diesel fuels. Most of these procedures are meaningful and important also for synthetic fuels. Some loose their meaning however for synthetic fuels (e.g. the cetan index). Further on, when comparing the properties of the synthetic fuels to the European norm for Diesel (EN 590), it should be kept in mind, that these fuels will form a new class of fuels, for which some adaptation of the EN 590 will be necessary. One of the main advantages of the FT-fuels is the absence of aromatics. With zero aromatics the density of the FT-fuels are necessarily out of the specification of EN 590.

A simple scheme to categorize the fuels uses the boiling range:

- Naphtha Initial boiling point < 100°C
- Kerosene Initial boiling point > 100 °C, < 180°C
- Diesel Initial boiling point > 180°C

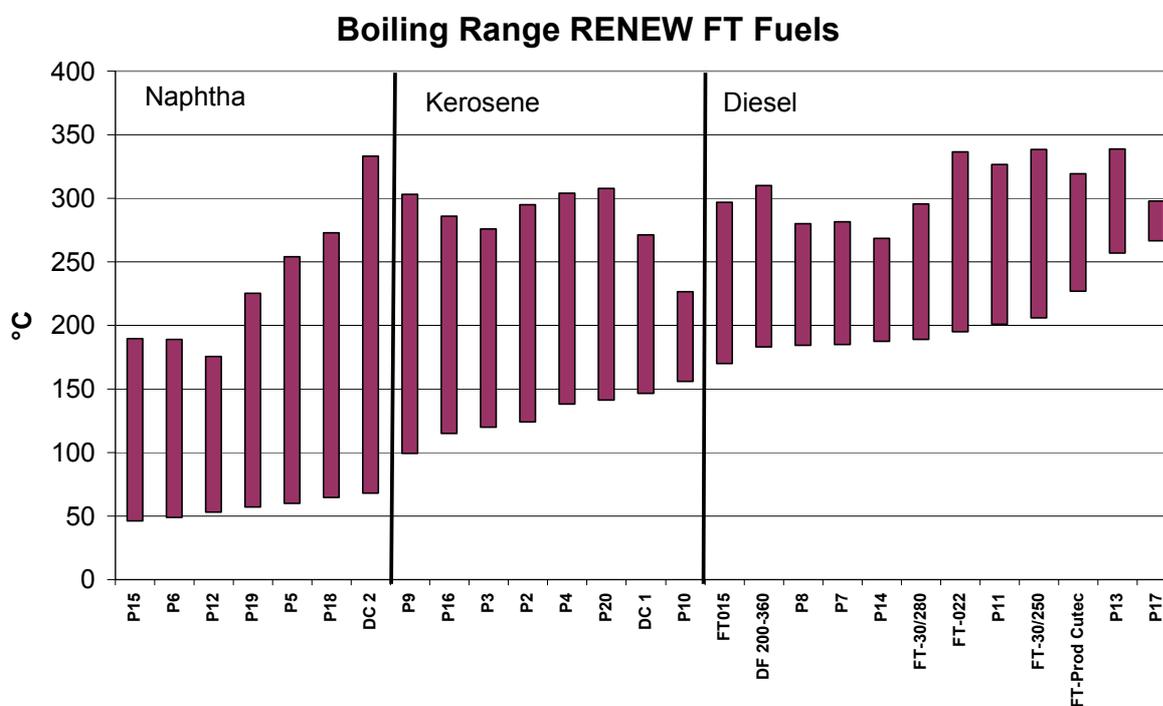


Figure 0-1: Boiling Range RENEW fuels

It should however be mentioned that this scheme was not applied strictly throughout the project. Some samples, which were categorized as Diesel, had a lower initial boiling point as planned (e.g. DC2). Also a boiling range higher than 200°C is not typical for conventional naphtha. None of the fuels used the upper boiling range between 330 °C and 380 °C, which is typical for conventional diesel. Reason for this is the formation of wax crystals if the fuel molecules get too long. Wax precipitation at working temperature plugs the fuel filters. This is measured by the cold filter plugging point (CFPP). The required CFPP (EN 590: -20°C) limits the upper boiling range of FT-fuels.

Another categorizing scheme could be the processes which were used to produce the fuels. Most of the fuels were straight run FT-fuels. These fuels use the primary synthesis product and the only finishing treatment is to cut out the suitable boiling range by distillation. There were also fuels tested, which were produced from FT-wax by hydrocracking. CERTH and UET produced hydrocracked BTL from wax produced at the UET facility.

Finally the producers used different synthesis processes and catalyst.

- UET used a fixed bed reactors with a commercial Co-catalyst
- TU –Vienna used a slurry reactor with an experimental catalyst
- CUTEC used a fixed bed reactor with various catalysts

It could be interesting to compare the fuel properties from the producers. It should however be noted, that the processes at TU-Vienna and at CUTEC were in an early stage of development. So the properties of these fuels will change more, when the processes advance.

The **density** of the UET fuels lie between 0,7 g/cm³ and 0,785 g/cm³ and therefore below the lower limit of EN 590 (> 0,82 g/cm³). Density for these low aromatic fuels is mainly influenced by the boiling range (Figure 0-1). The samples of the TU-Vienna show somewhat higher density, corresponding to the higher content of aromatics.

The boiling range influences also the **flash point** and the low temperature behavior. A low initial boiling point, which is typical for the naphtha and kerosene type fuels, leads to an unacceptable low flash point (Figure 0-2). **This is a safety criterion.** To comply with the EN 590 specs (> 55) the initial boiling point should be greater than 180°C. If for new combustion processes like HCCI naphtha type fuels are necessary, the vehicle should take provision for the enlarged fire risk.

A correlation between the final boiling point and the **CFPP** could not be found ($R^2 = 0,0014$). Some of the UET fuels show low CFPP values (e.g. P6: -50°C) untypical for FT-Fuels. One reason could be the alcohol content, which was not analyzed by ITN in the straight run fuels.

The final boiling point is weakly correlated to the **lubricity** ($R^2 = 0,3948$). Higher contents of high boiling components lead to lower (better) HFRR values.

Correlation Flash Point and Initial Boiling Point

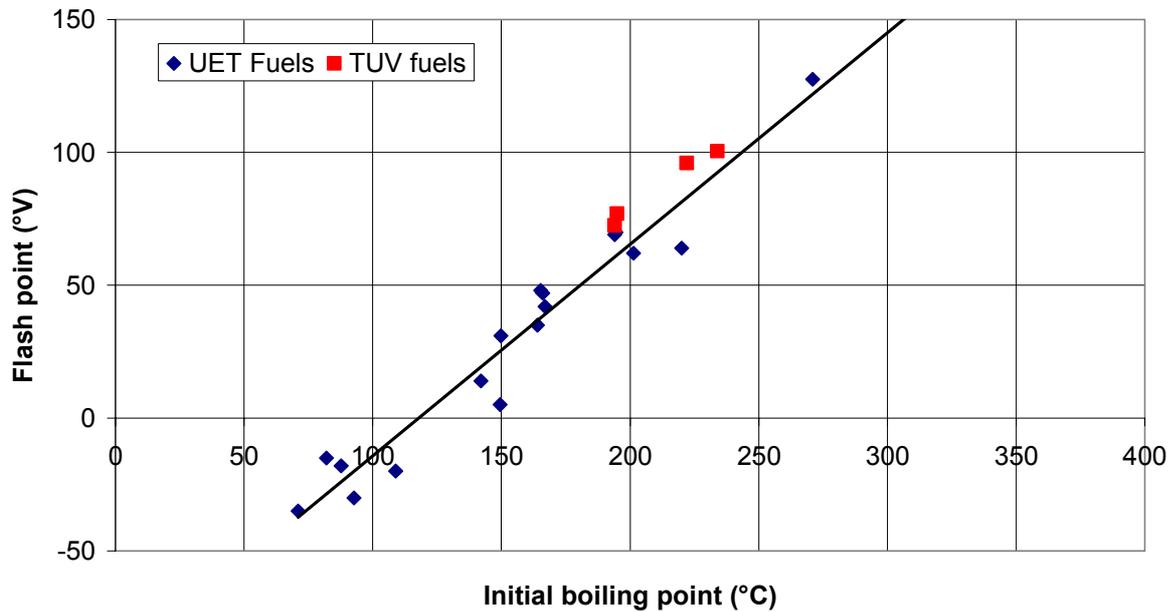


Figure 0-2: Correlation flash point and initial boiling point

Correlation Density and Center of Boiling Range

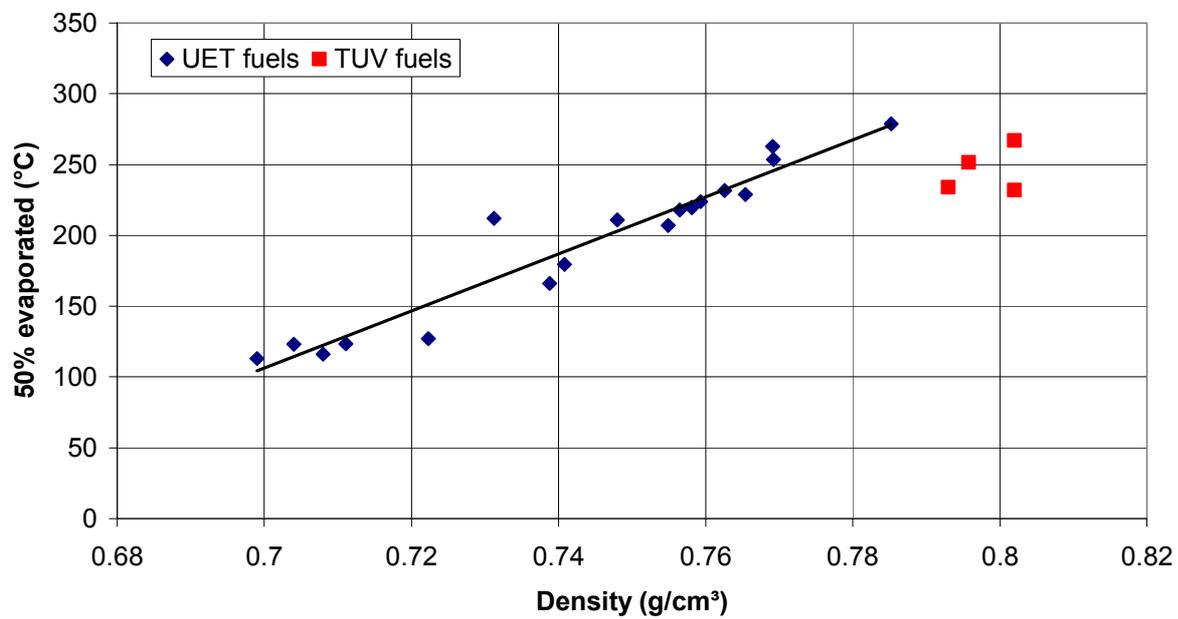


Figure 0-3: Dependency of the fuel density of the center of boiling range

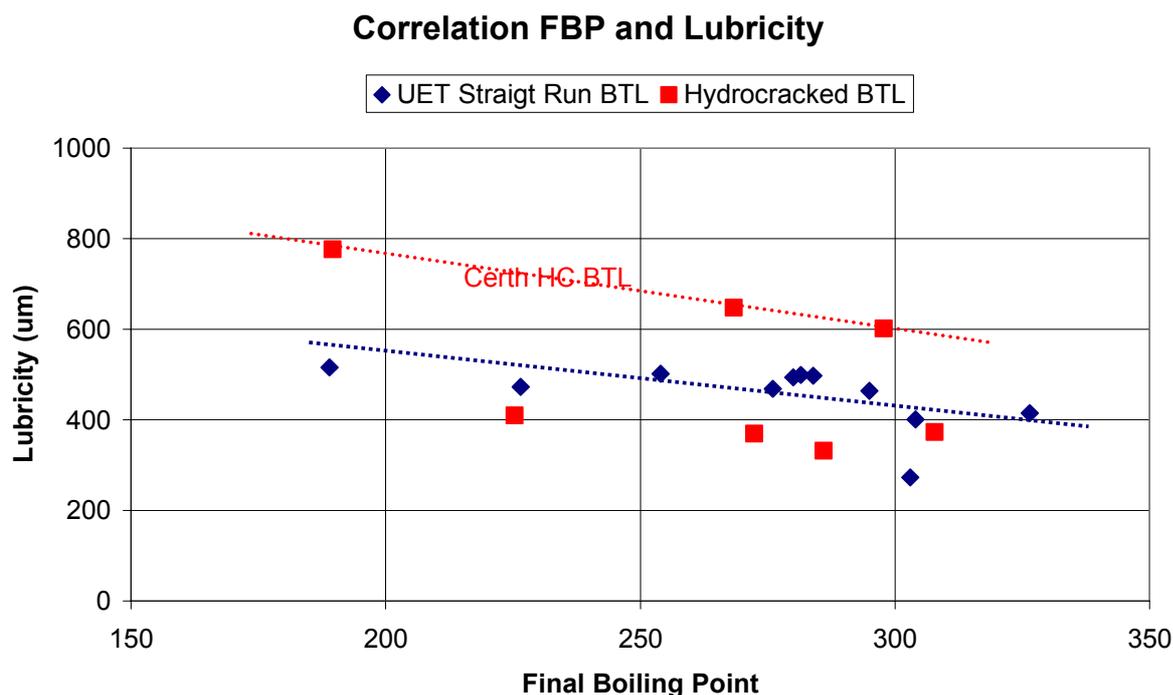


Figure 0-4: Correlation FBP and lubricity

The **colorific values** of the UET fuels lie between 42,6 and 43,9 MJ/kg showing no correlation to the density. The TU-Vienna fuels have lower calorific values (41,9 MJ/kg).

The **n-paraffin content** of the UET fuels are high (66,6 .. 88,58 %) leading to cetan numbers above 70 ($R^2 = 0,5811$). Next important component class in the UET straight run fuels are **olefins**. Unfortunately ITN did not analyze for **alcohols**. From DC analyses the straight run fuels contain some percentage of oxygen containing compound, mostly alcohols.

The high n-paraffin content can also be found in the hydrocracked fuel from UET. Obviously the hydrocracking process used by UET had not isomerisation property. The n-paraffin content of the hydrocracked fuels from CERTH is considerable lower (8 ..28%).

From the TUV fuels only one data for the n-paraffin content is available. It is remarkable low for a FT-fuel (23,5 %). The early products from TUV showed quite high aromatics (up to 10%).

The fuel from CUTEK is purely **iso-paraffinic**.

The **total aromatic content** of the UET fuels, both straight run and hydrocracked is generally low (<1 %). The TUV process however produced significant amounts of aromatics (up to 10 % from which are 5,6% poly-aromatics).

The same holds for the **sulfur content**. Because sulfur poisons the FT catalyst, generally low levels should be expected. UET fuels have sulfur content < 5 ppm, with exception of the two naphtha fuels delivered for Regienov (P5 = 9 ppm S, P6 = 6 ppm S).

The TUV fuels showed surprisingly high sulfur content (between 21 ppm and 184 ppm S).

As for experimental processes and fuels could be expected, some fuels were significantly out of specifications in some important fuel parameter. This does not mean that these processes are not able to produce appropriate fuels. The process parameters should however be optimized and observed. Some noticeable out liners are:

- High water content maybe caused by contamination during transport (P5)
- Generally low lubricity of the UET fuels. This could be overcome with appropriate additives
- Low oxidation stability of the hydrocracked products from the UET process

The compatibility of the fuels to materials used in the fuel system will be described in the following chapters.

1 Material tests

New fuels have to proof, that they are compatible to all typical materials in the vehicles fuel system and engine. Beside the main function as a combustible energy carrier there are other necessary properties which a modern fuel has to fulfil. For example, a modern fuel protects metallic parts against corrosion or prevents moving parts from abrasion by its lubricity. Some of these functions are inherent to the fuel, other could be provided by additives.

EN 590 sets limits to some fuel properties which are important for the compatibility with materials. These are shown in Table 4.

Property	Norm	Limit (EN 590)	Unit	Commentary
Copper strip corrosion	EN ISO 2160	1		rating
Lubricity	ISO 12156-1	< 460	□m	Wear in HFRR Test
Total contamination	EN 12662	< 24	mg/kg	
Water content	EN ISO 12937	< 200	mg/kg	KF-Titration

Table 4: EN 590 limits to fuel properties regarding compatibility with materials

The “World Wide Fuel Charta” (WWFC), a recommendation of the international car and engine manufactures sets additional limits for the ferrous corrosion and the content of acids. Organic acid generally cause high corrosion.

Property	Norm	Limit (WWFC)	Unit	Commentary
Ferrous corrosion	ASTM D 665	light rusting or less		rating
Total acid Number	ASTM D 974	< 0,08	mgKOH/g	

Table 5: WWFC limits to fuel properties regarding compatibility with materials

These fuel properties have been tested by the Institute of Petroleum Processing (ITN) for most of the RENEW BTL fuels. The data for the various fuels can be found in the respective ITN report or in the excel fuel data base (see previous chapter).

Fuel which were used for engine tests at Volkswagen AG and DaimlerChrysler AG were also analysed in-house before the engine tests.

There are several norm tests for the compatibility of plastics and rubbers with fuel. As these norms are designed to qualify the polymer materials they are not part of the fuel quality norm.

Norm, technical rule	Content	Materials
ISO 1817	Rubber, vulcanized Determination of the effect of liquids	Elastomers
DIN 53 521	Testing of rubbers and elastomers, determination of the resistance to liquids, vapours and gases	Rubbers, elastomers Similar to ISO 1817 More general
VDA 675 302	Elastomer components in vehicles, test method for stability, impact of test fuels	Elastomers

Table 6: Norm tests for the compatibility of plastics and rubbers

Beside these more general test procedures there are specific in-house test and supply specification for components containing elastomers or thermoplastics at the car manufacturers.

ITN tested the standard materials according ISO 1817 with UET-BTL. DaimlerChrysler did similar test according VDA 675 302. Additionally some critical components were tested with a DC-specific test procedure.

UET-BTL was used for vehicle and engine test at Volkswagen, Regienov and DaimlerChrysler. These tests were run only for comparable short time. Nevertheless if there were severe incompatibility of the fuel with the fuel system and the engine it should become manifest during the tests.

1.1 *Elastomer material*

There are two main categories of polymer materials coming into contact with the fuel:

- Elastomer materials, either in low pressure fuel lines or in seals,
- Thermoplastic materials as a construction material for the tank, housing of fuel filter and pumps and auxiliary components.

Typical elastomer materials are (for nomenclature see DIN ISO 1629):

- NBR, Nitrile Butadien rubber, a co-polymerisate of butadiene and Acrylnitril
- HNBR, Hydrogenated NBR
- VMQ, Vinyl-Methyl-Polysiloxan, a silicon rubber
- FPM, a fluorinated polymetylen rubber
- ACM, Acryl rubber

NBR and HNBR have excellent durability with hydrocarbons, but tends to swell reversible in aromatic hydrocarbons. The temperature range is -30°C to about 100°C.

They can be destroyed by contact with ozone. NBR's are the most common rubber materials in vehicles.

Silicon rubbers are less vulnerable to ozone and other oxidizing reagents. Temperature range goes up to 200°C. Silicon rubbers have however low mechanical strength and can swell considerable in fuel.

Acryl rubbers show good temperature behaviour and are resistant against oils and fuels.

Best stability in contact with chemicals show fluorinated rubber, either FPM or FVMQ.

Typical thermoplastic construction materials for parts in the fuel system are

- PE, HDPE, polyethylene or high density polyethylene
- PP, Polypropylen
- PA 6, PA 66 , Polyamids
- POM-C, POM-H , Polyacetal either as a homo-polymer or as a co-polymer

The most important thermoplastic resins are HDPE (tank) and PA (housings and transducer).

The determination of resistance of rubbers to fuels and liquids can be done according ISO 1817 (similar DIN 53521 or VDA 675 302). The test sample is immersed in the fuel, which is held at constant temperature, for at least 100 h. Then the change of mass, volume and length of the sample as well as the change in hardness and tensile stress-strain properties after immersion are evaluated. For the most common polymer materials standardized samples (bars and discs) are available.

ITN did elastomer compatibility test with fuels P1, P2 and P16 (Table 7).

Elastomere type	Properties	P1	P2	P16	City diesel
FPM	Δ Hardness	1.6	2.6	-0.6	2.1
	Δ tensile strength	2.4	2.2	-15.1	-12.1
	Δ elongation at break	7	6.3	8.8	10.4
	Δ volume change	0.04	0.08	1.5	2.1
ACM	Δ Hardness	n.t.	n.t.	-2.2	13.7
	Δ tensile strength	n.t.	n.t.	-21.3	-19.9
	Δ elongation at break	n.t.	n.t.	-7	-10.9
	Δ volume change	n.t.	n.t.	8	13.6
VQM	Δ Hardness	n.t.	n.t.	-12.5	-19.4
	Δ tensile strength	n.t.	n.t.	-46.5	-36.6
	Δ elongation at break	n.t.	n.t.	-51.7	-22.9
	Δ volume change	n.t.	n.t.	82.1	87
NBR	Δ Hardness	-8.6	-9.8	-6.6	-12.9
	Δ tensile strength	-17.5	-19.8	-29.7	-10.6
	Δ elongation at break	-6.9	-8.4	-10.9	-12.4
	Δ volume change	13.2	13.9	9.4	12.9

Table 7: Results of the elastomer tests at ITN

DaimlerChrysler did similar tests with a fuel, not analysed by ITN, with properties similar to P7 (Figure 1-1 and Figure 1-2).

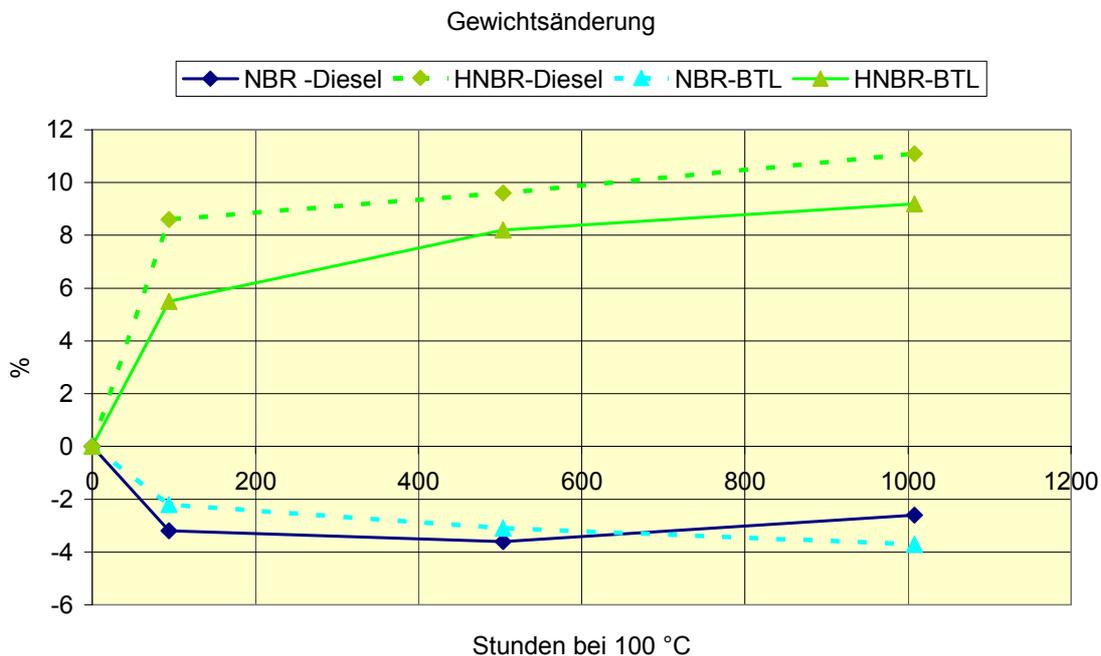


Figure 1-1: Weight change of NBR and HNBR in diesel fuel and in UET-BTL

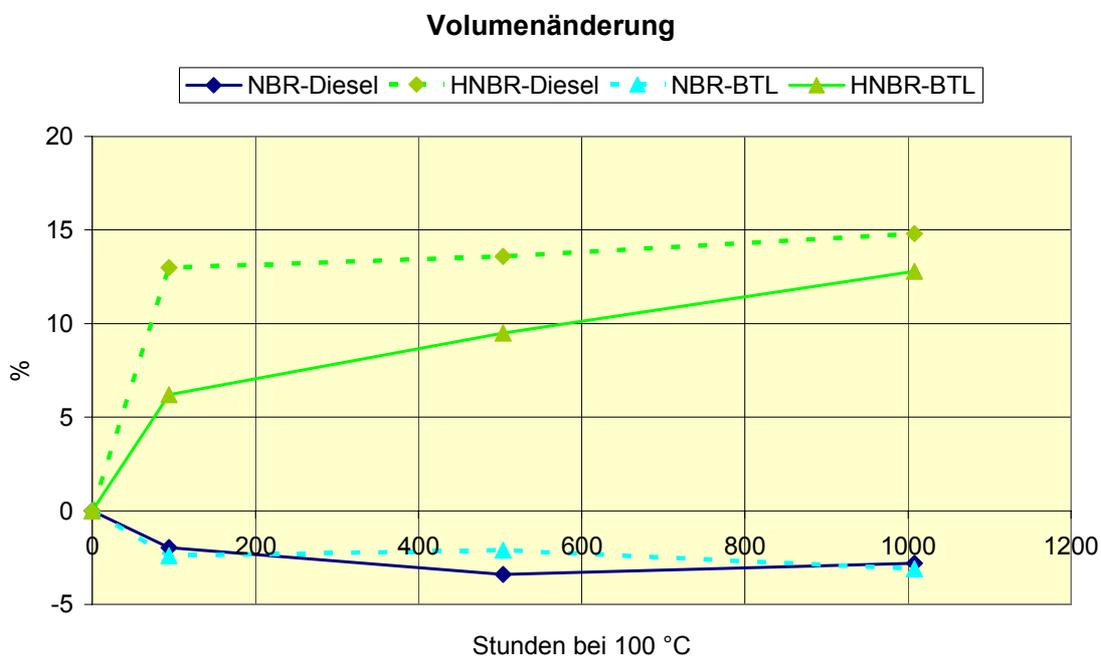


Figure 1-2: Volume change of NBR and HNBR in diesel fuel and in UET-BTL

DaimlerChrysler did similar test with materials from the fuel tank, which is made of stretch-blow moulded multilayer HDPE material. The results were similar to the elastomer materials tested before. HDPE has a considerable uptake of fuel and geometric change. BTL shows however no worse behaviour than conventional diesel.

The ITN and the DaimlerChrysler test results show, that BTL fuel has no problems with the commonly used elastomer materials and thermoplastics in the fuel system. Results are slightly better than with conventional diesel, probably due to the absence of aromatics.

1.2 Metal coated material

Insufficient fuels can cause severe corrosion of metallic components in the fuel system and the engine. In the high pressure part of the fuel system mainly steel components are in contact with the fuel. In the tank and fuel lines electric contacts containing copper are vulnerable to corrosion. The test for ferrous- and copper corrosion works similar: a metallic test strip is immersed into the fuel at elevated temperature. After the required time the strip is compared visually with standards and rated. The ferrous corrosion test is done with additional water.

Test	Norm	Temperature	Duration	Number of ratings
Copper Corrosion	DIN ISO 2160	50 °C	3 h	4
Ferrous Corrosion	ASTM D 665 DIN 51585	60° C	24 h + Water	4

Table 8: Copper and ferrous corrosion test

All fuels passed the copper corrosion test with exemption of one sample of TU-Vienna. All test fuels showed however severe corrosion in the ferrous corrosion test (results ITN). High ferrous corrosion is often found when the fuel contains acids.

Acid Content of Some BTL fuels

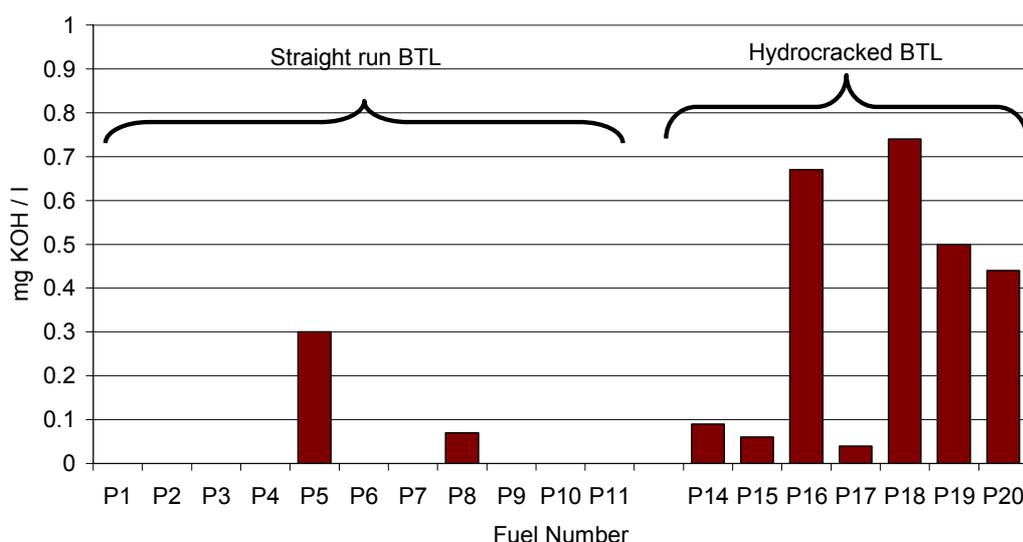


Figure 1-3: Acid content of some UET-BTL fuels (Results ITN)

The acid content has not been evaluated for all fuels. Figure 4 shows, that for some of the straight run fuels and for all of the fuels which were hydro-cracked by UET the acid value exceeds the recommended limit of 0,08 g KOH / l fuel (WWFC). But also the CERTH hydro-cracked samples P14, P15, P17 with low acidity showed poor corrosion behaviour.

It should be mentioned that the ASTM D 665 test is designed to evaluate the corrosion **inhibition** quality of a mineral oil. (Scope: This test method covers the evaluation of the ability of inhibited mineral oils, particularly steam-turbine oils, to aid in preventing the rusting of ferrous parts should water become mixed with the oil. This test method is also used for testing other oils, such as hydraulic oils and circulating oils.) Obviously BTL has no inhibition ability. **This does not mean that BTL in the absence of water causes ferrous corrosion itself.**

A corrosion inhibitor additive could however be necessary. ITN tested three commercial additives but found no improvement (see deliverable ITN 1.13-3)

On the initiative of Volkswagen ITN did also corrosion test with other (coated) metal sheets. This tests were done according a modified VW test procedure (1000 h at 100°C partly immersed). The test panels were:

- Stainless steel X5CrNi 1810
- Electrolytic hot – tinned 8 µm Sn
- Dx 55 DX AS 120 Aluminized panel
- AlMg4,4 Mn 0,4
- Feuerverzinkt ~ 7,1 µm hot-dip galvanized zinc coated panel
- Copper
- Brass

The tests were done with straight run UET-BTL P8. After the test the weight change was measured and the appearance was rated visually (see Table 9).

After 6 weeks the first four panels were almost unchanged and showed no signs of corrosion (Figure 1-4). At the hot-dip galvanized zinc sample the protective zinc coat was partly flaked off. Corrosion caused a significant weight loss (-0,177 g). A weight loss is a sign for an advanced corrosion process, because in the initial phase the sheet weight is increase by the adherent corrosion products. Only if the corrosion products are dissolved by the corrosive medium or it flakes off mechanically the metallic sheet loose weight.

The copper panel showed a black / green tarnish (probably copperoxid, coppercarbonate) and a weight loss of -0,120 g. Similar the brass panel showed green / khaki corrosion products and a weight loss of -0,235 g.

The tests were repeated with UET-hydro-cracked BTL P16 and a commercial additive (APSP1). The results for the zinc coated and the two non-ferrous samples were even worse (see Figure 1-5):

Sample	P8 (weight loss)	P16+ APSP1 (weight loss)
hot-dip zinc coated panel	-0,177 g	-0,235 g
Copper	-0,120 g	-3,035 g
Brass	-0,235 g	-0,280 g

Table 9: Weight change in corrosion tests

The test demonstrates the necessity of proper material selection in the fuel system.

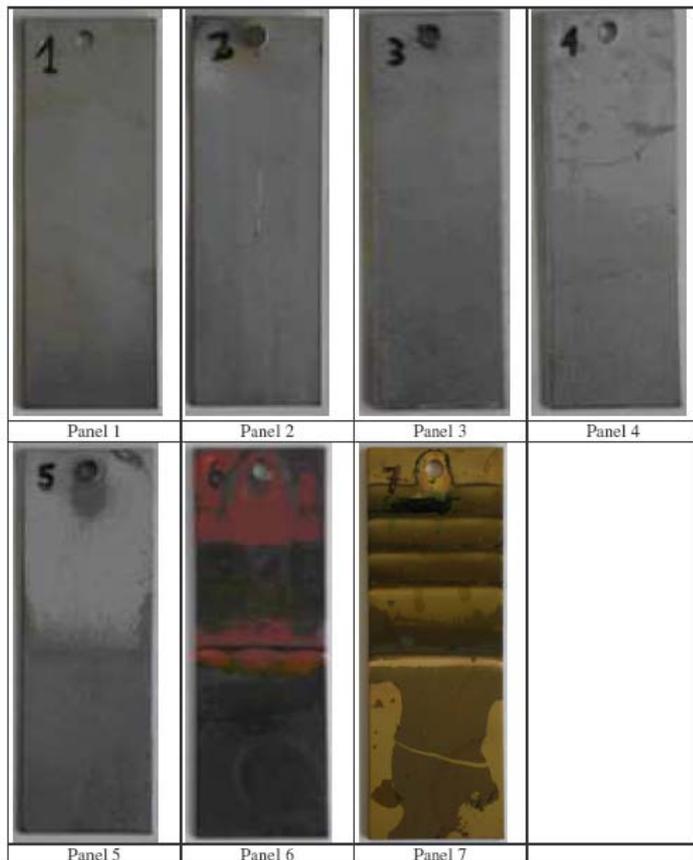


Figure 1-4: Appearance of the test strip after the 1000 h test (P8 without additive)

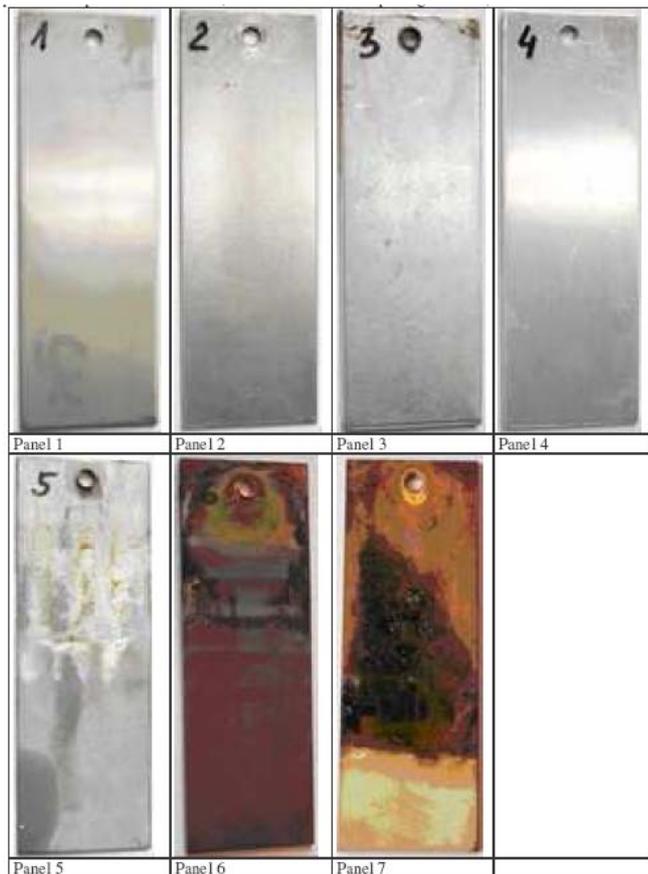


Figure 1-5: Appearance of the test strip after the 1000 h test (P16 with APSP1 additive)

During the engine and vehicle test at Volkswagen and DaimlerChrysler no problems with corroded components were observed. Regienov however suffered strong fouling of the injector needle with one of the kerosene fuels. This fuel was however contaminated with water at the transport and is therefore untypical.

It should be mentioned that the BTL-fuels, which were tested in the RENEW project, will not be the final BTL-fuels on the market. The commercial BTL-fuel will be completely hydro-cracked and hydro-treated. So the high content of oxygenates (alcohols, aldehyds and carbon acids), which are typical for the straight run fuels and may have caused the corrosion problems, will not be in the final commercial product.

2 Emissions and consumptions

2.1 Test results of engines equipped with Unit injectors

A Golf V equipped with a modern four cylinder 2 l diesel engine (TDI PD 2L 4V 103 KW) was used for the dynamometer test. The engine uses a modern unit injector. Maximum power output is 103 kW. The vehicle complies with the EURO IV exhaust emission standards. An oxidation catalytic converter is used but no particulate filter.

Volkswagen AG made tests with three different UET fuels

- BTL kerosene (P10)
- BTL kerosene high (P7)
- BTL diesel (P11)

Properties of these fuels can be found in the attached Excel database.

Reference fuels are conventional diesel according EN 590 and a mineral oil based kerosene.

Two different optimized applications were developed for and tested in the NEDC

- Optimized NOx emissions
- Optimized particulate emissions

Figure 2-1 shows the emissions of the three BTL fuels relative to the emissions of EN 590 reference fuel in the standard application for the NOx optimized application. Similar Figure 2-2 shows the results of the particulate optimized application. The three fuels behave very similar, although BTL diesel P11 seems to be slightly more advantageous in the particulate optimized case, whereas BTL kerosene performs slightly better in the NOx optimized application.

CO and HC are reduced substantially with all BTL fuels. Emission levels are 73% below the EU4 limit for HC and 95% for CO. Kerosene shows the highest HC and CO emissions which can be explained with the highest volatility of the fuel.

CO₂ emission and fuel consumption is similar for both application, although the PM optimize case shows a slightly better efficiency. The average CO₂ reduction is 5%. Volumetric fuel consumption increases 6% whereas gravimetric fuel consumption is reduced by 4%.

Usually the emission level of new cars are well below the limits of the actual norm to have a safety margin and to compensate for aging effects in the aftertreatment system. A comparison with such a new vehicle underestimates the emission benefits of BTL fuel relative to the standard emission limits. Figure 2-3 and Figure 2-4 shows the emissions relative to the actual EU4 limits.

Relative Emissions in the NOx Optimized Application

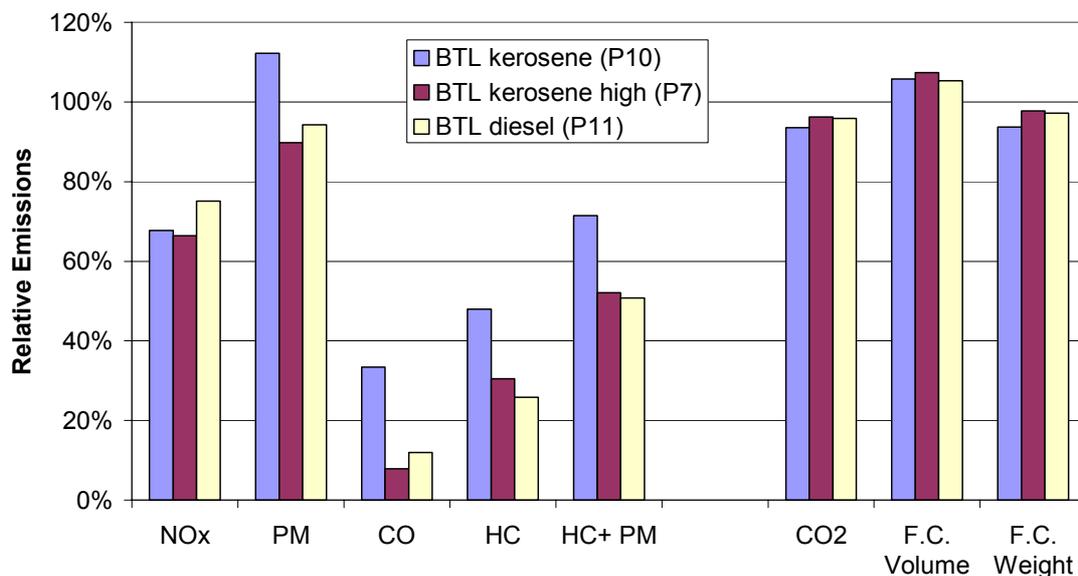


Figure 2-1: Relative emissions of the three BTL fuels compared to conventional EN 590 diesel fuel in the NOx optimized application

Relative Emission of the Partikulate Optimized Application

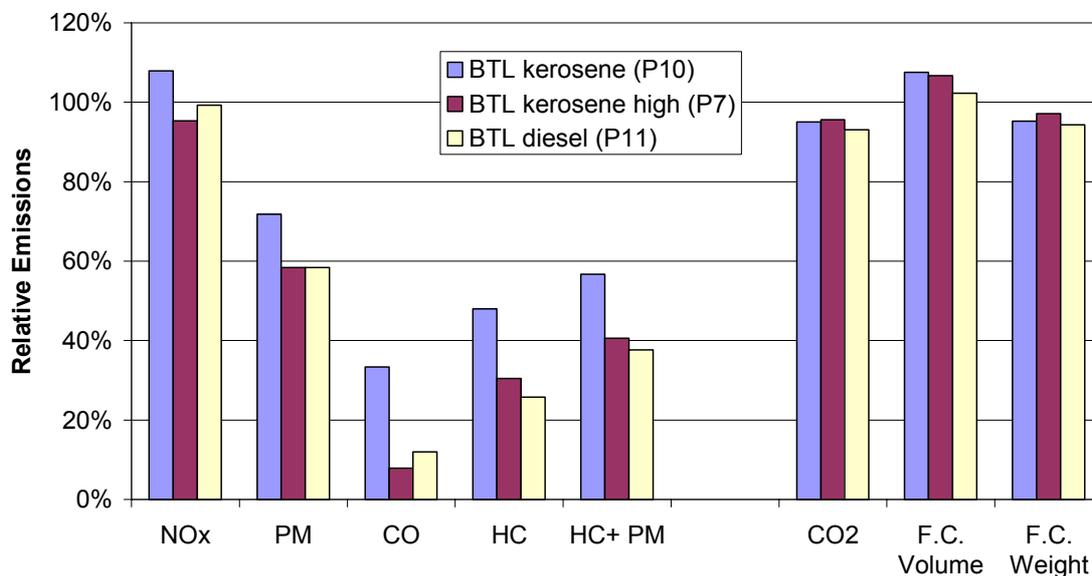


Figure 2-2: Relative emissions of the three BTL fuels compared to conventional EN 590 diesel fuel in the PM optimized application

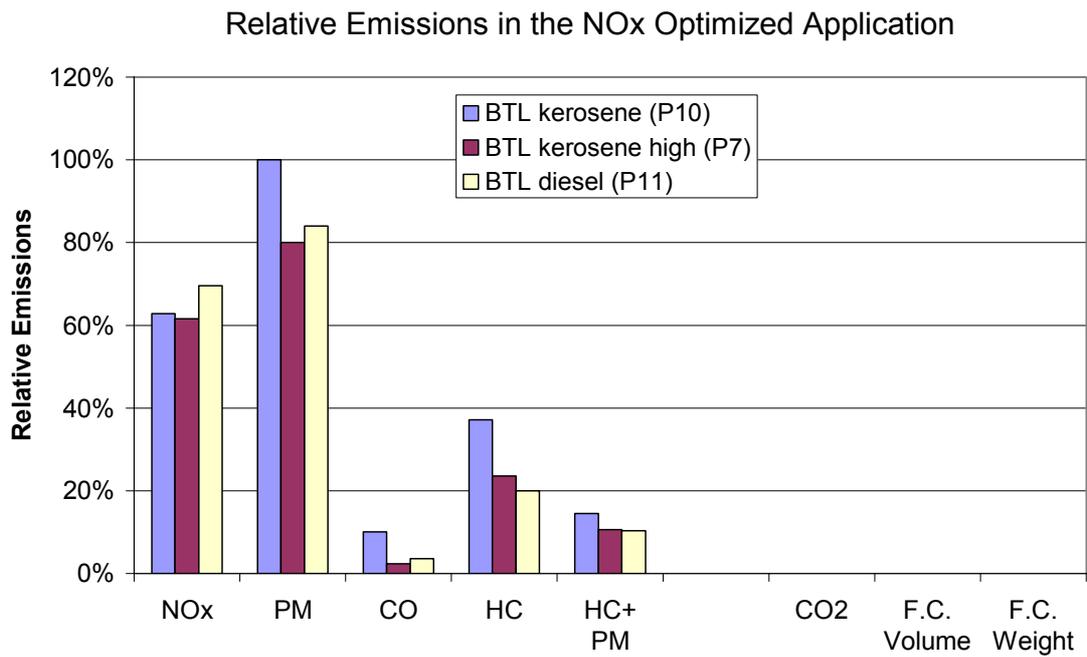


Figure 2-3: Relative emissions of the three BTL fuels compared to EU4 emission limits in the NOx optimized application

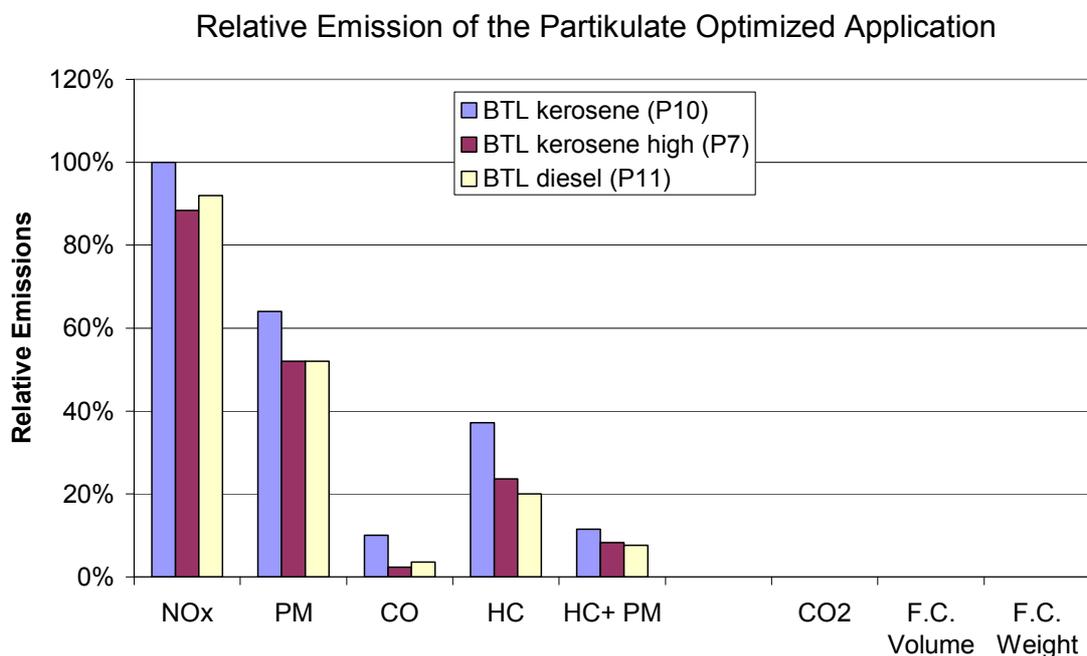


Figure 2-4: Relative emissions of the three BTL fuels compared to EU4 emission limits in the PM optimized application

2.2 Investigation of influence of Cetan No.

With regard to a detailed combustion analysis in an engine equipped with unit injectors the influence of cetane no. on emissions were investigated.

The available BtL-fuel from UET is suitable for investigating solely the effect of the Cetane no. since it has a very high cetane number. The idea is to blend this fuel with a component having a very low cetane number, so that the cetane number of the fuel is reduced. By choosing tetra-isobutane as a component only the density is affected besides the cetane no. since the boiling point is within the boiling range of the BtL fuel. In that way three fuels with different cetane numbers were prepared.

The experiments were carried out on an engine test bench with the four cylinder 2 ℓ diesel engine with unit injectors. The maximum power output of the engine is 103 kW. Tests on the engine test bench included variation of the injection timing and exhaust gas recirculation.

Three different Cetane no. were adjusted by adding different amounts of tetra-isobutane (tib). In the Table 10 fuel properties are shown.

properties	test methode ASTM	unit	tib	BtL 41	BtL 56	BtL 70
density @ 15°C	D4052	g/ml	0.791	0.777	0.766	0.760
LHV (Vol)		MJ/l	34.8	34.1	33.7	33.5
Distillation						
IBP	D86	°C	210	192	155	153
FBP	D86	°C	250	269	261	265
cetane number	D613		15.4	41	55.7	69.8

Table 10: Fuel properties

A technical available tib was used, i.e. it is a mixture of 90% tib (C₁₆) and some C₁₂ and C₂₀-isoparaffin. Therefore it has a boiling range and not a boiling point.

The test procedure was very similar to the engine tests which had been conducted within the RENEW project.

4 steady state operating points were selected which have been investigated on the engine test bench. On this test bench it is possible to measure the in-cylinder pressure. From the pressure the heating rate is derived, which explains the actual behavior of the fuel during the burning in the cylinder. The selected points characterize the New European Driving Cycle (NEDC) for the used engine:

- 1460 rpm, 20 Nm
- 1640 rpm, 55 Nm
- 1920 rpm, 80 Nm
- 2340 rpm, 110 Nm

Besides the pressure the emissions (HC, CO, PM, NOx) were measured as well.

These experiments were performed with BtL 41, BtL 56, BtL 70 and reference diesel.

The exhaust gas recirculation rate (EGR) was varied as well as the start of injection.

The following points can be derived from these investigations of the influence of the Cetan no. in a unit injector engine:

- ignition delay is described by the Cetan no.
- comparison between diesel and BtL56 shows very clearly again the potential of BtL fuels in terms of particle and NOx reduction.
- high cetan no. (high n-paraffin-content and low density) seems to implicate longer combustion
- longer combustion is rather caused by a retarded injection than by slower combustion of n-paraffin. Therefore in terms of combustion behaviour the hydraulic behaviour of the fuel is obviously more decisive than the chemical reactivity of the components for a unit injector engine
- with respect of the influence of Cetan no. on emissions no clear trend could be shown. Hence, a high Cetan no. seems to be not particularly beneficial for unit injector engines in terms of emissions.

Especially the last results looks somehow new, since it is generally well known from literature, that a high cetane no. is beneficial for particularly the HC and CO emissions (World Wide Fuel Charter 2006, ACEA, JAMA, EMA). Since this was not found in these engine tests, some vehicle tests were conducted on the roller test bench. Therefore, three fuels of the Cetane no. 65, 60 and 39 had been prepared in the same way as described above. These fuels were than tested sequentially in the vehicle (Golf V) by measuring HC, CO, NOx and particulate matter in NEDC tests without any modification in the engine software or hardware. Figure 2-5 shows the emission results relative to the diesel emissions.

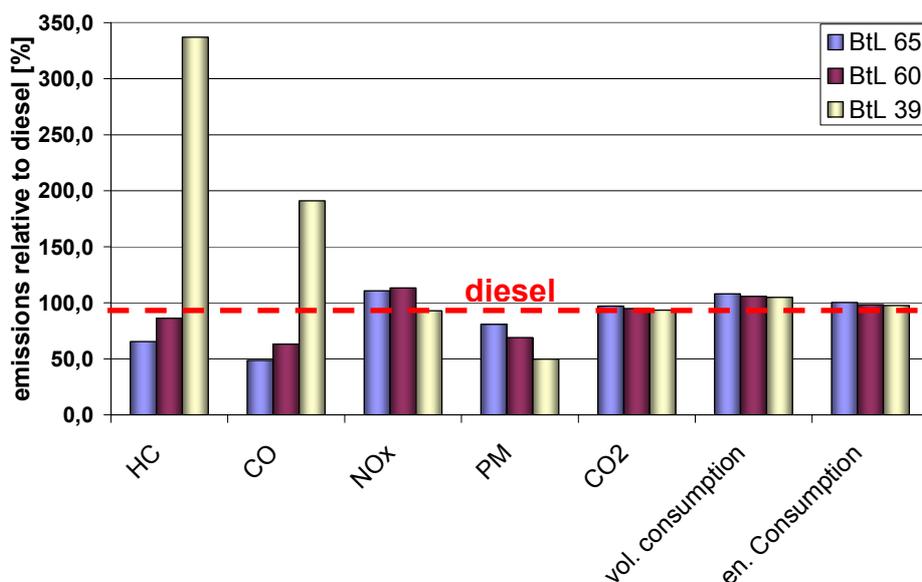


Figure 2-5: Influence of Cetane no. on vehicle emissions in NEDC

It becomes clear, that with decreasing Cetane no. the HC and CO emissions increase and the NO_x and particulate matter (PM) emissions decrease. A high Cetane no. implicates a short ignition delay, hence less time for homogenisation of the fuel-air mixture. This leads to a more pronounced diffusive combustion which finally tends to decrease HC and CO but increases NO_x and particulate matter. On the other hand a low Cetane no. implicates a longer ignition delay, hence more time for homogenisation of the fuel air-mixture. This involves less particles, less NO_x, but more HC and CO emissions. Figure 5 shows exactly that dependency on the Cetane no..

Concluding it can be said, that the generally known impact of a high/low Cetane no. is found also in the vehicle emissions with a unit injector engine. Since these results base on the mean of several roller test bench tests they are considered to show the reality.

2.3 Test results of engines equipped with Common rail injection systems

A Mercedes E class car equipped with a modern 3 l V6 diesel engine (OM 642) was used for the dynamometer test. The engine uses a common rail injector. Maximum power output is 165 kW. The vehicle complies with the EURO IV exhaust emission standards. An oxidation catalytic converter is used as well as a particulate filter. As DaimlerChrysler now uses particulate filter technology in all new diesel passenger cars the standard application uses this additional degree of freedom to reduce NO_x emissions. The limits of a reasonable NO_x reduction are confined by the increase of fuel consumption.

Dynamometer test were done with a straight run UET –BTL (Fuel 1 in the attached Excel data base) with a boiling range between 68°C and 333 °C. Since the primary effect of BTL fuel demonstrated in the engine bench tests is a reduction in particulates the particulate filter will level out PM emissions from BTL and conventional fuel. Therefore the dynamometer test was done with particulate filter and without.

Figure 2-6 shows the relative emissions in the NEDC for the car with particulate filter. BTL shows emission benefits for NO_x, CO and HC compared to the conventional fuel. Particulates seems to be slightly enhanced. But this apparent increase is probably an effect of measurement precision. The filter reduces the particulates both for conventional fuel and for BTL fuel to such a low level (0,002 g/km compared to the EU4 limit of 0,025 g/km) that precise measurements are difficult.

The red bars show the emissions relative to the EU4 limits. The impressive reduction of PM, CO and HC is of course assisted by the aftertreatment components (oxycat and filter). The comparison to the conventional fuel (blue bars) however shows a significant influence of the BTL fuel. The reduction of NO_x is only caused by the fuel. The reduction is slightly less than the NO_x- optimized application from Volkswagen.

To demonstrate the benefits of PM reduction of BTL in the raw gas the particulate filter was removed. Figure 1-3 shows the results. NO_x, CO and HC emissions are similar to the results with filter. The PM reduction from the BTL fuel (blue bar) is 28%, which is not as high as the PM – optimized application of Volkswagen. The PM emissions of the car without the particulate filter would not be in the limits of EU4.

The slight reduction in CO₂ – emissions and gravimetric fuel consumption, and the increase of the volumetric fuel consumption is comparable to the Volkswagen results.

Relative Emission of BTL in the NEDC

Vehicle with Oxycat and Partikulate Filter

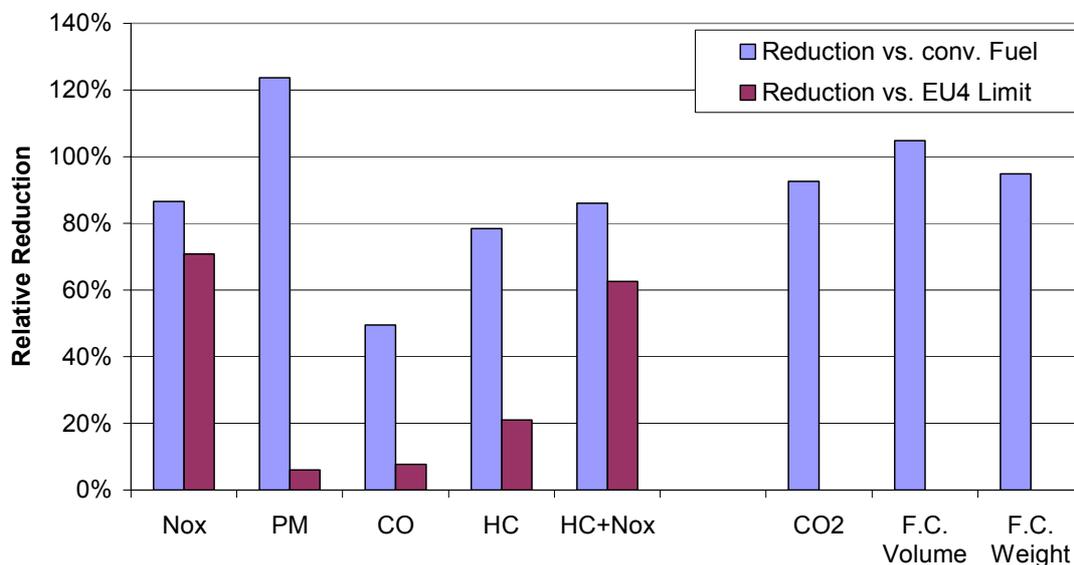


Figure 2-6: Relative emissions of UET - straight run BTL compared to conventional EN 590 diesel and EU4 limits. Vehicle with oxidation catalyst and partivulate filter

Relative Emissions of BTL in the NEDC

Vehicle with Oxycat , without Particulate Filter

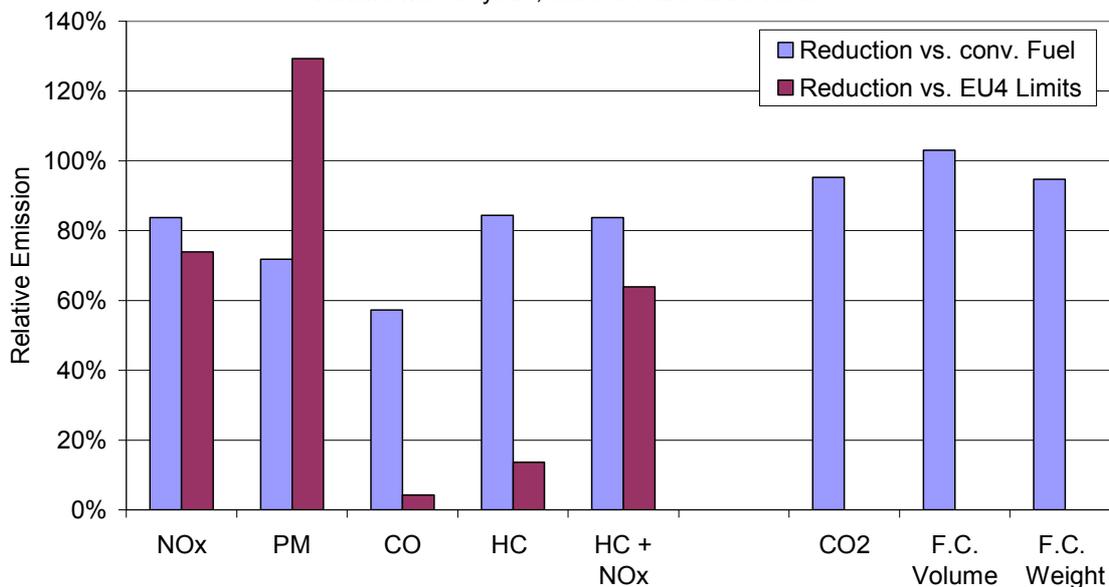


Figure 2-7: Relative emissions of UET - straight run BTL comaped to conventional EN 590 diesel and to EU4 limits. Vehicle with oxidation catalyst, without particulate filter

Parallel to the work within the RENEW project DaimlerChrysler did an engine optimization for GTL fuels [1]. This optimization was not confined on software parameters, parameters which can be changed by the electronic control unit, but changed also hardware parameters of the engine, such as the injection system and the compression rate. This engine is a dedicated GTL engine which means that the drivability with conventional fuel is reduced and the emission limits with conventional fuel will not be met.

Figure 2-8 shows the results of this dedicated engine. A NO_x reduction of 72% relative to the EU4 limits were realized. CO and HC increase but are well below the limits. CO₂ emissions and fuel consumption is similar to the results shown before, which means that the NO_x reduction is accomplished without a fuel consumption penalty.

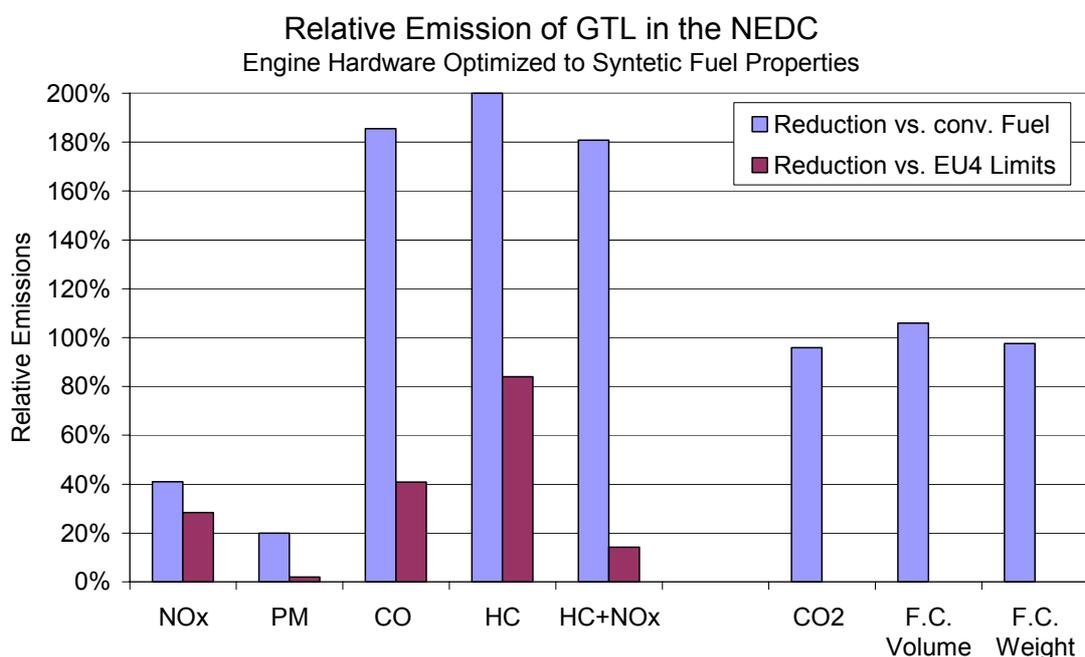


Figure 2-8: Relative emissions of GTL fuel in a hardware optimized engine compared to a standard application with conventional EN 590 diesel and to EU4 limits. Vehicle with oxidation catalyst and particulate filter

This encouraging result show the potential of synthetic FT diesel. Because such an optimized vehicle can not switch between synthetic fuel and conventional fuel the availability of neat BTL or GTL on the market is a prerequisite for such a development.

2.4 Summary of the passenger car tests

As shown above the emission benefits of BTL fuels depend on the applied combustion strategy and the exhaust gas aftertreatment technology. Table 11 gives average emission reduction factors relative to the EU4 limits.

Technology	NOx	PM	CO	HC	HC+ CO	CO2	F.C. Volume	F.C. Weight
State of the Art, Oxycat , PM opt.	-7%	-44%	-95%	-73%	-91%	-5%	6%	-4%
State of the Art, Oxycat , NOx opt.	-35%	-12%	-95%	-73%	-88%	-5%	6%	-4%
State of the Art, Oxycat + DPF	-29%	-94%	-92%	-79%	-37%	-5%	6%	-4%
Future dedicated BTL , Oxycat + DPF	-72%	-95%	-59%	-16%	-85%	-5%	6%	-4%

Table 11: Emission reduction factors for BTL fuel and different emission reduction technologies

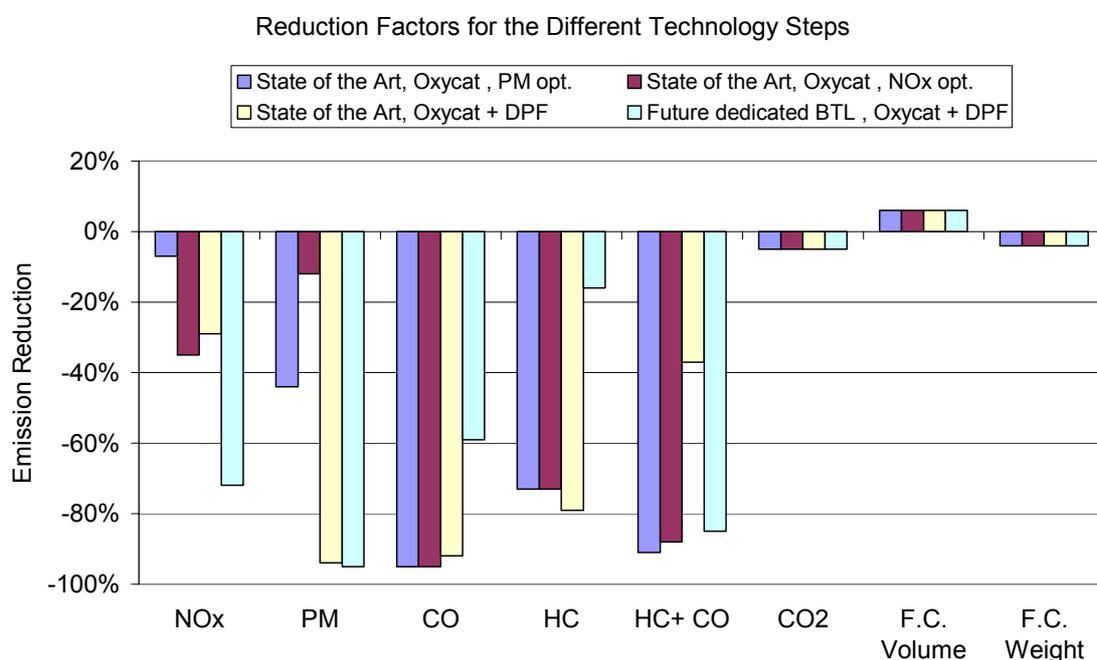


Figure 2-9: Emission reduction factors for BTL fuel and different emission reduction technologies

2.5 Test results of future advanced combustion engines (HCCI)

Renault / Regienov tested special BTL fuels from UET in experimental HCCI engines. HCCI is the abbreviation of Homogeneous Charge Compression Ignition. HCCI is an advanced combustion process with a high emission reduction potential for NOx and particulates.

In normal diesel process the fuel is injected into the hot compressed air near top dead centre. After a short induction period the fuel spray is auto ignited in a small volume around the spray cone where air and evaporated fuels mix. This small burning volume is rich of fuel and therefore burns with high temperature, which causes high NOx and high soot production.

The advantage of this diffusion controlled inhomogeneous combustion is that even small amounts of injected fuel will burn.

At low load only the amount of injected fuel has to be reduced, which means that the diesel engine is efficient also at low and part loads.

Conventional gasoline engines use homogeneous air/fuel mixtures. The high octane rating of gasoline and the lower compression ratio of the engine prevent this mixture from auto ignition. The homogeneous combustion is characterized by low NO_x and almost no soot production. Because the homogeneous mixture can only be spark ignited and burn in a small range of air/fuel ratio, SI engines have to reduce the amount of air at low and part load. If this is done by throttling, losses in the gas-exchange cycle are inevitable. Hence the SI engine has a lower efficiency at low and part load than the CI engine.

The HCCI process tries to combine the benefits of both. There are different strategies for HCCI which cannot be described in detail here. At Regienov early injection is used (see Figure 2-10). Injection starts at -70 °CA in the compression stroke. The air load is cold and the fuel has time enough to homogenize. Near TDC the load is hot enough for auto ignition. Combustion starts all over the volume and is finished fast. This produces a steep pressure increase.

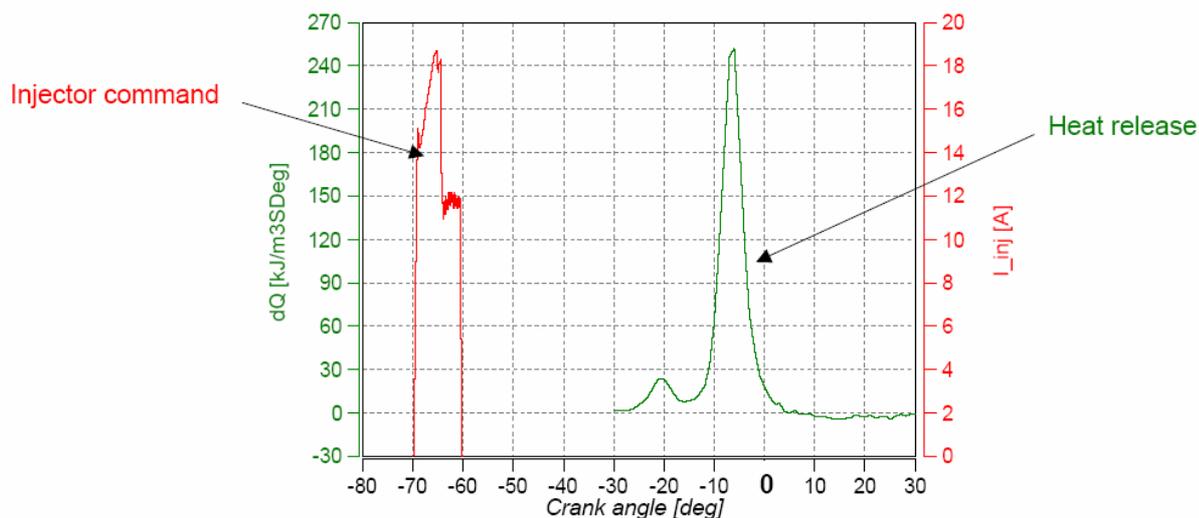


Figure 2-10: Basic characteristic of HCCI

Although HCCI combustion produces little soot and NO_x it suffers serious restriction and disadvantages.

- HCCI is not suitable high load. Homogeneous combustion of the full load will produce high peak pressures, which are not controllable.
- HCCI has higher HC and CO emissions
- HCCI produces higher combustion noise

Hence the future HCCI engines will use a combination of homogeneous and partly homogeneous and conventional inhomogeneous combustion. The overall emission level of the engine will be determined by the ratio of this combustion schemes.

Within RENEW Regienov carried out several test campaigns with 2 GtL fuels with different characteristics and one conventional diesel (Table 12).

GTL 10 has a cetane number equivalent to usual Diesel (around 50) but is highly volatile whereas with GTL 20 its "bottom distillation curve" volatility is equivalent to conventional Diesel, but with a lower final boiling point and a noticeably higher cetane number.

<i>Item</i>	<i>Unit</i>	GTL 10 "Naphta"	GTL 20 "Kerosine"	Usual Diesel (124 A)
Density 15°C	kg/m3	672,6	736,1	834
Distillation :	IBP	°C	43	152,5
	10%	°C	61	159,5
	50%	°C	95	167,0
	90%	°C	126	185,5
	95%	°C	-	-
	FBP	°C	166	208
Cetane number	-	45-55	64,5	54

Table 12: Fuel characteristics for HCCI tests at Regienov

The conventional Diesel fuel and GTL 10 fuel were tested according to Regienov HCCI conditions (highly advanced injection timing (50 to 70 °CA, instead of rather +/- 1°C around TDC for conventional Diesel combustion)), aiming at promoting the best homogeneous mixture. Emissions limits for particles were fixed for not exceeding a Smoke SN = 2 (Bosch Number) and NOx at the threshold detection.

The first test campaign, based on a very limited number of experiments, led to the following intermediate results, allowing for some preliminary trends to be drawn:

- even with the conventional Diesel fuel, the early injection strategy (50°C), coupled with low compression ration (12:1) allows to reach relevant values of BMIP (6.4 to 6.7 bars) at 1500 and 2500 r.p.m; with emissions values never exceeding smoke number (SN) 0.7 and detectable NOx
- GTL 10 (low Cetane Number, high volatility and narrow distillation range) behaviour is highly dependant on the injection timing. : 50°C allows to reach BMIP around 6.2 bars at 2000 r.p.m. under excellent emissions conditions, while 70°C allows to increase BMIP up to 9 bars with equivalent low emissions results, but under constraint of unacceptable noise 98 dB

The first campaign was followed by a second one covering a wider set of experimental conditions (higher engine speed up to 3700 rpm, 3 different intake manifold pressures) and including also the GTL 20 fuel.

Figure 2-11 shows exemplary results for soot emissions with increasing power (BMIP) at constant 3700 r.p.m. and intake manifold pressures of 2, 2.4 and 2.7 bar.

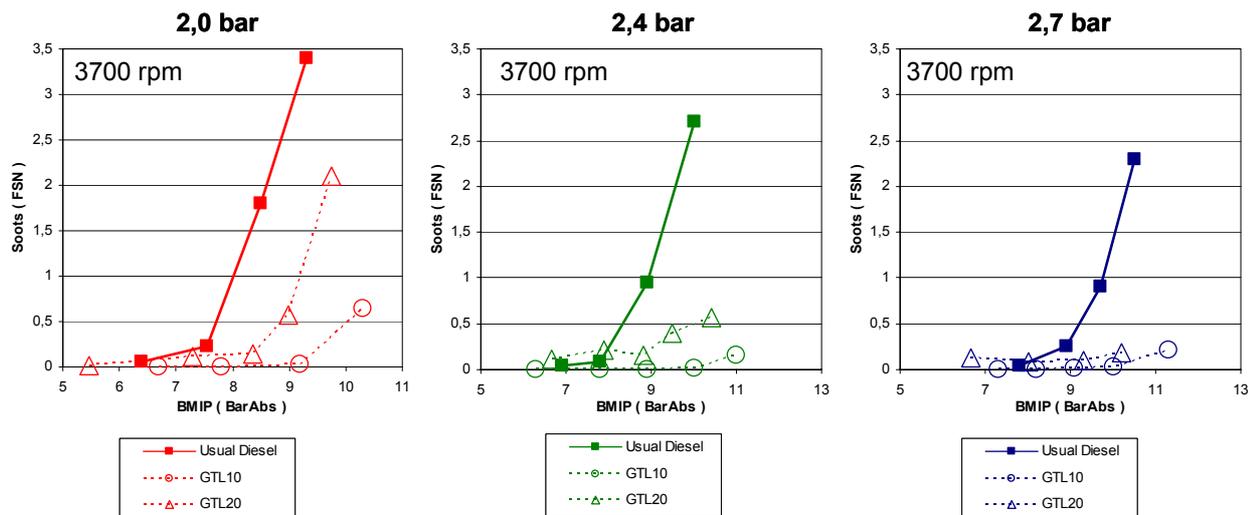


Figure 2-11: 10 Soot emission results at different intake manifold pressures

From this extended test program, the main following conclusions can be drawn:

- low Cetane Number (< 50) has to be favoured for low noise HCCI combustion:
→ better results rank as follows : GTL 10 / conventional Diesel / GTL 20
- synthetic fuels (GTL 10 and 20 and probably also comparable BTL fuels) offer very attractive results on PM emissions (as estimated through smoke number measurements) when compared with the conventional Diesel fuel : extremely low levels of aromatics and negligible Sulphur content can explain this very positive trend).
- In addition, higher volatility (IBP/40 °C – FBP/160 °C) seems to be even more favourable to lower the smoke emissions under HCCI conditions: → GTL 10 / GTL 20 / Conventional Diesel Fuel

No tests with BTL-Naphta fuels were elaborated within RENEW due to quality problems of supplied samples. Nevertheless some results on BtL-Naphta were achieved due to collaboration between the two Integrated Projects RENEW and NICE. It was possible to sent BtL-fuel from RENEW to the NICE.-project. Within SP1 UET delivered 1000l BtL wax to CERTH. CERTH produced after preliminary research in catalysts liquid fuel out of this wax via hydrotreatment. Different cuts with respect to the boiling range have been delivered to the NICE-project. The colleagues in NICE conducted engine tests on the behaviour of such hydrocracked BtL-fuel and provided the results to the RENEW project.

A fuel sample being in the diesel boiling range (Renew_CN75) and a sample characterised with a naphtha boiling range (Renew_CN36) have been tested by Renault in single cylinder tests. The main properties are listed in Table 13.

	Method	EN590 (Ref. fuel)	Renew_CN36	Renew_CN75
Density at 15°C [kg/m ³]	ASTM D4052	836.0	699.3	785.2
Cetan number	ASTM D613	51	36.3	74.8
Viscosity at 40°C [mm ² /s]	ASTM D445	2.557	0.5571	3.266
Flash point [°C]	NF EN ISO 13736	66.5	-	127
Sulfur [mg/kg]	PLASMA	44	<10	<2
Carbon [% wt]	ASTM D5291	86.42	84.18	84.91
Hydrogen [% wt]	ASTM D5291	13.51	15.73	14.85
Oxygen [% wt]	ASTM D5622	<0.20	<0.20	<0.20
LHV [kJ/kg]	ASTM D240	43243	46439	44669
AFRS ¹		14.59	15.10	14.90

Table 1: Main properties of the tested fuels

Table 13: Main properties of the tested fuels

Subfigures 1 and 2 in Figure 2-12 show the boiling range and the main components of the fuels.

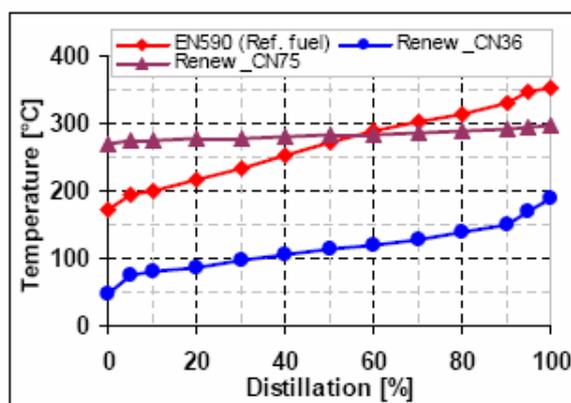


Figure 1: Distillation of the fuels

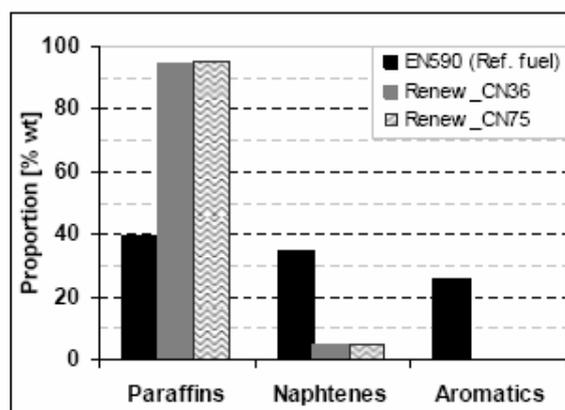


Figure 2: Composition of the fuels

Figure 2-12: Distillation and composition of the fuels

With these fuels tests on HCCI combustion were carried out on a single cylinder test bench. Different operating points were chosen, part load as well as one full load point. The latter present actually conventional diesel combustion, since it is not possible to adjust HCCI conditions in full load regime.

However, the main result is, that with Renew_CN36, i.e. a naphtha type fuel, a considerable enlargement of the operation range under HCCI-combustion was achieved. The limits for reaching maximum HCCI-load are NO_x-emissions below 0.1 g/kWh and noise below 83 db. The criteria was defined for maximum HCCI-load as 230 g/kWh. The enlargement of the HCCI-range is shown in Figure 2-13 and Figure 2-14, which depict the max HCCI load for 1500rpm and the maximum HCCI load with supercharging. The latter being a suitable “engine” tool for enlargement of the HCCI-operating range.

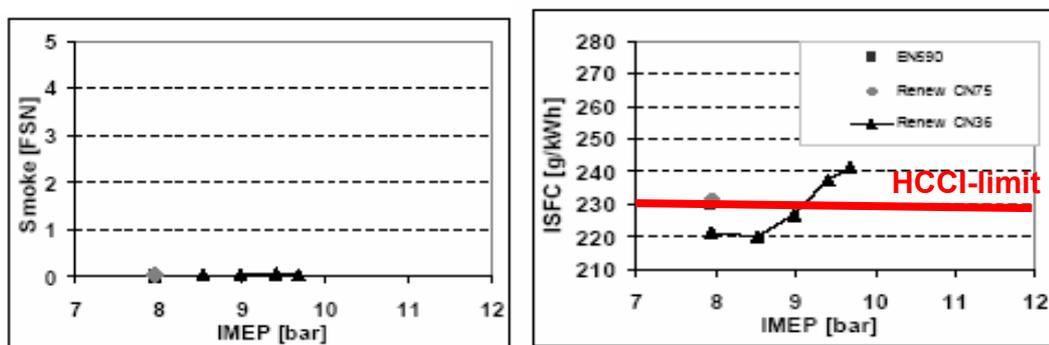


Figure 2-13: 1500rpm, smoke and specific fuel consumption versus mean effective pressure

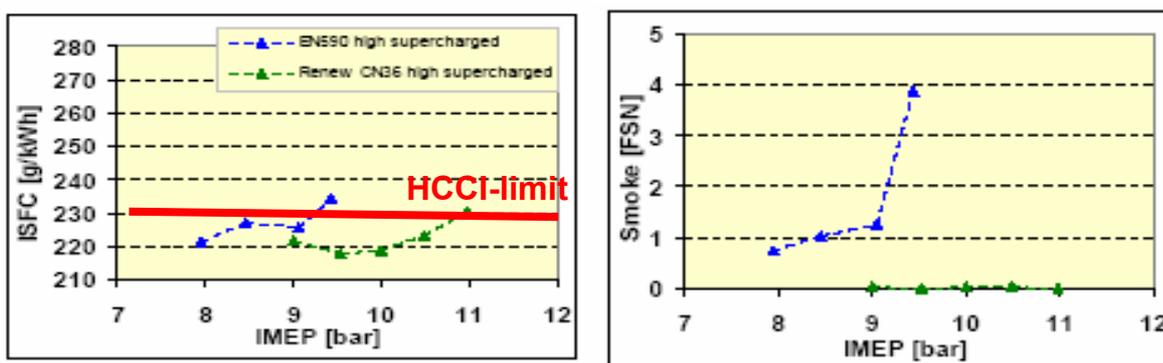


Figure 2-14: 1500rpm supercharging, smoke and specific fuel consumption versus mean effective pressure

The enlargement is about 12% to 18% which are considerable and interesting results, especially, since no smoke was measured whatever the load.

At full load Renew CN36 burns a little more slowly than the other fuels. As a consequence, the global efficiency is slightly lower. Nevertheless, the best IMEP is reached due to its good limit equivalence ratio at the smoke number limit.

Concluding the hydrocracked naphtha type fuel, Renew_CN36, has a very good potential to enlarge HCCI-combustion range. In fact, by combining this fuel with high supercharging, which is a further technology studied in NICE, a solution is presented to overcome the current HCCI barriers.

2.6 Test Results of commercial-vehicle engines with DME fuel

VTEC tested DME blended with methanol and water in a heavy duty diesel engine in order to determine the impact of these impurities on engine performance. The objective was not to optimize the engine to combustion of DME, although necessary modifications of the engine hardware (common rail DME fuel injection system, long root EGR and an oxidation catalyst) have been made. The engine was a six cylinder 9.4 l heavy duty engine (Volvo D9A 300hp Euro3, torque 1360Nm and power 210kW). The engine should comply with Euro 5 exhaust emission legislation, e.g. soot 0.02 g/kWh and NOX 2 g/kWh.

Regulated emissions, unregulated emissions and particle size distribution were measured with conventional technique, FTIR (Fourier Transform Infra Red) and SMPS (Scanning Mobility Particle Spectrometer), respectively.

Operating points, with focus on normal cruising engine speed, from the 13 point European Stationary Cycle, ESC, were chosen to study the engine performance in detail. The test procedure for trucks differs principally from the test procedure for passenger cars. Trucks are not tested as a whole vehicle in a standardized driving cycle on a chassis dynamo. Only the engine is measured on a test bench on 13 load / engine speed points in the relevant operation range. Emissions at these load points are added using standardized weighting factors and expressed as mass per power output.

The total amount of impurities tested were up to 10% by weight, which is circa ten times more than is expected for diesel fuel type DME. The impurities had very limited effect on emissions but affected the combustion in such a way that more energy was released during the initial combustion phase. The conclusion is therefore that engine performance will not be affected by the expected content of water and methanol in fuel grade DME. Other potential impurity effects, such as long term effects on fuel system, have however not been considered.

It was, as mentioned before, not the task of VTEC to optimize the DME combustion and to measure the emission reduction according ESC. So these values are not available. It was however observed qualitatively during the test campaign that the main emissions NO_x and particulates are reduced significantly. CO was increased but can be effectively reduced by an oxidation catalyst. It is further concluded that number of particles from a DME fuelled diesel engine is circa 1000 times lower than for a state of the art diesel engine in the soot range. In addition, most of the unregulated emissions were negligible.

2.7 Considerations on biomethane and ethanol

Methane and ethanol were not tested in the RENEW project. Both fuels are used in spark ignition engines. When operated at stoichiometric air fuel ratio ($\lambda = 1$) efficient three way catalyst (TWC) can reduce NO_x, CO and HC emissions. Problems arise however with methane which cannot be oxidised by the catalyst at low temperature. Therefore hydrocarbon emissions of NG driven vehicles consist mainly of methane.

Technology	Unit	NOx	CO	HC	Source / Vehicle
EU 4 limits	g / km	0,08	1	0,1	
Gasoline	g / km	0,046	0,840	0,050	DaimlerChrysler
E85	g / km	0,048	0,480	0,062	E 320 FFV
Change	%	4%	-43%	24%	
Gasoline	g / km	0,070	0,550	0,070	Fiat Multipla Bipower
NG	g / km	0,020	0,680	0,250	Source ADAC
Change	%	-71%	24%	257%	

Table 14: Typical emissions reduction from in house tests respective from literature

With **ethanol** (E85) a reduction is only observed with the CO emissions. HC increase while NOx is nearly unchanged. All emissions are however well below the EU 4 limits.

With **methane** or natural gas we find a significant reduction of NOx while CO and HC increase dramatically. **The vehicle does not meet the EU 4 HC limits when fuelled with NG.** This is caused by the low conversion rate of methane in the tree way catalyst.

Ethanol shows the same combustion efficiency than gasoline. The low energy content (26,5 MJ/kg compared to 43,6 MJ/kg for gasoline) entail high gravimetric and volumetric fuel consumption.

Methane exhibit the best CO₂-reduction of the tested SI-fuels because of it outstanding H:C ratio. The combustion efficiency is significantly better than the efficiency of gasoline. This is enabled by the high octane rating and improved mixture properties. The most severe disadvantage is the low density which causes high volumetric fuel consumption. At 200 bar the equivalent tank volume is 2.5 times greater than with gasoline. Considering the heavy compressed gas cylinders which are not integrated easily into a vehicle dedicated NG vehicle have only an unsatisfactory cruising range.

Technology	CO2	Fuel consum. by Volume	Fuel consum. by Weight	Fuel consum. by Energy
Ethanol (E85)	-3%	35%	50%	0%
Methane	-23%	256%	-12%	-7%

Table 15: Change of fuel consumption and CO₂ emissions of Ethanol and Methane relative to gasoline

3 Cold start behaviour

3.1 Experiments

Using a Golf with 2.0 l TDI (103 kW) engine, unit injectors, electronic control unit (ecu) EDC16, chassis dynamometer tests have been performed. As test fuels, CEC diesel reference fuel and biomass-to-liquid-fuels type P7 and P10 delivered by UET have been investigated (properties see Table 1). As ecu data-sets the standard application and an altered application, which has been adapted to BtL fuel P7 have been used. The altered application data-set has been modified with respect to start of injection, duration of injection and rate of exhaust gas recirculation.

Chassis dynamometer tests have been performed at 20 and -7 °C.

State of the art of low-temperature NEDC emission tests at -7 °C are usually tests without analysing particulate matter emissions; for our purposes, however, this cold emission test has been modified including particulate matter emissions.

Investigations at temperatures near the CFPP limit (here: -18°C for CEC fuel and P7) have to be restricted to the consideration of the starting phase behaviour only as the chassis test bench can not be cooled down to -18 °C and the measurement equipment for exhaust gas components are not designed for that low temperatures as well.

Producer		UET	UET	Haltermann / DuPont
Charge	Dimension	P7	P10	CEC Reference Diesel Fuel
Density (15 °C)	kg/m ³	758,0	740,3	834,3
Viscosity (40 °C)	mm ² /s	1,541	1,014	2,90
Cetane Number CFR	-	78,9	68,2	49,4
HFRR (60 °C)	□m	536	462	324
Flash Point	°C	64,0	43,0	91,0
IBP	°C	179,0	156,0	218,1
FBP	°C	275,7	213,0	364,0
Sulfur	mg/kg	8,3	<10	9,6
Net Caloric Value	MJ/kg	43,82	44,29	n.d.
CFPP	°C	-18,5	- 47	-19
Total Aromatic Content (FIA)	%-w	n.d.	n.d.	22,5
Carbon Content	%-w	84,74	85,45	n.d.
Hydrogen Content	%-w	15,05	14,11	n.d.
Oxygen Content	%-w	0,21	0,44	n.d.
Mean Molar Mass	g/mole	177,32	145,92	n.d.
H/C molar	-	2,116	1,968	n.d.
O/C molar	-	0,039	0,082	n.d.

Table 16: Typical Properties of UET Fuels and of European Reference Diesel Fuel (n.d. = not determined)

The fuel consumption of the NEDC tests using fuels UET P7 and UET P10 has been calculated using an altered formula derived from the official fuel consumption calculation of the European Union. This new formula is better adapted to alternative fuels not complying with fuel standards: Instead of a fixed carbon mass-content according to the carbon content, which corresponds to a molar H/C ratio of 1,85, the experimental determined carbon content is introduced into the formula

$$FC = \frac{C \cdot E_{HC} + 0,429 \cdot E_{CO} + 0,273 \cdot E_{CO_2}}{\frac{10 \cdot \rho}{C}}$$

with C = Carbon mass-ratio of the fuel [-], EHC = mileage-related hydrocarbon emission

for the respective fuel [g/km], ECO and ECO₂ as described before, ρ = density [kg/l].

The rotational speed fluctuations have been evaluated to describe the influence of the fuel on the engine running smoothness at low temperatures. In order to get an estimation of these fluctuations, the acquired data points of the rotational speed have been discriminated whether occurring above or below the mean signal line. Two envelope curves have been calculated from these discriminated partial data sets. The standard deviations of the two partial data sets have been calculated and added as a measure for these rotational speed fluctuations.

The influence of the fuel on cold start engine running smoothness has been described as the relative change of the standard deviations of the rotational speed patterns. The relative change, RC (dim = %), has been calculated according the formula

$$RC = 100 \cdot \frac{SD_{BtL} - SD_{Ref}}{SD_{Ref}}$$

with SD = standard deviation of the rotational speed pattern

Ref = CEC Reference fuel

BtL = Biomass-to-Liquid fuel

The uncertainty of this relative change has been calculated according the Gaussian error propagation formula:

$$\Delta RC = \sqrt{\left(\frac{\partial RC}{\partial SD_{Ref}}\right)^2 \cdot \Delta SD_{Ref}^2 + \left(\frac{\partial RC}{\partial SD_{BtL}}\right)^2 \cdot \Delta SD_{BtL}^2}$$

with

$$\frac{\partial RC}{\partial SD_{Ref}} = 100 \cdot \frac{SD_{BtL}}{SD_{Ref}^2}$$

and

$$\frac{\partial RC}{\partial SD_{BtL}} = \frac{100}{SD_{Ref}}$$

3.2 Emission test results

The emission test results at -7°C using the standard engine calibration are shown in Figure 3-1.

Figure 3-1 relative changes referring to CEC diesel fuel at 20 and -7 °C are shown.

The overall trend to lower emissions using BtL fuel is valid for hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NOx) and particulate matter (PM) at -7 °C. At 20 °C HC, CO and PM is decreased, too, only NOx-emissions are increased, which is due to the lower density of the BtL and the resulting driving at lower EGR rates, leading to an increase of peak temperatures of the combustion. The lower density of BtL corresponds with an moderate increase of fuel consumption, but a moderate decrease of the CO₂ emission, which is due to the higher hydrogen content of BtL fuel.

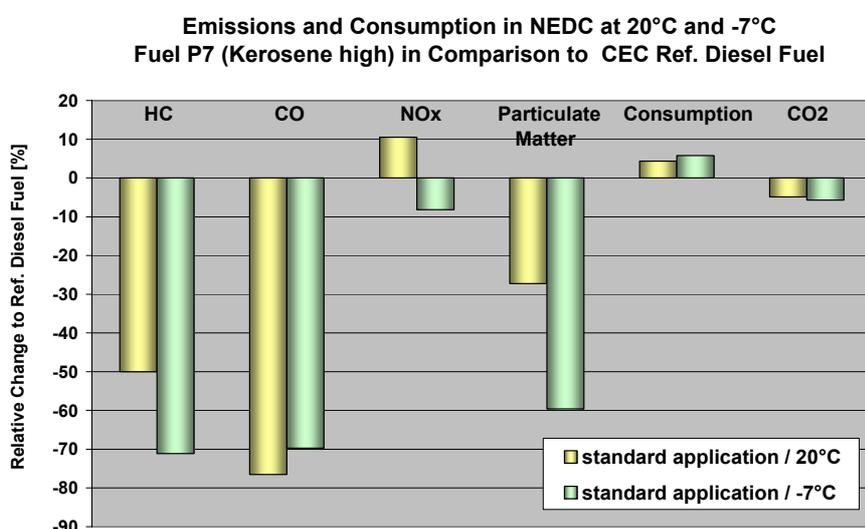


Figure 3-1: Emission and consumption behaviour of BtL-fuel P7 in comparison to reference diesel at standard temperature and -7°C measured with standard ECU data set

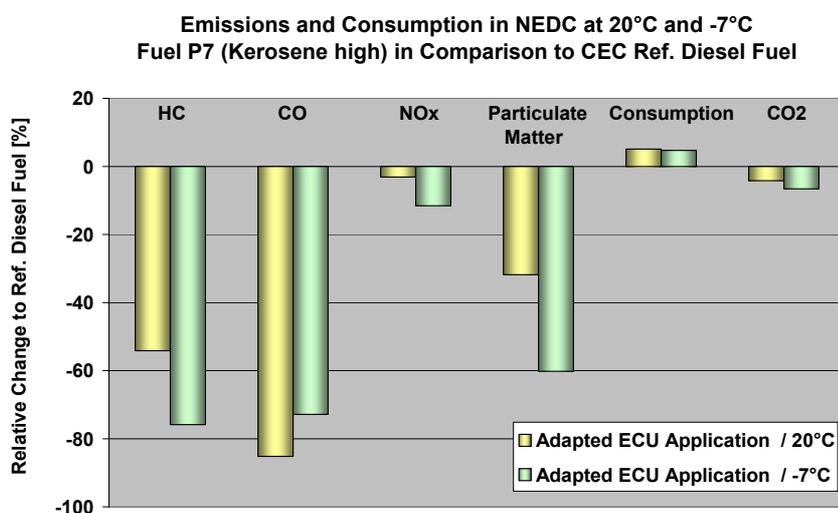


Figure 3-2: Emission and consumption behaviour of BtL-fuel P7 in comparison to reference diesel at standard temperature and -7° measured with adapted ECU data set

In Figure 3-2 relative changes referring to CEC diesel fuel at 20 and -7 °C are shown, however, using an adapted engine calibration for this particular fuel. From the comparison between the tests at 20 °C and -7 °C one may recognise that nearly all exhaust emissions including carbon dioxide are decreased by the UET P7 fuel. At cold start conditions the trend is much more significantly especially for particulate emissions.

**Emissions and Fuel Consumption, 20 and -7 °C, 2 Applications
Fuel P7 (Kerosene high) in Comparison to CEC Reference Diesel**

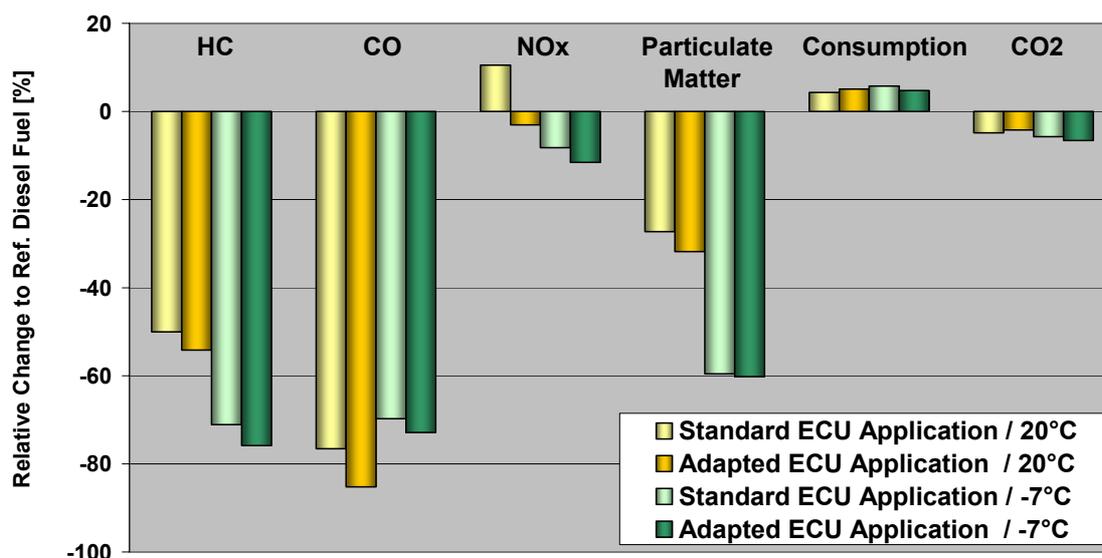


Figure 3-3: Overview on emission and consumption behaviour of BtL-fuel P7 in comparison to reference diesel at different temperatures and different ECU application

In Figure 3-3, relative changes of emission results from the previous diagrams are presented together for a better overview.

You may see a slightly higher emission reduction using the adapted engine application compared to the standard engine application for all emission types. This ecu data-set, however, were not generated for minor temperatures but under standard ambient conditions of 20 °C. Therefore, results with the adapted data-set may not represent the highest reduction potential at -7°C.

A significantly higher emission reduction with respect to hydrocarbons and particulate matter at -7 °C, compared to 20 °C were detected. This typical difference between regular emissions and cold chamber emissions reflects the better cold start properties of the UET P7 fuel.

The fuel consumption (which is calculated from emission tests) ranges in the same order of magnitude for both applications. A relative change of emissions or fuel consumption below

5 % cannot be estimated as significant.

For an approximate calculation of the experimental limits of detection being valid for typical fuel economy and emission measurements, see Appendix 1 at end of chapter 4.3.

In Figure 3-4, a comparison between the limited emissions, fuel economy and CO₂ -emissions of fuel P7 and fuel P10 is given, as using the standard engine application. Again the relative emission and fuel economy changes compared to CEC reference fuel are shown.

The kerosene “high” (P7) with a higher final boiling point shows more advantages with respect to exhaust gas emissions than the kerosene “light”, which is a fuel without higher molecular components.

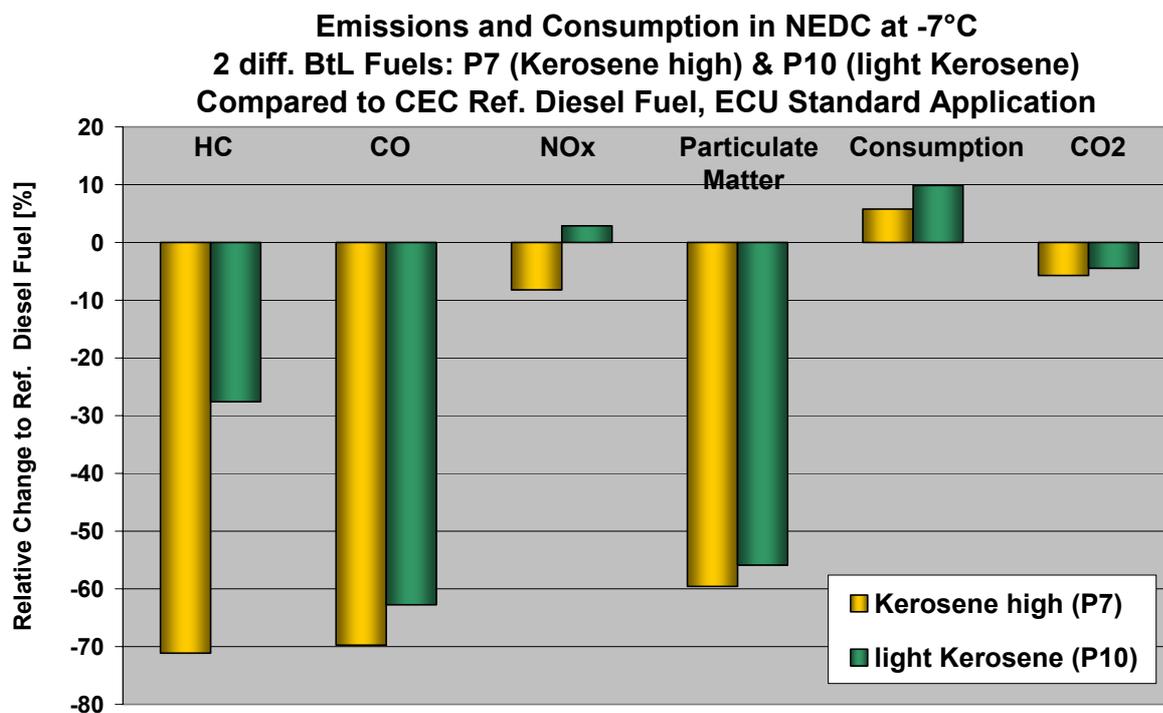


Figure 3-4: Emission and consumption behaviour of two BtL-fuels (P7, P10) in comparison to reference diesel at -7°C measured with standard ECU data set

A moderate decrease of the final boiling point can help to reduce emissions, because of a better fuel mixture preparation in the cylinder before ignition. But a further decrease of the final boiling point obviously won't bring more advantages neither at standard conditions nor at -7°C, it will lead to a downward positive effect.

Emission and Fuel Consumption Changes in NEDC at 20°C and 7°C, BtL P7 and P10 Compared to CEC Reference Diesel Fuel

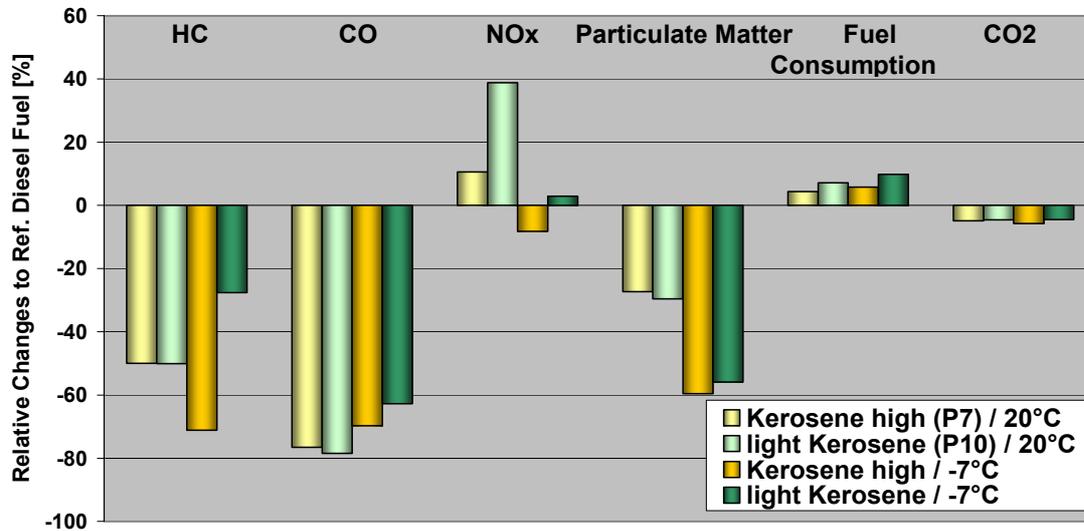


Figure 3-5: Overview of emission and consumption behaviour of two BtL-fuels (P7, P10) in comparison to reference diesel at standard temperature and -7°C measured with standard ECU data set

In Figure 3-5, a comparison between the limited emissions, fuel economy and CO₂-emissions of fuels P7 and P10 is given for 20 °C and for -7 °C, as using the standard engine application. The pale colours indicate 20 °C and the darker colours -7 °C, yellow colours indicate fuel P7 and green colours fuel P10. Again the relative emission or fuel economy changes compared to CEC reference fuel are shown. In general, the more pronounced emission reduction with P7 is obvious, with fuel P7 the tendency to increase NO_x-emissions is lower than with fuel P10. The better cold driveability of both fuels compared to diesel fuel leads to a tendency to more pronounced emission reductions at -7 °C than at 20 °C; the particulate matter emission changes at -7 °C is approximately double as high than at 20 °C.

The fuel economy changes are rather low and range approximately near the limits of the standard deviation of the method.

3.3 Starting phase consideration

The chassis dynamometer cold chamber tests at -7 °C have been evaluated not only with respect to exhaust gas emissions but also with respect to typical engine data. Additionally some cold start tests were carried out at -18 °C in order to get in formations on the cold start behaviour of the fuel under stringent conditions (-18°C is nearby the CFPP point of the references diesel as well as P7 fuel).

Significant differences between cold start properties of the investigated fuels are shown in the time until starting cutout and the time until stable idling is reached.

These data are evaluated in Figure 3-6 to Figure 3-9.

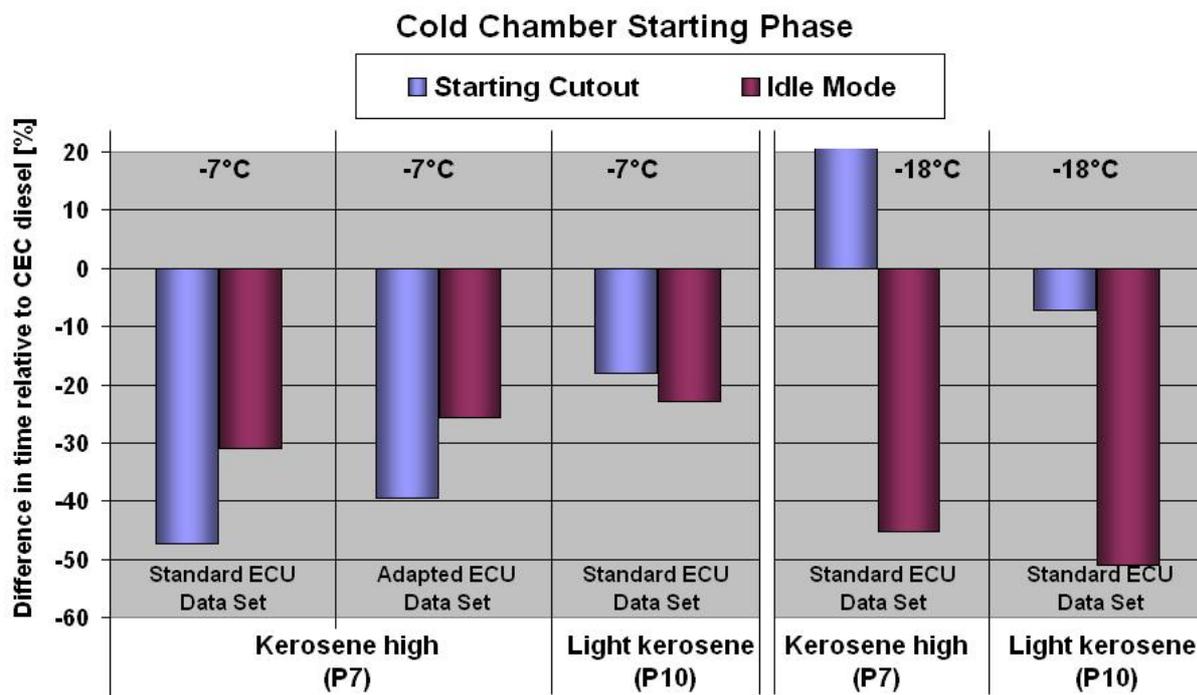


Figure 3-6: Time consideration of starting cut out and idle mode with different BtL-fuels in comparison to reference fuel at different temperatures (-7°C, -18°C)

The changes of starting cutout times and times to idle mode relative to CEC Reference diesel fuel are shown in Figure 3-6 for both -7 and -18 °C start tests. Nearly for all comparisons BtL fuels exhibited shorter starting times than CEC Reference diesel fuel, only for the comparison of fuel P7 relative to CEC Reference at -18 °C, BtL fuel exhibited a longer starting cutout time despite of the same CFPP limit. Here the viscosity under test conditions which was not adapted via additivation in the BtL fuel may cause some starting disadvantages. The viscosity of the BtL fuel is out of the standard EN 590 range which is measured at 40°C. At temperatures below 0°C, the viscosity could have still bigger disadvantages like a poor spray formation etc. This is only a working hypothesis and has to be proved in further more differentiated investigations.

With regard to the timing until idle mode, all tests under -7 and -18 °C have shown a shorter time.

Pattern of Rotational Speed during Starting Phase at -7°C
Cold Chamber Test Golf TDI 2,0l 4V 103 kW (Unit Inj.)

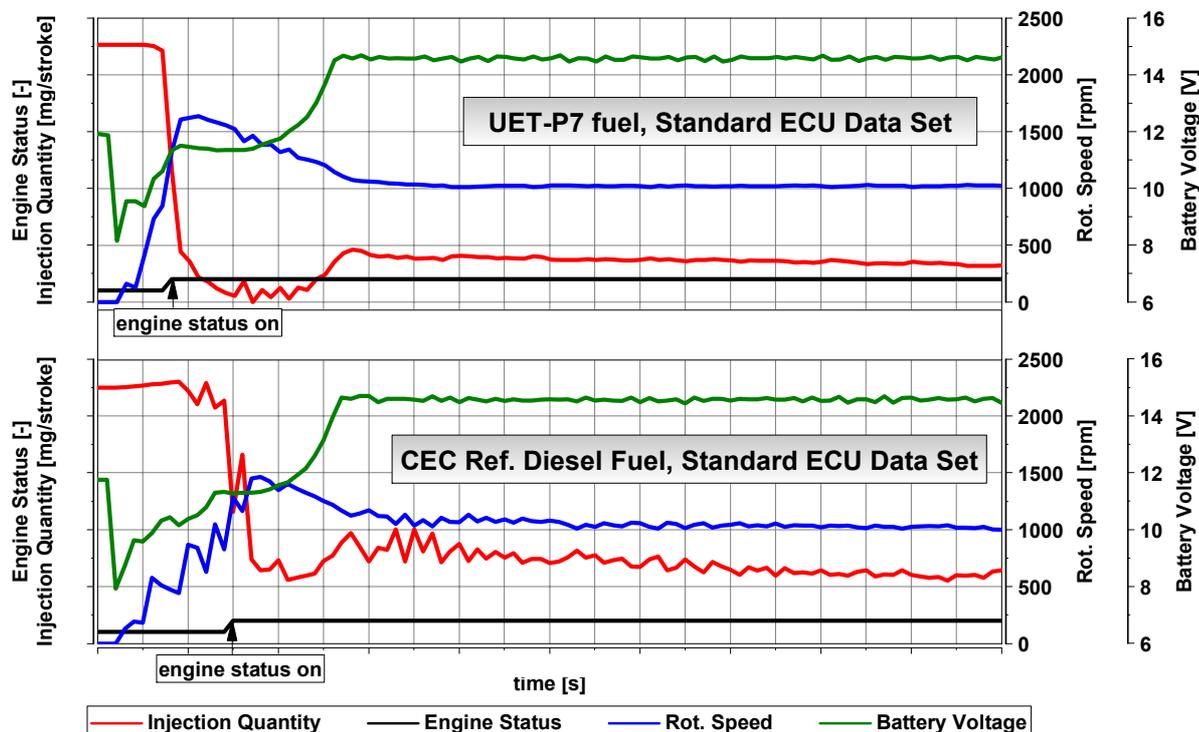


Figure 3-7: Cold start behaviour at -7°C: course of rotational speed and injection quantity at starting phase with BtL kerosene high (P7) and reference diesel

Figure 3-7 shows the cold start phase which corresponds to the first seconds while the engine starts; it is obvious that the status “engine on” is reached earlier and that in the period until starting cutout is obtained the rotational speed pattern seems much more stable for fuel P7 than for CEC reference fuel. The tendency for a better drivability respectively lower deviation of the rotational speed pattern continues until the idle mode is reached. This can be seen both in the rotational speed and the injection rate.

Similar trends can be seen in Figure 3-8 for fuel P10, however, the improvement of cold start behaviour is not so significant for this fuel than for fuel P7: The time until starting cutout is only slightly shorter for P10 and during the engine rev-up time until idle mode some deviations in rotational speed pattern as well as the injection rate can be found. Nevertheless the engine running is smoother and very stable in the following of the idle run.

Pattern of Rotational Speed during Starting Phase a -7°C
Cold Chamber Test Golf TDI 2,0l 4V 103 kW (Unit Inj.)

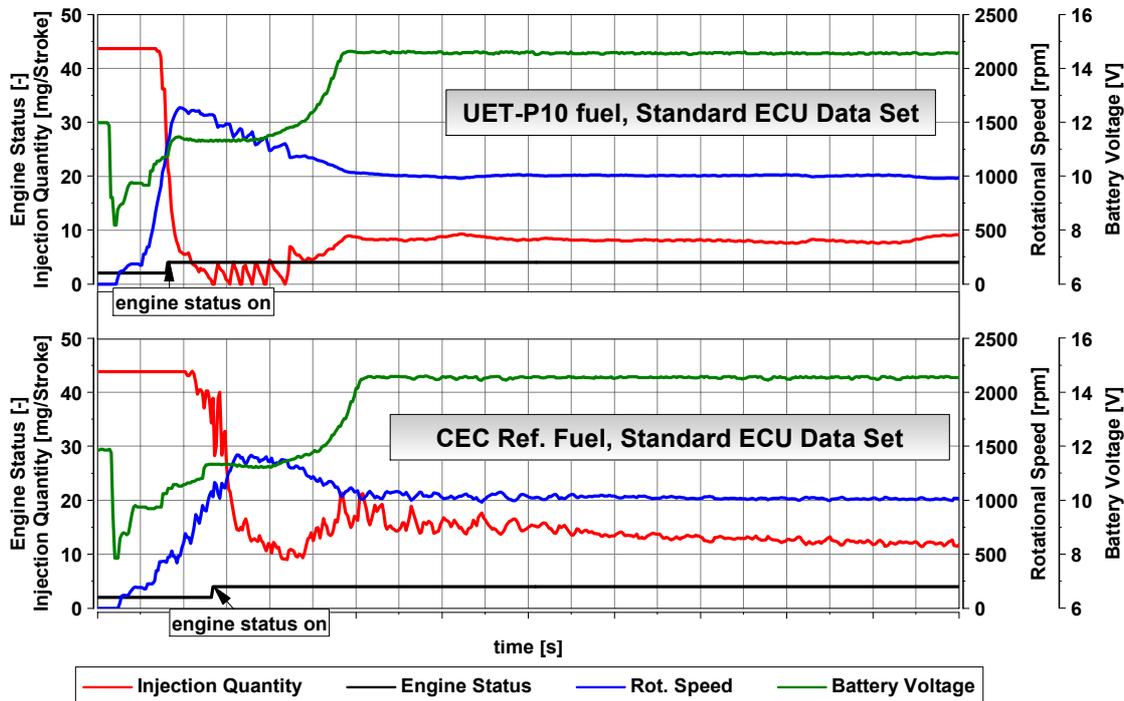


Figure 3-8: Cold start behaviour at -7°C: course of rotational speed and injection quantity at starting phase with BtL light kerosend (P10) and reference diesel

Pattern of Rotational Speed during Starting Phase at -18°C
Cold Chamber Test Golf TDI 2,0l 4V 103 kW (Unit Inj.)

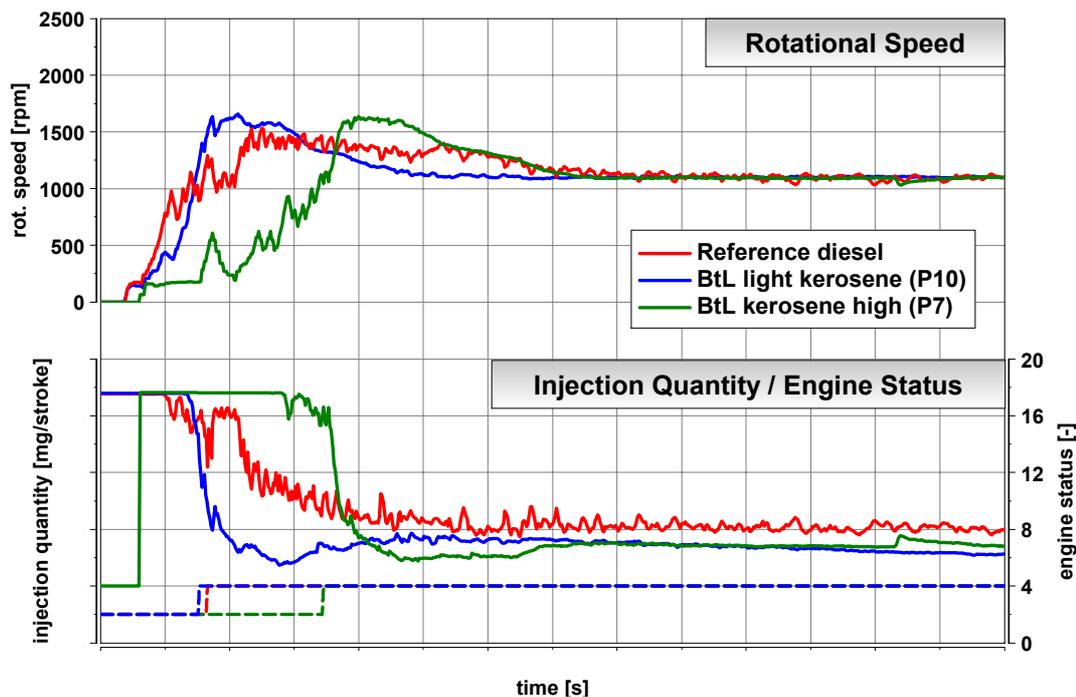


Figure 3-9: Cold start behaviour at -18°C: course of rotational speed and injection quantity at starting phase with BtL kerosene high (P7), BtL light kerosene (P10) and reference diesel

At -18 °C, only the cold start phase could be investigated, the results of which are shown in Figure 3-9.

As a general trend, the standard deviation of the respective rotational speed patterns of BtL fuels has shown to be significantly smaller than that of conventional fuel.

For fuel P10, a significant improve of several seconds has been found until a stable idling is obtained probably due to the low CFPP (-47°C) and the very low final boiling point.

The time to starting cutout has been shorter with CEC reference fuel, whereas with fuel P7, it was found that the engine had more starting troubles. After the starting cutout, however, P7 exhibited a significantly smoother rotational speed pattern than CEC reference fuel, too.

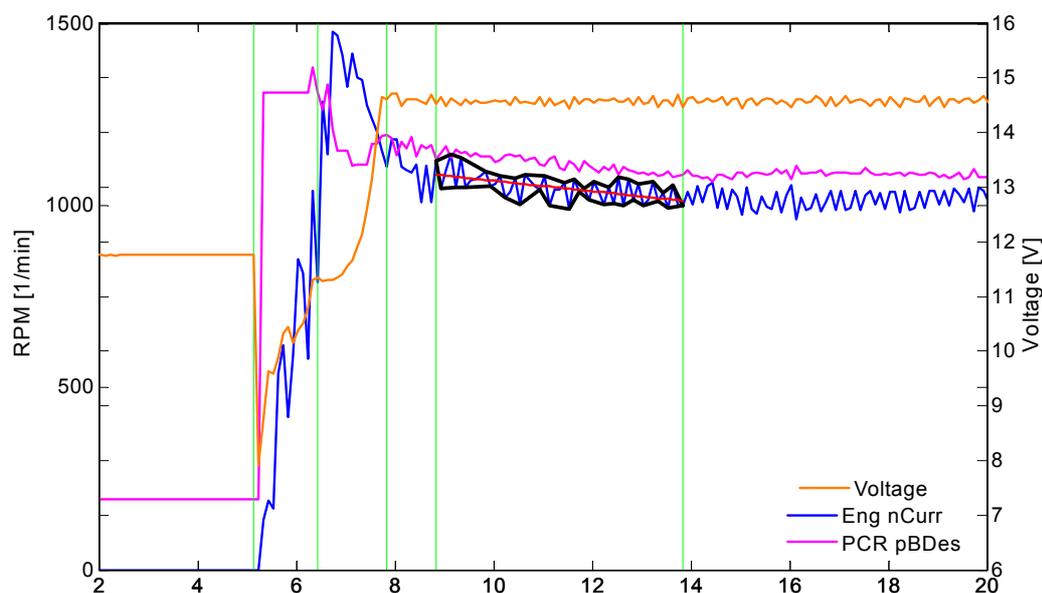


Figure 3-10: Scheme of a Rotational Speed Fluctuation Evaluation

In order to quantify the rotational speed fluctuations for both the reference fuel and the BtL fuels the relative change of the standard deviations of the rotational speed patterns were calculated and analysed.

From Figure 3-10 the evaluation of the uneven running after starting may be seen. In the black marked region, the rotational speed data points are used to calculate the standard deviation.

For all evaluations, the same time window of the rotational speed pattern has been used.

In Figure 3-11, the relative changes of the standard deviations of the rotational speed pattern after starting cutout at -7 °C are shown. The blue bars represent the changes of fuel P7 relative to CEC reference diesel fuel, the green bar represents the change of fuel P10 relative to CEC reference diesel fuel. Between the first two bars [CEC vs. Fuel P7 (Standard Data Set) and ... (Adapted Data Set)] no significant difference is obtained; this had to be expected, because the adaptation of injection timing, start of injection and amount of exhaust gas recirculation has been extended to the temperature range above 20 °C, only.

The reduction of the rotational speed fluctuations for fuel P10 is not so impressive as for fuel P7, but ranges near 50 %, too. The error bars for all three experiments show that for both fuels the observed effect is definitely greater than the error of estimation.

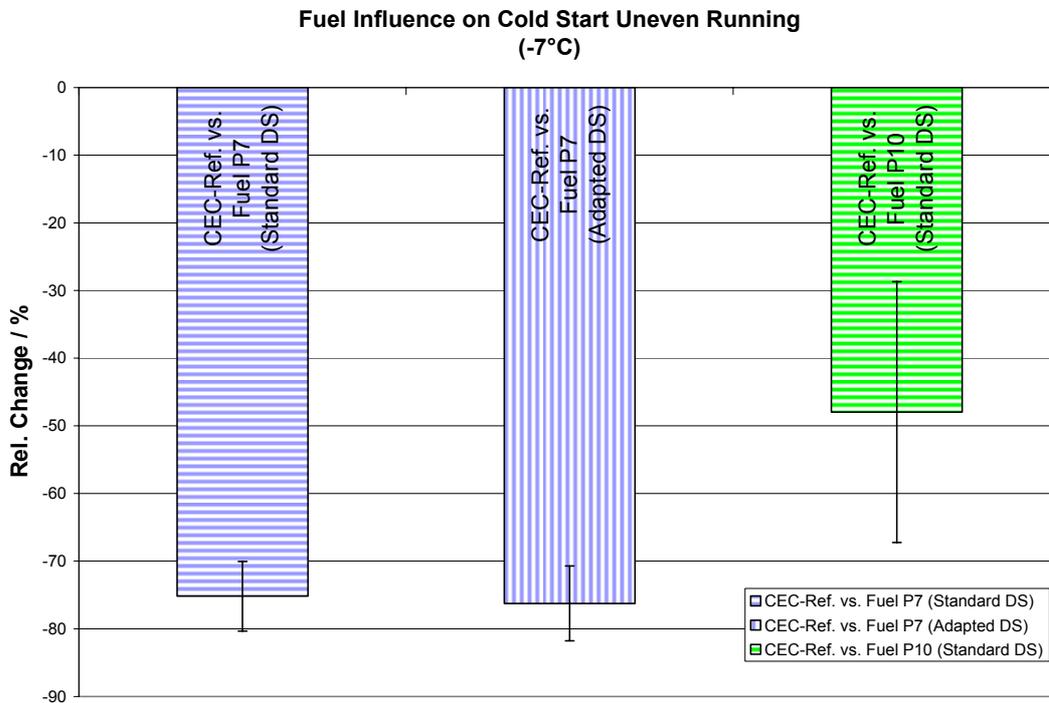


Figure 3-11: Engine behaviour with regard to running smoothness at -7°C in dependence of different Bt:-fuels compared to reference diesel

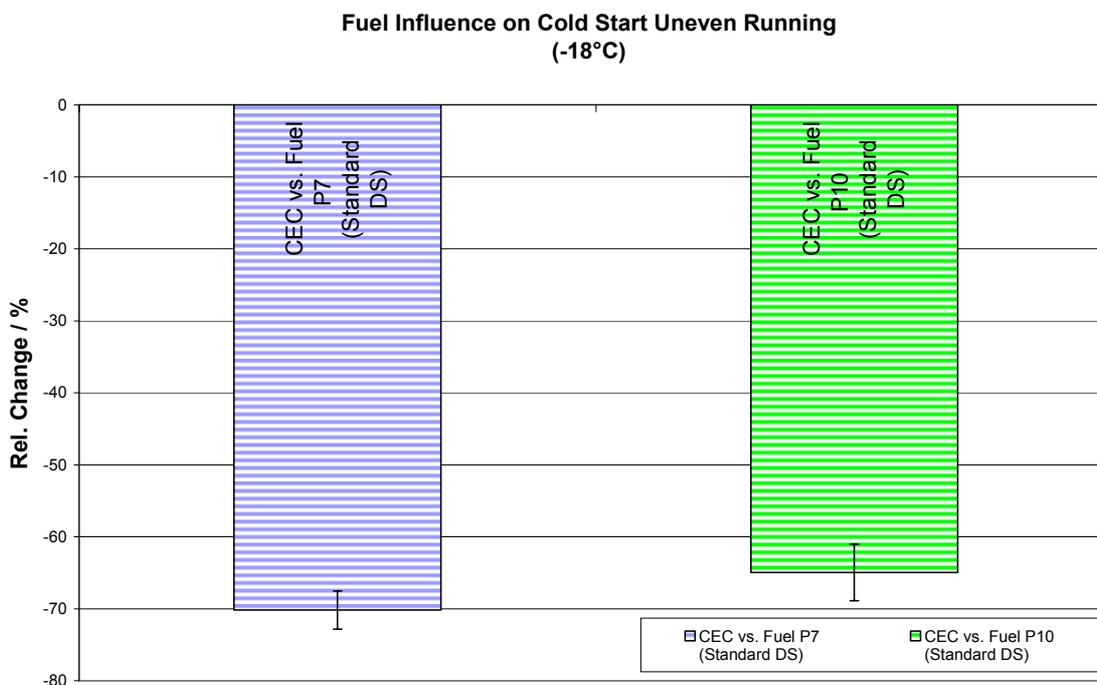


Figure 3-12: Engine behaviour with regard to running smoothness at -18°C in dependence of different BtL-fuels compared to reference diesel

In Figure 3-12 the reduction of the rotational speed fluctuations after starting cutout at -18°C for fuel P7 and P10, respectively, are shown. As before in Figure 3-6, the changes to CEC reference diesel fuel are presented.

Fuel P7 (Cetane Number: 78,9; CFPP: $-18,5^{\circ}\text{C}$) has shown to be only very slightly better than P10 (Cetane Number: 68; CFPP: -47°C) due to its higher cetane number. The cold start temperature, however, approaches the Cold Filter Plugging Point of fuel P7. On the other hand, fuel P10 might be more advantageous at very low temperatures because of its missing high molecular fraction. The cold start properties of this fuel, therefore, are similar to arctic diesel fuel. Because in the previous shown results at -7°C no advantage for the engine mapping adaptation to BtL has been found, these experiments have been performed with the standard data set, only.

In general, the BtL fuels are better suited at cold start conditions than conventional diesel fuel, as represented by the CEC reference fuel. The very high cetane number of the fuel P7 is reflected by the strongest reduction of the rotational speed fluctuations both at -7 and -18°C . At -18°C , however, the better ignition quality of BtL fuels, as expressed by cetane numbers, may be in a certain amount overruled by “unsufficient” viscosity of the fuel (it does not correspond to the standard EN590), if the start is performed at a very low temperature in the neighbourhood of its CFPP. This results in a longer starting cutout time and in a longer time to idle; therefore, the fuel P10 seems better suited in a general view at very low temperatures.

In comparison between the three test fuels, P7, P10 and CEC reference fuel, P10 exhibited the shortest time until stable idling and the shortest starting cutout, due to its composition similar to an arctic fuel quality (CFPP -47°C).

Appendix 1: Experimental limits of detection and standard deviations for chassis dynamometer emission results

A concentration is being determined with an accuracy of measurement, which is limited by the calibration accuracy of the calibration gas. For standard tests, the calibration is performed by a calibration gas sample, which is precise within 2 % error. Therefore, the standard limit of detection for a concentration is at least $\pm 2\%$.

A mass emission related to 1 km has to be calculated by the concentration of the sample in the exhaust bag, the concentration of the sample in the reference air bag, the driven distance and the CVS (constant volume sampling) volume, corrected by air pressure and temperature. For carbon monoxide, a typical standard deviation has been calculated by Gaussian error propagation to $\pm 4\%$. For carbon dioxide, the standard deviation ranges in the same order of magnitude.

If one has to compare two mass emissions related to driven distance and calculates the relative change of these emissions, it is reasonable to assume a standard deviation for this relative change of $\pm 5\%$. The same standard deviation can be estimated for relative changes of fuel economies, as they are calculated by hydrocarbon, carbon monoxide and carbon dioxide emissions during the same test.

4 Safety and toxicity aspects

4.1 Introduction

Facts about the effects on health and the environment for four different alternative fuels have been assessed. The fuels that have been studied are

- Dimethylether (DME) (CAS# 115-10-6)
- Ethanol (EtOH) (CAS# 64-17-5)
- Methanol (MeOH) (CAS# 67-56-1)
- Fisher Tropsch diesel (FT-diesel) (No CAS# available)

For each fuel has both acute and chronic effects been studied. The safety aspects (fire, explosion and handling) have also been studied.

4.2 Toxicity

4.2.1 Summary of the toxicity for the different fuels

DME has the lowest acute toxicity and methanol the highest. DME, methanol and ethanol have anesthetic effects at high exposure levels. The relative low volatility of FT-diesel fuel seldom makes it hazardous as vapor.

All fuels can cause acute skin, eye and respiratory irritation. Ingested methanol is very poisoning and aspiration of FT-diesel fuel can be fatal.

The most concern for chronic effects is the risk for cancer. The mutagenic properties of some of the different fuels have been studied quite well but for DME and FT-diesel there is little or no information available. Petroleum derived diesel fuel have been showed to give a higher risk of skin cancer probably due to the content of polynuclear aromatics (PNA). FT-diesel has very low aromatic contents and the risk for skin cancer should be very low.

Drinking of alcoholic beverages is related to cancer but there is no evidence that exposure to ethanol vapor at the exposure levels that are common in the working areas will give rise to cancer.

There are no indications that exposure to moderate levels of all the fuels is causing reproductive or developmental damages.

None of the different fuels are sensitizers but they are all degreasing agents that can cause dermatitis after prolonged skin exposure.

4.2.2 Need for further work

Since DME has only been used in small quantities until now long term studies of human exposure is missing. The possibility for DME to have a cancer genetic effect should be further investigated.

FT-diesel is also not studied as exhaustive as the other fuels and there is a need for more studies on the mutagenic and carcinogenic properties of this fuel.

4.3 Environmental

4.3.1 Emission to water and ground

Ethanol is relatively harmless in low concentrations, so it should not represent a danger to drinking water supplies. However, fuel ethanol may contain a strongly flavored denaturant to discourage people from drinking it, and this denaturant could pose a problem to drinking water supplies. Fuel methanol is dangerous in small concentrations, so a large methanol spill should represent a greater danger to drinking water supplies than the other fuels. There is no indication that DME release to water environment should pose a threat to the environment.

FT-diesel has the same environmental disadvantages as petroleum derived diesel.

There is still a lot of information missing on the environmental impact of the alternative fuels. Especially for DME and FT-diesel is facts missing since those fuels has not been in the market for so long time.

4.3.2 Emission to the air

The main concern for the emissions to the air is the formation of secondary pollutants during the combustion of the fuels. Air pollution is a serious threat to human health.

Exposure to ambient air pollution has been linked to a number of different health outcomes, from impaired pulmonary function to increased mortality in respiratory and cardiovascular diseases.

All fuels have a lower impact on the air pollution but there is still concern of combustion emissions of aldehydes from the alcohols. The formation of ultrafine particles from the different fuels should also be further investigated.

4.4 Safety

4.4.1 Physical properties for the fuels

Physical properties for the different fuels are presented in Table 17

	DME	EtOH	MeOH	FT-diesel
State at NTP	Gas	Liquid	Liquid	Liquid
Boiling point °C	-25	78	65	150-380
Vapour pressure 20 °C kPa	510	6.6	12.8	0.4
Flash point °C	-41	13	11	55-60
Flammability limits %	3.4-18	3.3-19	5.5-36	1-6
Flame temperature in air °C	2130	2030	1910	n.a
Min. ignition energy in air mJ	0.29	0.23	0,14	0.25
Autoignition temp °C	235 (350)	360	390	220-320

Table 17: Physical properties for the different fuels (n.a. not available)

4.4.2 Summary of safety aspects

DME, ethanol and methanol have less thermal radiation compared to gasoline and diesel. The invisible flame from a methanol fire and the slight visible flame from a DME fire is hazard for firefighters. Since DME is a gas there is a higher risk for explosion. The risk for static electricity should also be considered when handling DME. The alcohols have a much wider flammability limit and vapors are in the combustible range inside storage tanks. For the alcohols there is also high risk for misuse which can be fatal in the case of methanol.

4.5 Summary and conclusions

The results for the different fuels are summarized in the toxicity/safety risk matrix (Table 18). For comparison with regular fuels have also the properties for Gasoline, Diesel and LPG been include in the matrix.

	Toxicity		Environmental		Safety		
	Acute	Chronic	Air	Water/Ground	Fire	Explosion	Handling
DME	Low	(Low)?	Low	Low	Medium	High	Medium-high
EtOH	Medium	Low	Low	Medium	Medium	Medium	Medium-high
MeOH	High	Low	Medium	Medium-high	Medium-high	Medium	High
FT-diesel	Medium	Medium-high	Medium	Medium	High	Low	Low
Gasoline	Medium	Medium-high	Medium-high	Medium	High	High	Medium
Diesel	Medium	Medium-high	High	Medium	High	Low	Low
LPG	Low	Low	Low	Low	Medium	High	Medium

Table 18: Toxicity / Safety risk matrix of different fuels

From the matrix it can be concluded that there are both advantage and disadvantage for all fuels that have been investigated. For DME the advantages are the low toxicity both for humans and the environment. The drawback for DME is the safety considerations. Ethanol is a more safety fuel with a low toxicity. Methanol has a high acute toxicity which also influences the safe handling of the fuel. For FT-diesel there is as for diesel fuel a high safety risk when there is a fire. The toxicity and environmental is comparable with regular diesel.

5 Impact on payload

The storage properties of fuels are linked to several aspects such as liquid or gaseous state, energy density, etc. The fuel will also have impact on other components, in some cases different exhaust aftertreatment systems can for instance be used in combination with alternative fuels.

The energy density of the fuel is very important when it comes to long haul trucks and bus coaches. Less energy dense fuels are more suited for captive fleet applications such as taxis, buses and distribution trucks. The impact on payload is described below from three different aspects. These aspects are energy density, payload and cruising range.

5.1 Energy density

The energy density of fuels depends on the energy content and the density of the fuel. The LHV of various fuels can be found in Figure 5-1.

DME:

The lower heating value (LHV) of DME is 28,43 MJ/ kg. The density of DME is 668 kg/m³ in liquid phase at 0,5 MPa pressure (20°C). In comparison to conventional diesel fuel DME has approximately 66% of the energy density on mass basis (see Figure 5-2). Since a pressurized tank with a liquid phase needs some expansion room the energy density is reduced by approximately 10% . At atmospheric pressure DME has approximately 0,17% energy on mass basis compared to conventional diesel fuel. On volume basis DME has approximately 55% of the energy content compared to conventional diesel.

Ethanol:

The lower heating value of ethanol is 26,78 MJ/ kg. The density of ethanol is 790 kg/m³ at 20°C. The energy per volume of ethanol is 67% of gasoline.

FT-diesel:

The LHV of FT-diesel is approximately 44 MJ/kg. The density of FT-diesel can be varied in the production but is typically 780 kg/m³. Compared to conventional diesel the energy density of FT-diesel with the above mentioned density and heat value is approximately 3% lower on volumetric basis.

Bio-methane:

The lower heating value of bio-methane is somewhat dependent on the quality of the gas. Biogas which is used for vehicle applications normally contains approximately 97% methane and approximately 3% carbon dioxide. The LHV is 35,82 MJ/ Nm³. Biogas can either be used in liquefied state or compressed.

The most common application is compressed biogas at 20 MPa onboard the vehicle. A fuel tank with compressed bio-methane at 20 MPa has approximately 21% energy content compared to a similar size tank of conventional diesel fuel. At atmospheric pressure bio-methane has approximately 0,10% energy per volume compared to conventional diesel fuel.

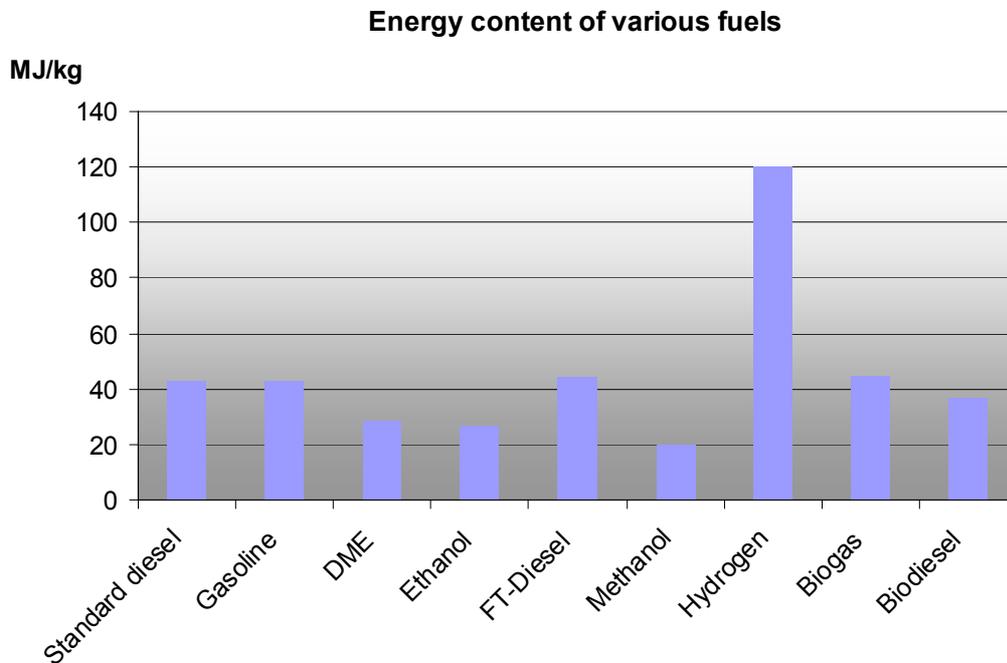


Figure 5-1 Energy content of various fuels

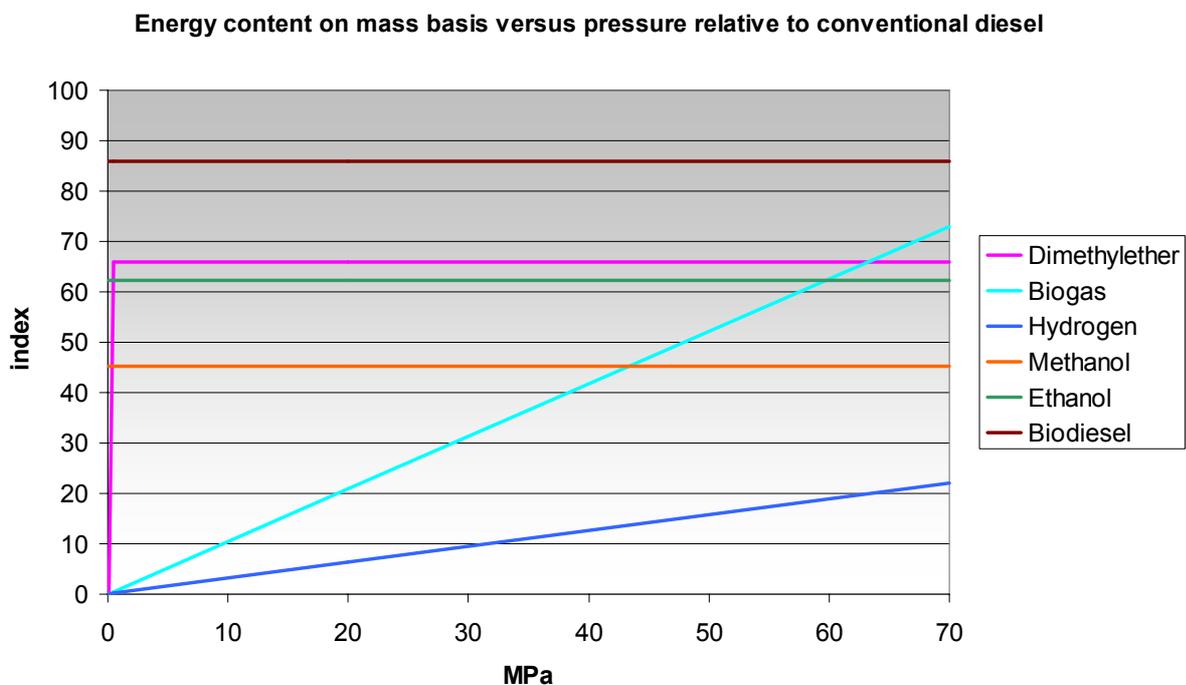


Figure 5-2; Energy content versus pressure

5.2 Payload

The payload of a commercial vehicle can either be restricted by volume or weight. The type of restriction is dependent on the application of the vehicle. In local distribution approximately 90% of the transports are restricted on volume. Therefore it is important that the fuel tanks do not significantly restrict volumetric load carrying capacity. When vehicles are compared it is important to take all systems that might be affected into consideration. The layout of the vehicle can influence the payload since the use of different subsystems such as exhaust aftertreatment might be influenced. The vehicle mass for each vehicle type is described below.

DME:

In order to have the same range a double size tank is needed for DME compared to conventional diesel fuel. However DME is still considered viable for long-haul transports. Due to lower noise and exhaust emissions it is possible to save space and weight by less emission after treatment systems and noise shields.

Ethanol:

Ethanol requires fuel tanks that are approximately 40% larger compared to conventional diesel. Since ethanol offers emission reductions less aftertreatment equipment is needed.

FT-diesel:

Since FT-diesel has slightly lower energy content on volume basis (~3%) the tanks should be slightly larger. However it is judged that there will be no impact on the payload for FT-diesel.

Bio-methane:

Bio-methane requires fuel tanks that are approximately five times larger compared to conventional diesel. Since bio-methane offers emission reductions less aftertreatment equipment is needed. The need for larger tanks will have an impact on payload since the tank system will be much heavier compared to conventional diesel fuel tanks.

5.3 Cruising range

The cruising range of a vehicle is not necessarily affected by the introduction of alternative fuels. However blending of i.e. ethanol into conventional gasoline will give the mix lower energy content per volume. This reduces the cruising range.

For fuels that need dedicated vehicles the cruising range needs to be taken into consideration in order to fulfil the features needed. In some cases a reduced cruising range does not have to be the same as conventional diesel.

In order to maintain the cruising range larger fuel tanks are needed for fuels that are less energy dense. The energy efficiency of the vehicle also affects the cruising range. The diesel engine has an advantage compared to Otto (spark-ignition) engines.

DME:

Since the energy efficiency of a DME fuelled diesel engine is approximately the same as for a diesel engine fuelled with conventional diesel fuel the energetic fuel consumption for these vehicles will be the same. The cruising range of a DME fuelled vehicle with the same size tank (on volume basis) will be approximately 55% of conventional diesel fuel. This implies that in order to get the same cruising range a DME tank needs to be approximately twice as large as a conventional diesel fuel tank.

Ethanol:

The volumetric consumption of ethanol increases compared to gasoline due to the lower heating value of ethanol. The increase is approximately 35% on volume basis.

FT-diesel: The cruising range is slightly affected due to the 3% lower energy content on volume basis. This is however a very small impact.

Bio-methane:

Due to the lower energy density of bio-methane the cruising range is approximately 21% of conventional diesel fuel. Thus in order to get the same range the tank volume needs to be approximately five times larger compared to conventional diesel fuel.

List of Figures

Figure 1: Boiling Range RENEW fuels	11
Figure 2: Correlation flash point and initial boiling point	13
Figure 3: Dependency of the fuel density of the center of boiling range	13
Figure 4: Correlation FBP and lubricity	14
Figure 5: Weight change of NBR and HNBR in diesel fuel and in UET-BTL.....	19
Figure 6: Volume change of NBR and HNBR in diesel fuel and in UET-BTL.....	19
Figure 7: Acid content of some UET-BTL fuels (Results ITN).....	20
Figure 8: Appearance of the test strip after the 1000 h test (P8 without additive).....	22
Figure 9: Appearance of the test strip after the 1000 h test (P16 with APSP1 additive)	23
Figure 10: Relative emissions of the three BTL fuels compared to conventional EN 590 diesel fuel in the NOx optimized application	25
Figure 11: Relative emissions of the three BTL fuels compared to conventional EN 590 diesel fuel in the PM optimized application	25
Figure 12: Relative emissions of the three BTL fuels compared to EU4 emission limits in the NOx optimized application	26
Figure 13: Relative emissions of the three BTL fuels compared to EU4 emission limits in the PM optimized application.....	26
Figure 14: Influence of Cetane no. on vehicle emissions in NEDC.....	28
Figure 15: Relative emissions of UET - straight run BTL compared to conventional EN 590 diesel and EU4 limits. Vehicle with oxidation catalyst and particulate filter.....	30
Figure 16: Relative emissions of UET - straight run BTL compared to conventional EN 590 diesel and to EU4 limits. Vehicle with oxidation catalyst, without particulate filter ..	30
Figure 17: Relative emissions of GTL fuel in a hardware optimized engine compared to a standard application with conventional EN 590 diesel and to EU4 limits. Vehicle with oxidation catalyst and particulate filter	31
Figure 18: Emission reduction factors for BTL fuel and different emission reduction technologies	32
Figure 19: Basic characteristic of HCCI.....	33
Figure 20: 10 Soot emission results at different intake manifold pressures	35
Figure 21: Distillation and composition of the fuels.....	36
Figure 22: 150rpm, smoke and specific fuel consumption versus mean effective pressure.....	37
Figure 23: 1500rpm supercharging, smoke and specific fuel consumption versus mean effective pressure	37
Figure 24: Emission and consumption behaviour of BtL-fuel P7 in comparison to reference diesel at standard temperature and -7°C measured with standard ECU data set.....	42

Figure 25: Emission and consumption behaviour of BtL-fuel P7 in comparison to reference diesel at standard temperature and -7° measured with adapted ECU data set42

Figure 26: Overview on emission and consumption behaviour of BtL-fuel P7 in comparison to reference diesel at different temperatures and different ECU application43

Figure 27: Emission and consumption behaviour of two BtL-fuels (P7, P10) in comparison to reference diesel at -7°C measured with standard ECU data set 44

Figure 28: Overview of emission and consumption behaviour of two BtL-fuels (P7, P10) in comparison to reference diesel at standard temperature and -7°C measured with standard ECU data set45

Figure 29: Time consideration of starting cut out and idle mode with different BTL-fuels in comparison to reference fuel at different temperatures (-7°C, -18°C).....46

Figure 30: Cold start behaviour at -7°C: course of rotational speed and injection quantity at starting phase with BtL kerosene high (P7) and reference diesel..... 47

Figure 31: Cold start behaviour at -7°C: course of rotational speed and injection quantity at starting phase with BtL light kerosend (P10) and reference diesel48

Figure 32: Cold start behaviour at -18°C: course of rotational speed and injection quantity at starting phase with BtL kerosene high (P7), BtL light kerosene (P10) and reference diesel48

Figure 33: Scheme of a Rotational Speed Fluctuation Evaluation.....49

Figure 34: Engine behaviour with regard to running smoothness at -7°C in dependence of different Bt:-fuels compared to reference diesel50

Figure 35: Engine behaviour with regard to running smoothness at -18°C in dependence of different BtL-fuels compared to reference diesel 50

Figure 36 Energy content of various fuels57

Figure 37; Energy content versus pressure57

List of Tables

Table 1: Fuel Types in Renew	7
Table 2: Overview of fuels and tests investigated in Renew	9
Table 3: Overview of fuels and their suppliers	10
Table 4: EN 590 limits to fuel properties regarding compatibility with materials	16
Table 5: WWFC limits to fuel properties regarding compatibility with materials	16
Table 6: Norm tests for the compatibility of plastics and rubbers.....	17
Table 7: Results of the elastomer tests at ITN	18
Table 8: Copper and ferrous corrosion test	20
Table 9: Weight change in corrosion tests.....	22
Table 10: Fuel properties.....	27
Table 11: Emission reduction factors for BTL fuel and different emission reduction technologies	32
Table 12: Fuel characteristics for HCCI tests at Regionov	34
Table 13: Main properties of the tested fuels.....	36
Table 14: Typical emissions reduction from in house tests respective from literature ...	39
Table 15: Change of fuel consumption and CO ₂ emissions of Ethanol and Methane relative to gasoline.....	39
Table 16: Typical Properties of UET Fuels and of Europeand Reference Diesel Fuel (n.d. = not determined)	40
Table 17: Physical properties for the different fuels (n.a. not available)	54
Table 18: Toxicity / Safety risk matrix of different fuels	54

SECTION 2

COMPARATIVE ASSESSMENT OF DIFFERENT PRODUCTION PROCESSES

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0 Executive Summary

A variety of technologies promises to have a high potential for the production of fuels for automotive application from biomass via a synthesis gas (BtL). Thereby the techniques to produce and to convert this synthesis gas into a synthetic biofuel differ in a wide range (e. g. with regard to input material, plant size, reactor types, development status). These different process technology approaches – which are analysed and further developed within Renew (SP 1-4) – may not only result in different product characteristics and engine performances (examined in Renew task 5.4.1) but also in advantages and disadvantages of the production route itself (efficiencies, development status, technical effort etc.). In order to allow conclusions which technologies are advantageous in which market niche and to assess the need for further development, a consistent technical assessment of the different pathways is required.

Against this background the main overall objective of the technical assessment is to

- perform a consistent comparison of existing BtL-concepts,
- show both pro's/con's and prospects/risks of the BtL-systems

This assessment has involved different viewpoints and expertise (academic scientists, technology developers, process industry operators) in order to present a clear picture on

- the profiles and characteristics of the different BtL-technologies
- the bandwidths of technical performance (in particular energetic aspects)
- the technical restraints (in particular some aspects of practical industrial realization)
- potential meaningful application fields
- R&D-challenges to be met to secure full industrial and commercial deployment.

To focus on the most important aspects, the technical assessment is structured to answer a selection of key questions in the field of

- concepts profiles / concept cluster
- technical performance of each concept
- industrial implementation perspectives

Concept Profiles and Assessment Method

The process chain of the production of synthetic biofuels can be simplified into six basic steps (cf. Figure 0-1). First, the solid biomass is pretreated mechanically, thermally and/or thermochemically before it is gasified into raw gas in the gasification unit. Then the raw gas is cleaned from tar, particles and other impurities (e.g. H₂S) and conditioned for synthesis, i.e. the gas composition is adjusted to the synthesis requirements (e. g. H₂/CO-ratio).

Afterwards the cleaned and ‘adjusted’ syngas is converted catalytically into raw products in the synthesis. This raw product is finally upgraded to a direct applicable motor fuel. This principle process chain and its steps is the basis for the following description of BtL-concepts.

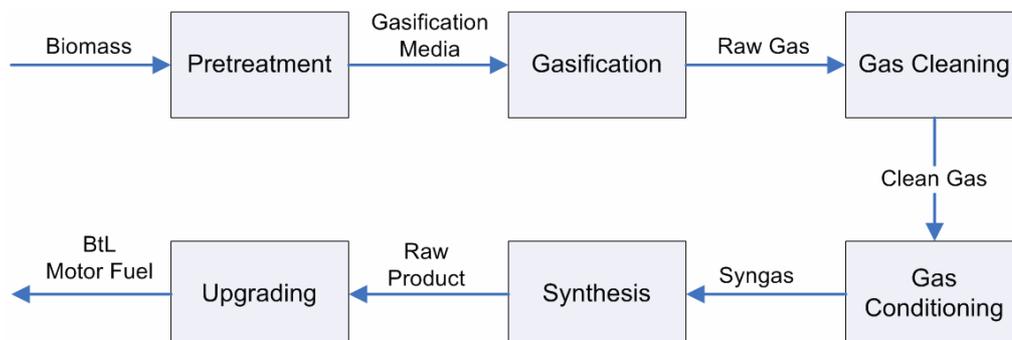


Figure 0-1: Production Process Chain of Synthetic Biofuels (Basic Steps)

BtL-concepts in the context of XtL

Within Europe different BtL-technologies are under development. Independent from conceptual work and basic research it is noticeable that the present demonstration activities are mostly clustered in German, Swedish, Finish or Austrian companies based on many reasons (experiences from coal or biomass gasification, national political drivers etc.). The BtL concepts investigated within RENEW are among the most relevant and developed ones. Before an overview on concepts considered, the sizes of XtL-technologies and similarities with BtL are presented in the following.

Sizes of existing XtL-plants. XtL is a synonym for the production of synthetic fuels from different feedstock. Gas to liquids (GtL) or Coal to liquids (CtL) are currently the most important industrial processes for synthetic (liquid) fuel production. Concerning the fuel synthesis part, GtL and CtL use similar technologies (Fisher Tropsch synthesis) but the feedstock and syngas production – and therewith also technical aspects (also shown in chapter 2 and 3) – are different. Because of historic and economic reasons, commercial XtL-plants have different sizes and installed capacities.

So far, only Sasol and Shell Fischer Tropsch technologies are implemented at industrial scale and are being further developed in new industrial GTL projects mostly in Qatar. GtL projects under development should bring the expected production capacity up to 174 000 barrel per day in 2010, a very small share of the large diesel market (see Figure 0-2).

Similarities of XtL and BtL. The differences in the plant sizes between BtL and GtL/CtL does not obligatory lead to completely new process design along the BtL production chain. There are many similarities between today’s commercial XtL- and future BtL-production routes.

Details on the choice of technology should to be taken from chapter 2 and 3, but some principal similarities with future BtL-plants are summarised in Figure 0-3. Thereby the main differences result from the feedstock properties and lead to partly re- or new-design of system components (pre-treatment of biomass & gasification, tar or sulphur-removal etc.). In contrast to that, after syngas production many technologies/experiences could directly be applied and are more restricted by economics (e. g. gas cleaning on scale of a few Megawatts).

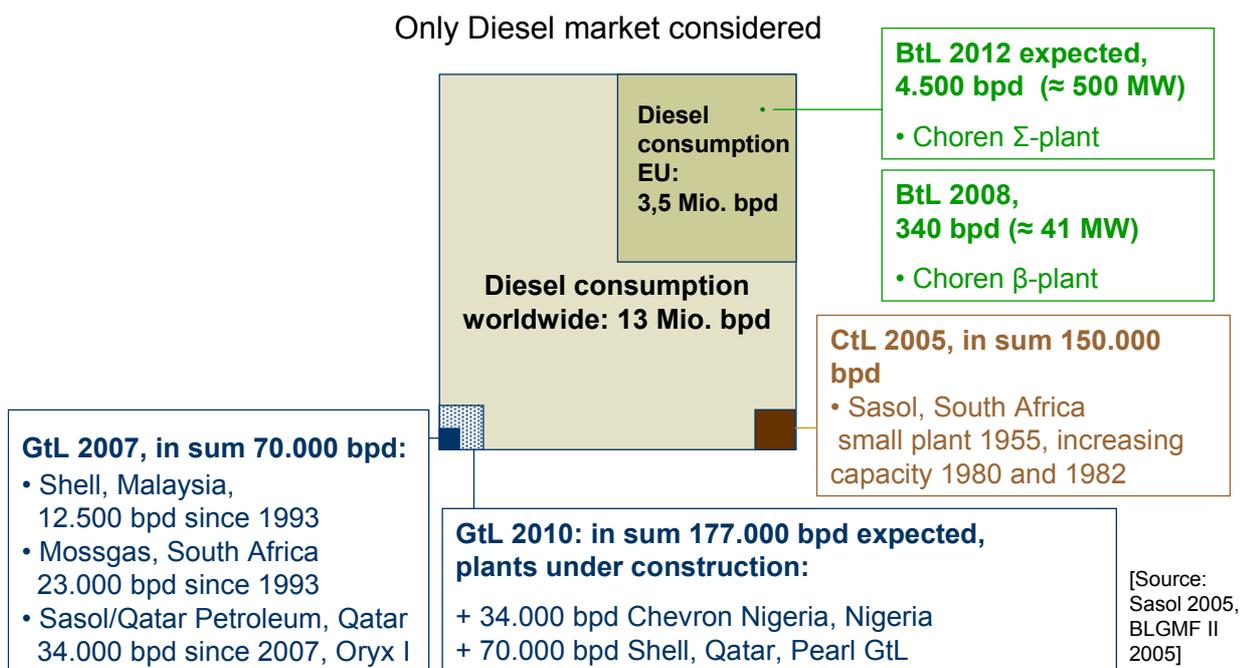


Figure 0-2: Scale of industrial/planned XtL-plants in comparison with world diesel consumption

	GtL	CtL	BtL
Feedstock	natural gas	(hard) coal	(woody) biomass
Feedstock CHO composition	$CH_4 \rightarrow H/C=4$	$CH_{0,6}O_{0,1} \rightarrow H/C=0,6$	$CH_{1,6}O_{0,7} \rightarrow H/C=1,6$
raw material deposit/caloric value	central / 37 MJ/kg	central / ≈ 33 MJ/kg _{wf}	decentral / ≈ 18 MJ/kg _{wf}
natural water content	low	low	high
effort on pretreatment/milling to mm's	low	high / feasible	high / R&D
pressure level	constant high	restricted by feedstock	restricted by feedstock
effort on gas cleaning	low	high	high
CO ₂ -removal from rawgas	not needed	Rectisol	concept specific
effort on gas conditioning	low	high	high
synthesis/product upgrading	commercial technology	commercial technology	commercial technology
importance of waste water handling	depending of FT-synthesis	high	high

Figure 0-3: Similarities and differences between BtL and GtL/CtL (red-differences, green-similarities)

Differences between Renew Concepts. At present the production of synthetic biofuels is under discussion for various options of biomass feedstock pre-treatment, type of gasifier, gas cleaning as well as different options for product synthesis and final upgrading. Further on, it could be realised in different scales under usage of different types of biomass feedstocks and with different potential integration schemes with existing industrial facilities (pulp & paper, refining, petrochemicals etc.). Considering this variety of potential options, the different BtL-production concepts will be evaluated within this TA. A more detailed overview is given in chapter 3.2 and describes the “Philosophy of Design” of each concept.

However, the main influence on concept design is given by (a) the capacity/scale and (b) the integration of (by-)products within the energy system (stand alone concepts, district heat system, pulp mill or refinery integration). Depending on these overall options the system of gasification, starting from this the pre-treatment and finally the gas cleaning can be designed in many different ways. Figure 2-4 gives an overview of the design aspects of the different concepts analysed in Renew. Thereby, these concepts are oriented on present research, development and demonstration activities of (industrial) partners of SP 1 – 4. However, also other than the analysed concepts designs are possible – like e. g. the production of FT-Diesel integrated into a pulp mill.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D	CFB-E
Scale	Medium	Large	Medium	Medium	Medium	Small / (Medium)	Medium
End Product	FT-Diesel		DME	Ethanol	FT-raw-product		Ethanol
Gasification	EF				CFB		
- thermoch, pretreatment	carbonisation	pyrolysis	—————	torrefaction			
- Gas cleaning / conditioning	conventional physical absorption:				dedicated technologies		conv. physical absorption:
	Selexol	Rectisol		Selexol			Selexol
Industrial Integration*	Stand alone / Location	Refinery Integration	Pulp mill	Stand alone / Location	Refinery Upgrading	District Heat +Refinery	Stand alone / Location

Figure 0-4: Main technical differences between Renew concepts defined to technical assessment (*Industrial integration concepts as studied in RENEW: integration of mass- and energy flows of the BtL-plant with other industrial plants / consumers)

Assessment Method and Quality

Considering the fact that each of the concepts has been developed within a specific background of technical and economic context leading to a specific optimisation of the process conditions, differences in the technical performance are observed. To compare the most relevant differences, a multicriteria assessment methodology has been applied which is described in chapter 4. This method allows to evaluate different pros and cons on

- efficiency,
- flexibility,
- industrial development status of selected technology options

Therewith a transparent technical assessment could be ensured. The quality of this assessment is (only) limited by the quality of the original data and information. Because of the present development status in this contrast it must clearly be pointed out that:

- It is unavoidable that the data and information applied for the following analysis origins from different sources (simulation, estimation or detailed engineering from third parties) and are based on different development status of the partners involved (pilot plants, laboratory experiments or literature). Thereby not in each concept case a 100 % data consistency could be achieved.
- The most relevant parameters for indicator calculations were fixed within Renew but different calculations and databases have been used by the partners from SP1-4. Additional uncertainties are added by different calculations and databases¹.
- Beside this, also differences in terms of the level of maturity and the concepts developers 'philosophy' (intention) exists. For this purpose, a higher level of process information and more specifically defined plant location conditions would be required. This would demand a much more thorough engineering effort which is not included within this assessment.

Thus, this TA must be considered as a preliminary evaluation of selected questions rather than a comprehensive study; i.e. an analysis with the depth of a pre-feasibility study. Based on the goals of this evaluation and based on the available data quality of recently developed BtL concepts, this work represents a rigorous evaluation of selected concepts by the relevant technical criteria.

Technical Performance of the Concepts

Efficiency

One of the main process indicators (also with high relevance for economic and environmental issues) is the overall efficiency of the conversion plant. To calculate efficiencies different definitions are possible and legitimate in so far as coherent boundary definition is ensured. Figure 0-5 and Figure 0-7 summarises the overall efficiency of the concepts assessed based on agreed definitions (cf. chapter 5.1).

- a) "main fuel" applying the "Conventional Method": Here the focus is on motor fuels applicable without further upgrading (grey column left to the staple)
- b) "all liquids" applying the "Conventional Method": the focus is on all fuels that can be applied as motor fuel with or without further upgrading (black column right to the staple).

¹ For example SP 4 has provided Deliverables on their technical developments after finishing of this technical assessment. These information can act as further information source.

- c) “all energy outputs” applying “CHP-F Method”: The coloured staple reflects the sum of single efficiencies, calculated on the CHP-F method, whereby the colours are representing the parts listed in the legend of the figure. The sum is the overall efficiency according to the CHP-F method.

Based on this efficiency calculations the following conclusions can be drawn:

- The qualitative differences between the concepts are not influenced by the calculation methods applied (as far as the same energy flows are included). But for a comparison with quantitative data from other studies the question “how was the efficiency defined” is of high importance to draw conclusions.
- The concept specific differences mainly result from the development focus/design specificity:
- Independent of the method of efficiency calculation the BLEF-DME concept is the most efficient. This results from the higher efficiency of the DME synthesis compared to the other synthesis routes (like FT hydrocarbon production) and the process integration of heat and power provision with a pulp mill².
- With today’s conceptual design for Diesel production from solid biofuels (scenario “starting point” (SP)), the highest efficiency have been calculated for the cEF-D concept. Reasons for this are the high cold gas efficiency of the gasifier compared to other entrained flow (EF) gasification concepts, the high level of reactive components for the synthesis (CO/H₂) in the syngas compared to the fluidized bed gasifiers and the assumed energetic integrations (e.g. heat or tail gas recovery).
- In the future (scenario “maximum fuel” (MF)) the ICFB-D (MF) concept shows promising opportunities for optimisation of the fuel production efficiency. The main reason for this is change of design focus from trigeneration to solely fuel production. However, these improvements have to be proven.
- Considering diesel production, the 50 MW ICFB-D (SP) concept is the weakest since not optimised on high diesel yield; but as the focus of this concept is on tri-generation, this concept has the most efficient use of biomass of all concepts considered. The main reason is the utilisation of low temperature heat, which has been considered in the special designed ICFB-D concept.
- Concepts dedicated to ethanol production by means thermo-chemical pathway yields lower efficiencies. This is due to the data used for modelling comes from literature, therefore some processes may not be fully reliable, resulting lower efficiencies in several process steps. Further technology development in alcohols synthesis is indeed required, and not big technology improvement was assumed for doing the calculations.

² Gasifier is fed with 600 MW black liquor from the pulp mill. To balance the original steam and electricity from black liquor only 500 MW of woody biomass are required. This optimised process integration is one reason for the higher efficiency.

- In comparison with thermal efficiencies of CtL (35-50 %) and GtL (55-65 %) the expected BtL-efficiencies are in the upper end of a realistic range when considering the main differences and similarities (e. g. heating value of the feedstock, cold gas efficiencies, number of process steps) but need to be demonstrated/verified in real plants.
- Using external hydrogen allows higher fuel yields (approximately doubling of the BtL-output). But such “external hydrogen provision” (in Renew analysed via electrolysis-hydrogen) leads to significant lower primary energy efficiency (approximately bisection of the efficiency)”.

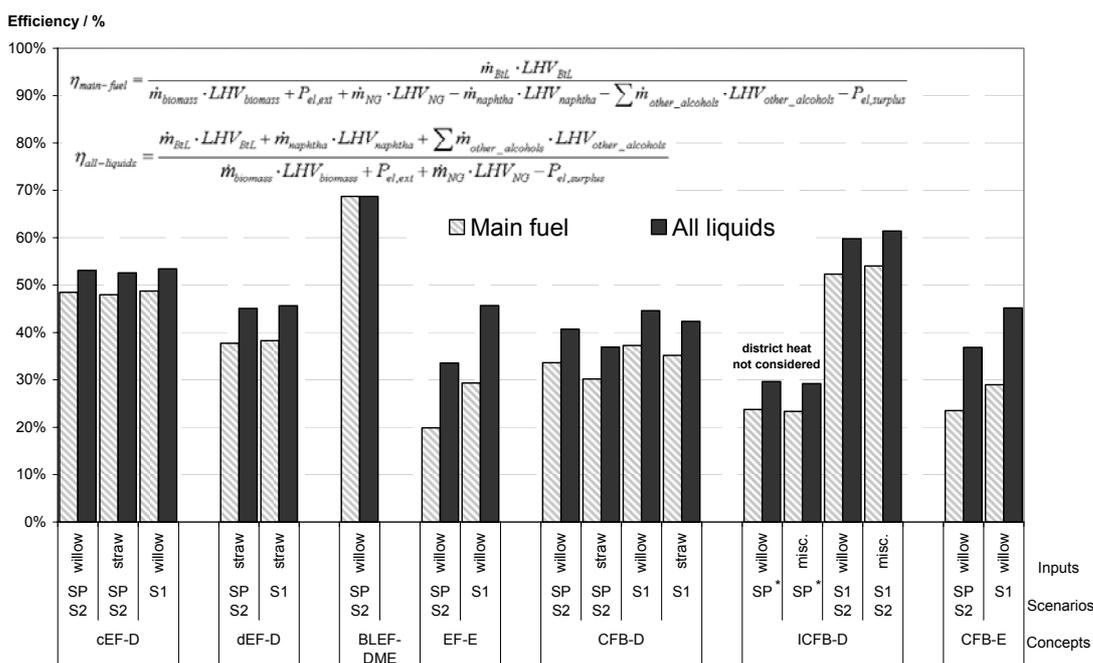


Figure 0-5: Overall Efficiency of the Renew-concepts based on the conventional calculation method (main fuel and all liquids); * For Trigeration Concept ICFB SP-scenario only conversion rate from biomass to fuel is presented – i.e. district heat output has not been considered within the efficiency calculation; el-electrical; NG-Natural Gas; ext-external

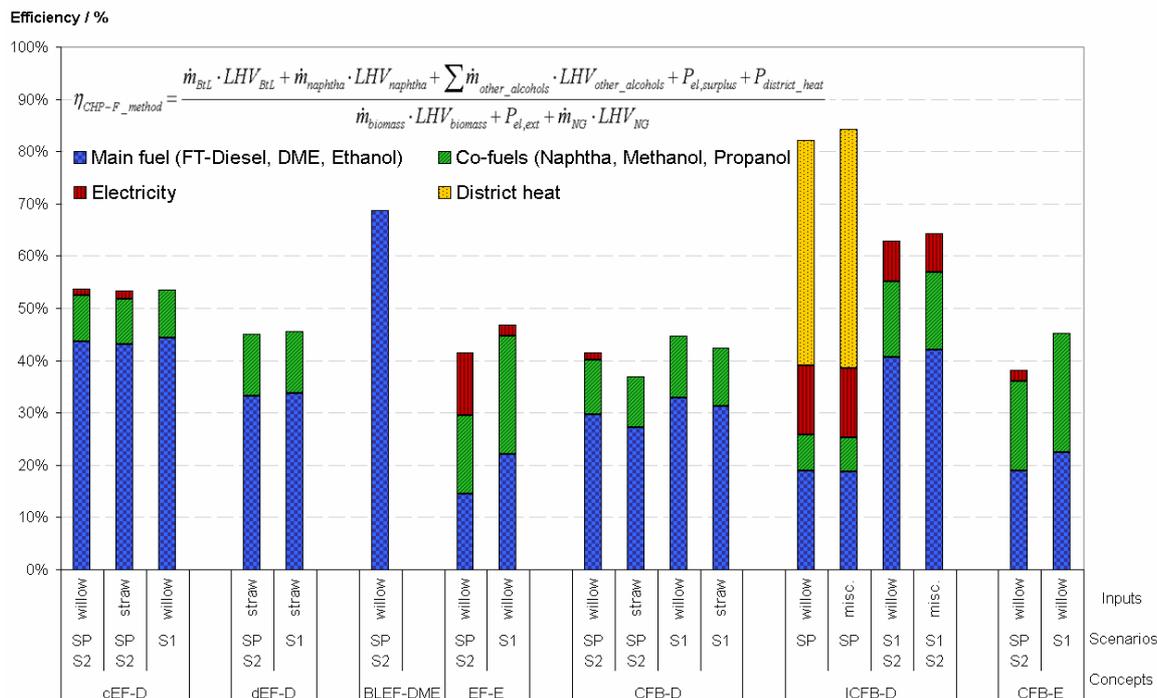


Figure 0-6: Overall Efficiency of the Renew-concepts based on the CHP-F method; el-electrical; NG-Natural Gas; ext-external

Flexibility

Besides efficiency, the following flexibility related criteria are also of importance from an industrial viewpoint to compare the different concepts:

- Choice of feedstock: which biomass types and properties can be commercially used (and lower future cost)?
- Choice of end product: which syngas production and clean up concepts can be combined with which synfuel production process ?
- energy integration: what are the opportunities and limiting factors to improve the efficient use of energy by optimised process integration ?

These questions have been analysed based on different indicators and are discussed in detail. But based on the knowledge available at present the following conclusion can be drawn:

- Identification of the “most flexible concept” and therewith the potential best industrial performance can not be drawn yet. For each of the three mentioned criteria (feedstock, end product, energy integration) the specific conditions of the BtL industrial plant (i.e type and volume of feedstock, local industrial synergy etc.) will have a crucial influence on technical choices and the overall performance will result from optimisation between conflicting goals (like for example maximum biofuel production versus maximum bioenergy production and CO2 saving). Therewith none of the concepts can be excluded or favoured in general.

- In principle, the feedstock flexibility of the BtL concepts is high because gasification is able to deal with a broad range of type and quality of feedstocks in so far they contain carbon and hydrogen. This is valid for EF but also CFB-gasification. But only a couple of feedstock has already been tested in pilot plants. Commercial application should be technical possible, but need demonstration and verification on an industrial level. For practical reasons (different storage, conditioning and transport systems for different types of biomass), commercial BtL-plants will probably be adapted to 5 - 6 biomass types at maximum.
- Regarding the end product flexibility (or choice of synfuel process) the scale of the envisaged BtL-plant will have a major influence because of economic considerations. For the BtL production in large scale the syngas conditioning can adapt the syngas quality to the synthesis process demands (FT, DME, Alcohols) in principle. As result of these assessment works there is no obvious “show stopper” of product flexibility from a strictly technical viewpoint. This will more or less depend on location specific conditions and economics (economy of scale). But for small (and medium) scale it is obvious from techno-economic viewpoint that the product flexibility is limited. For example the upgrading of FT syncrude into commercial grade fuels and/or blend components can only be implemented in a refinery environment for techno-economic reasons. Thus, for small scale application processes a “lower effort synthesis” (SNG or Methanol) could be one technical option in short- or medium term.
- Since the energetic integration has a high influence on the overall efficiency (see above) and therewith on the BtL-cost it is a main criteria for future plant developments. But in many cases it could be a limitation in finding suitable locations/offsets. For example the high process integration of pulp-mill Annex plants (cf. BLEF-DME concept) leads to high efficiencies but can only be installed directly at such location. The same is true for concepts producing large contents of district heat (as ICFB-D). Therewith this aspect is not limited by the available BtL-technologies but rather by finding suitable locations.

Development Status

Besides efficiency and flexibility, the technical assessment of the different RENEW concepts has been extended to a preliminary qualitative evaluation of the development status of the technologies involved, based on an industrial perspective. A selection of industrially relevant criteria have been analysed regarding the overall concept, the gasification, the gas cleaning and gas conditioning as well. The criteria investigated have been selected because they allow to address some of the most critical industrial challenges in the implementation of new and complex technologies. The intention is not to request and/or perform in depth studies corresponding to each of them in the framework of the RENEW project but rather to identify those concepts that have started to tackle them and can thus be considered as more industrially advanced.

These criteria are essentially based on qualitative assessment and should not be considered as a quantitative measurement of relative maturity of the different concepts:

- Scale up issues: number of steps/needed from actual status up to commercial scale and justification (reactor design, scale up factors, experiences from other plants, calculation method etc.)
- Process design issues: availability of advanced process data (detailed mass and energy balance, utility flows...) reflecting in depth investigation of different process conditions (start of run, mid run and end of run) needed to for the engineering design of the industrial plant.
- Critical items identification, sourcing and management: for example, identification and preliminary selection of reliable catalyst and/or other critical component providers.
- CAPEX/OPEX data: availability, methodology for calculation and level of detail/accuracy of these data gives an indication of the level of industrial development.
- Availability of plot plan, process water flow, HSE studies (HAZOP, HAZID ..): similar to the cost issues the concept development will be influenced by site issues. Thus, the availability/status of site related engineering work gives an indicator on level of development.
- Process modelling status and quality: overall chain process modelling as well as specific process units modelling of mass, thermodynamic, kinetics and/or fluid dynamics data also reveal the level of development for such complex process chains.

Concept scenario	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D	CFB-E
	SP + MF					SP / MF	SP + MF
scale up steps	1,5	(1)	1,5	no gasifier	2	1/2	no gasifier
mass balances (start/end run)	β: existing ε: progress	not available	included	not available			
cat. provider contracted	1	-	3	-	-	(1)	-
CAPEX/OPEX	available	not available	available	simulation level	not available	avail. / n.a.	simulation level
plot plan	available	not available	available	not available	not available	not available	not available
water flow plan	β: existing Σ: progress	not available	available for gasifier	not available	not available	not available	not available
HSE studies	β: existing Σ: progress	not available	not available	not available	not available	partly / n.a.	not available
modelling quality	test data + mass balances	mass balances	(test data +) mass balances	mass balances	mass balances	(test data+) mass balances	mass balances

Figure 0-7: Comparison of Renew-concepts from viewpoint of selected industrial criteria (Scale up factors: number of steps/needed from actual status up to commercial scale; mass balances: knowledge regarding the changes of process conditions under start up/end run; cat. Provider: number of commercial providers contracted for synthesis catalyst provision in future plants; CAPEX/OPEX: knowledge of capital- and operation-related costs for the main equipment with preliminary sizing data; plot and water flow plan, HSE issues: developments status of project specific plant design assessed by availability of a plot plan and water flow plan and HAZID and/or HAZOP studies; modelling quality: knowledge of quality of data sources of SP5; n.a.-not available)

Based on these industrial indicators it can be concluded that there are significant differences between the Renew concepts in terms of maturity. This results mainly from the different time-frames of process developments of the technology providers (3 up to more than 10 years experiences) and the development focus (from research institutes up to industrial enterprises with different departments for engineering, construction etc.). Regardless these large differences it also has to be pointed out, that none of the concepts can be called “proven technology” that can be bought off-the-shelf. Some of the concepts show a promising maturity justifying the development of a first industrial demonstration project in 50 MW-range together with (industrial) monitoring. Others need further development and demonstration in pilot scale (<10 MW-range) also including monitoring.

Research and demonstration demands

Research, demonstration and monitoring are needed in different fields:

- Feedstock preparation, this includes for example
 - Integration of feedstock with low ash melting point into CFB,
 - thermo-chemical pre-treatment for EF,
 - handling of feedstock of different qualities
 - feeding systems, e.g. feeding into pressurized reactors
- Gas cleaning and conditioning; especially for low temperature gasifier (i.e. CFB)
- Modelling/Analysing/Monitoring of critical process facilities
- Raw product upgrading including refinery integration of syncrude

But the most important technical measures for further development of BtL-plants is to develop scale-up strategies including the integration of the different process steps along the complete chain (biomass to transportation fuel) in order to demonstrate the effective process performances and reliability that should be expected to secure financing. Thereby the focus (also from economic viewpoints) must be to achieve industrial reliability and technical performance (energy integration to achieve high efficiency/yields).

Time Horizon of BTL-Implementation

Besides technical criteria investigated above (efficiency, flexibility and development status) other system-technical aspects have to be considered from an industrial viewpoint. Particularly this includes questions of

- promising scale for future BtL-concepts but also
- the expected time frame of commercial availability.

Scale of Future BtL-plants

Based on the existing differences in “Philosophy of Design” (see chapter 3.2) three “scale classes” can be distinguished in the RENEW project:

- Small scale plants (50 MW range) leveraging integration into existing heat and electricity infrastructure (e.g. district heat). These are hardly BtL units presently since the main output is more heat and electricity, bio synfuels being a co-product. The conceptual advantage of Tri-generation under production of a straight run fuels (also CH₄ or perhaps MeOH or) is to turn communities self sufficient.
- Medium scale BtL-plants (200 – 500 MW range) as stand-alone but most probably integrated in industrial process (process steam provision, pulp mill, refinery, etc.). The limiting factor is the biomass supply on a mostly local basis.
- Large scale BtL plants (1 – 5 GW range) as stand alone or refinery integrated, located at sea side to secure a very large supply of feedstocks and leverage on economy of scale.

As combination of these ranges there are further concepts producing interim products in small scale (like pyrolysis oil or FT-raw product in 50 – 100 MW range) with subsequent processing up to automotive fuel in medium or large scale (200 – 5000 MW range).

Depending on these principal approaches different system-technical criteria are influenced like e.g.:

- Logistic effort for biomass provision
- Specific engineering and installation effort

Therefore in Figure 0-8 a classification of the different Renew-concepts regarding scale and BtL-yields is shown and lead to the following pros´and cons:

- Small Scale Plants
 - “easier” implementation because smaller projects
 - lower biomass logistic effort
 - high overall efficiencies via integration (e.g. district heat)
 - higher technical effort/ specific costs
 - limited BTL-yields and therewith a multitude of plants needed for significant BtL-production
 - crude wax integration in refineries is needed
- Large scale
 - higher liquid fuel yields and less plants needed per unit of biomass converted
 - lower specific costs,
 - challenge in terms of large projects (esp. financing)
 - energy and feedstock integration is a key issue

- Decentral/central approach shows a possibility to decouple the counter-trends of logistic effort and specific installation effort. Thus, a compromise of both advantages (small and large scale) could be achieved but requires further R&D on technical issues (how to handle the interim products as pyrolysis oil or crude wax).

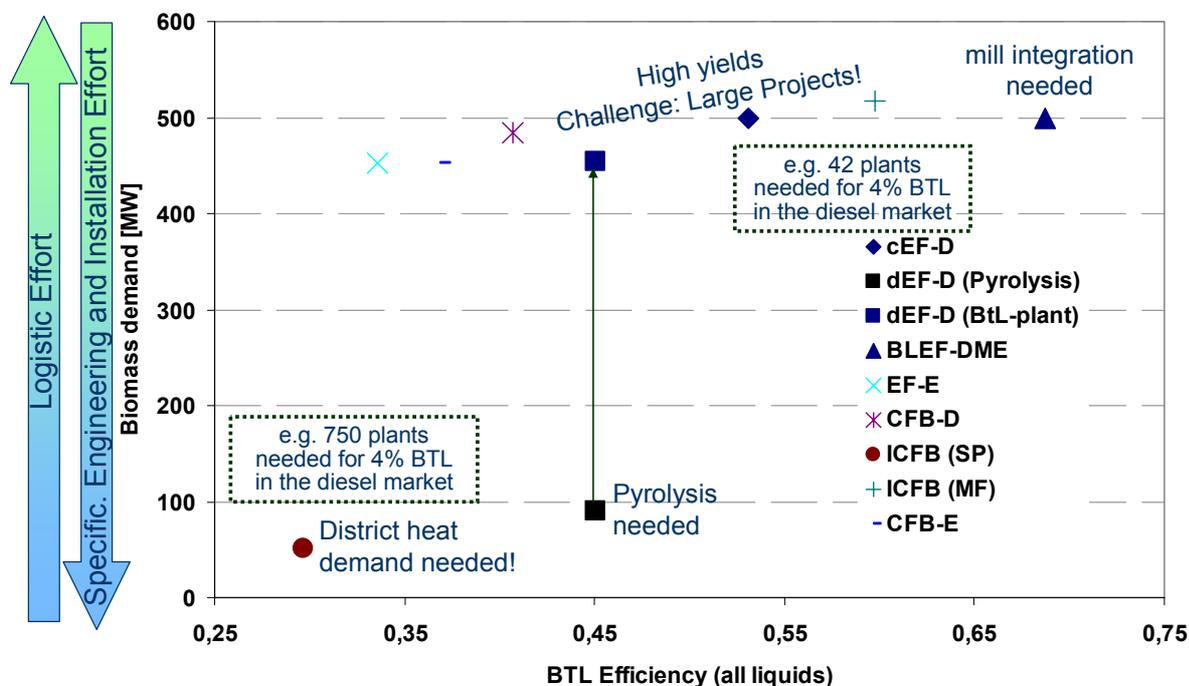


Figure 0-8: Plant sizes and efficiencies of the Renew-concepts

Development Stages and Time Horizon

The time horizon of a market implementation of synthetic biofuels will be driven by the solution of the mentioned technical challenges but also the development steps needed. Therewith the time horizon is influenced by the present development status of the different concepts. This is shown in Figure 0-9 which and points out the timeframe for development steps from the first evidence up to commercialisation.

Against this background and agreed with the technology developers the following conclusions can be drawn:

- With high effort, first industrial produced BtL from world scale units could be obtained in 2012 at the earliest.
- Because no single concept appears yet to be most suitable for any potential context, different concepts for different application fields/local contexts should emerge, each will need demonstration of critical components and overall performance of the complete chain. Overall BtL industry should benefit from cumulated experience gained in the different concepts.

- Based on the required technical development and demonstration demand a significant contribution of BtL to worldwide transportation fuel demand can not be expected in the next decade. However, within selected regions BtL-fuel from future large scale plants could play a larger role.

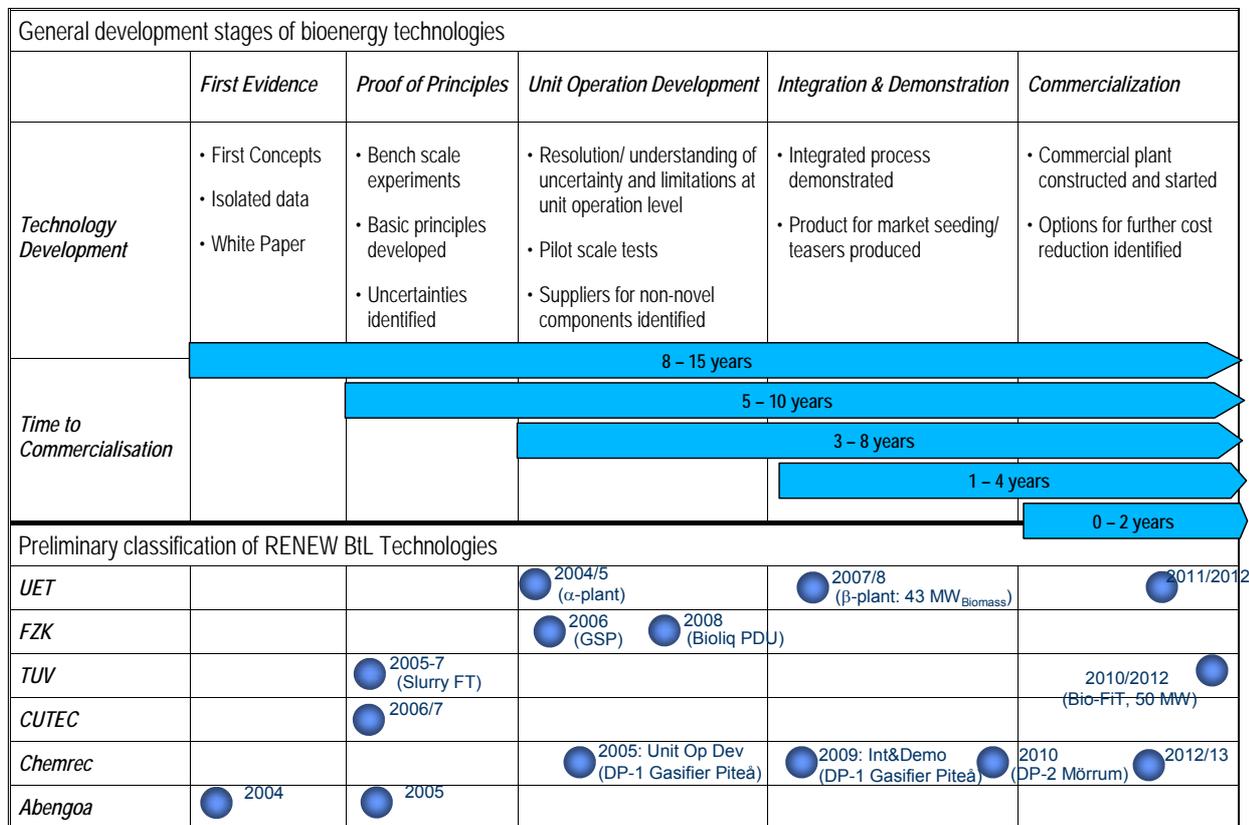


Figure 0-9: General development steps of bioenergy technologies and classification of technology developers which are responsible for data provision for the renew concepts (UET-data provider for cEF-D concept, FZK--data provider for dEF-D concept, TUV-data provider for ICFB-D concept, CUTEC-data provider for CFB-D concept, Chemrec-data provider for BLEF-DME concept, Abengoa-data provider for EF-E and CFB-E concept)

Summary and Conclusions

The goal of this work was to analyse and evaluate different concepts for synthetic biofuel production from a technical viewpoint. This was done to perform a consistent comparison of BtL-concepts being currently developed and to show both pro's/con's and prospects/risks of the BtL-systems from different viewpoints. Because of the differences in development stages and application purposes of these concepts a "multicriteria assessment" method was developed, based on a combination of quantitative and qualitative data.

This assessment shows that 3 concepts have already achieved a more advanced technical status (cEF-D, BLEF-DME and ICFB-D). But it also could be shown that none of them has reached an industrial production.

- cEF-D: EF-gasification of biomass has been demonstrated. The installation of the first overall process on BtL-production will be finalised in 2008. Engineering of future medium to large scale processes is ongoing.
- BLEF-DME: syngas production from black liquor has been demonstrated. The efficiency gain of the concept depends on integration with existing industrial facility (pulp mill). Demonstration of whole concept planned to start up 2010..
- ICFB-D: fuel gas/syngas production has been demonstrated. Addition of lab-scale syngas cleaning and FT-synthesis production has been shown under stable conditions.

Therewith implementation of the ongoing pilot and demonstration projects should bring valuable insight into the effective performance that could be expected as well as delivering critical design data for detailed engineering of BTL-plants on the large scale.

List of Abbreviations and Constants

The following abbreviations were used in this document. Along with these abbreviations, also some constants are listed which are used in calculations. Other applied constants may be found in chapter 9.3.4.

α	Chain growth probability, selectivity
<i>Abengoa</i>	Greencell Abengoa Bioenergy, Sevilla, Spain
Al_2O_3	Aluminium oxide
<i>ASF</i>	Anderson-Schulz-Flory distribution
<i>ASU</i>	Air Separation Unit
<i>ATR</i>	Autothermal reforming
<i>BLEF-DME</i>	Entrained flow gasification of black liquor for DME production
<i>bpd</i>	barrels per day
<i>BtL</i>	Biomass-to-Liquid
C_x	Hydrocarbons with chain length x
<i>C&C</i>	Gas cleaning and gas conditioning
<i>cEF-D</i>	Centralised entrained flow gasification for FT-Diesel production
<i>CFB</i>	Circulating Fluidized Bed
<i>CFB-D</i>	Centralised autothermal CFB-Gasification for FT-Diesel production
<i>CFB-E</i>	Allothermal CFB-Gasification for Ethanol Production
<i>Chemrec</i>	Chemrec AB, Stockholm, Sweden
$-CH_2-$	Carbon chain part, so called 'building stone'
CH_4	Methane
<i>CHP</i>	Combined Heat and Power Generation
<i>CHP-F</i>	Combined Heat, Power and (synthetic bio-)Fuel Generation
C_nH_m	Hydrocarbons
<i>Co</i>	Cobalt
<i>CO</i>	Carbon Monoxide
CO_2	Carbon Dioxide
<i>COS</i>	Carbonyl Sulphide
<i>CrO</i>	Chromium oxide
<i>CtL</i>	Coal-to-Liquid
<i>CHP-F</i>	Combined Heat, Power and Fuel
<i>Cu</i>	Copper

<i>CUTECH</i>	Clausthaler Umwelttechnik-Institut GmbH, Clausthal-Zellerfeld, Germany
<i>dEF-D</i>	Decentralised entrained flow gasification for FT-Diesel production
<i>DME</i>	Dimethylether
<i>eq.</i>	Equal
<i>etc.</i>	Et cetera
$E_{el}Equ$	Electrical Energy Equivalent for the conversion of Electrical Energy into Oxygen;
$\dot{E}_{Transport}$	Transport power for the 'gasifier' input (slurry) – only relevant for FZK
<i>EF</i>	Entrained Flow
<i>EF-E</i>	Centralised Entrained Flow Gasification for Ethanol Production
<i>EU</i>	European Union
<i>Fe</i>	Ferrum, iron
Fe_2O_3	Ferrum oxide
<i>FT</i>	Fischer-Tropsch
<i>FT-D</i>	Fischer-Tropsch Diesel
<i>FZK</i>	Forschungszentrum Karlsruhe, Karlsruhe, Germany
<i>gasif</i>	Gasification
<i>GtL</i>	Gas-to-Liquid
ΔH	Enthalpy of reaction
<i>h</i>	Hour
H_2	Hydrogen
H_2O	Water, Steam respectively if contained in gas
H_2S	Hydrogen Sulphide
<i>ha</i>	Hectare
<i>HCF</i>	Fluorocarbons
<i>HCl</i>	Hydrogen chloride
<i>HCN</i>	hydrocyanic acid
<i>HPC</i>	Heavy paraffin conversion process
<i>hrs</i>	Hours
<i>HTFT</i>	High Temperature Fischer Tropsch Synthesis
<i>HTV</i>	Hochtemperaturvergaser - High Temperature Gasifier
<i>ICFB</i>	<i>Internally Circulating Fluidized Bed</i>
<i>ICFB-D</i>	Allothermal CFB-gasification for FT-Diesel production
<i>incl.</i>	Including
<i>k</i>	Criterion

$LHV_{biomass}$	Lower heating value of standard biomass according to boundary conditions ($LHV_{willow-salix}$ (w=30%) = 12,16 MJ/kg; $LHV_{wheat-straw}$ (w=15%) =13,1 MJ/kg; $LHV_{miscanthus}$ (w=20%) =13,64 MJ/kg) [Boundary, 2005, Scenarios and Boundary conditions]
LHV_{CO}	Lower heating value of carbon monoxide
LHV_{BtL}	Lower heating value of usable fuel (target energy BtL product; see \dot{m}_{BtL})
LHV_{gasif_media}	Lower heating value of gasification media according to boundary conditions FZK: $LHV_{gasif_media} = x$ (slurry from decentralized pyrolysis process) Chemrec: $LHV_{gasif_media} = x$ (black liquor) All others: $LHV_{gasif_media} = LHV_{biomass}$
LHV_{H_2}	Lower heating value of hydrogen ($LHV_{H_2} = 120,1$ MJ / kg)
$LHV_{i,raw_product}$	Lower heating value according to specifications from plant developers mentioned in questionnaires
LHV_{RG}	Lower heating value of raw gas
$LHV_{naphtha}$	Lower heating value of naphtha
LHV_{NG}	Lower heating value of natural gas ($LHV_{NG} = 36,8$ MJ/kg, $\rho_{NG} = 0,8$ kg/Nm ³) [Boundary, 2005, Scenarios and Boundary conditions]
LHV_{SG}	Lower heating value of syngas
$LTFT$	Low Temperature Fischer Tropsch Synthesis
lts	Litres
$\dot{m}_{biomass}$	Mass flow rate of biomass before preparation/free plant gate with specifications according to boundary conditions (water content w: wood 30%; straw 15%; miscanthus 20%)
\dot{m}_{BtL}, LHV_{BtL}	Mass flow rate and lower heating value of usable engine fuel (target energy BtL product) according to boundary conditions: 1) FT-diesel: temperature boiling range [180-360] °C, $LHV_{FTdiesel} = 44$ MJ/kg (C ₁₀ – C ₂₀) 2) DME: $LHV_{DME} = 28,43$ MJ/kg @ p = 5 bar; T = 20 °C, $\rho_{DME} = 0,668$ kg/Nm ³ [Boundary, 2005] 3) Ethanol $LHV_{Ethanol} = 26,8$ MJ/kg [FNR, 2006]

\dot{m}_{CO}	Mass flow rate of carbon monoxide
\dot{m}_{gasif_media}	Mass flow rate of gasifier feedstock;
\dot{m}_{H_2}	Mass flow rate of hydrogen
$\dot{m}_{i,raw_product}$	Mass flow rate of synthetic raw product according to boundary conditions [Boundary, 2005]: 1) FT-raw product liquid, without <C5 2) DME + Methanol 3) Ethanol
$\dot{m}_{naphtha}$	Mass flow rate of naphtha output
\dot{m}_{NG}	Mass flow rate of natural gas
\dot{m}_{x,O_2}	Mass flow rate of Oxygen (x = surplus/add)
\dot{m}_{RG}	Mass flow rate of raw gas
\dot{m}_{SG}	Mass flow rate of syngas
<i>MeOH</i>	<i>Methanol</i>
<i>MF</i>	<i>Maximum Biofuel Scenario</i>
$\eta_{PE_el_conv}$	Efficiency of converting primary energy sources into secondary energy Electricity
η_{trans_el}	Efficiency of transmitting electricity
$\eta_{PE_naphtha_conv}$	Efficiency of converting primary energy sources into secondary energy Naphtha
$\eta_{PE_heat_conv}$	Efficiency of converting primary energy sources into secondary energy Heat
N_2	Nitrogen
<i>Na</i>	Sodium (Latin natrium)
<i>n.a.</i>	Not available
<i>n.e.</i>	Not existing
<i>Ni</i>	Nickel
<i>NG</i>	Natural Gas
<i>NH₃</i>	Ammonia
<i>NTV</i>	Niedertemperaturvergaser - Low Temperature Gasifier
<i>PE</i>	Primary Energy
$P_{el,C\&C}$	Electricity for the gas cleaning and gas conditioning unit
$P_{el,ext}$	Electricity for the system supplied from the external grid based on an energy mix [EU, 2006]

$P_{el,gasif}$	Electricity for the gasification unit
P_{el,H_2}	Electricity allocated for hydrogen
$P_{el,input}$	Electricity – overall plant balance with all additional/surplus fuels allocated, Positive: plant is consuming electricity Negative: plant is producing electricity
$P_{el,net}$	Electricity generated in plant (generation)
$P_{el,output}$	Electricity generated in plant (generation)
P_{el,x,O_2}	Electricity allocated for hydrogen (x = surplus/add)
$P_{el,surplus}$	Electricity produced internally, fed into the grid and not used in the plant
<i>PG</i>	Primary Goal
<i>ppm</i>	Parts per million
<i>PSA</i>	Pressure swing adsorption
<i>pt</i>	Point
\dot{Q}_{Heat_x}	Thermal power (x ='gasif' or 'C&C')
$\dot{Q}_{surplus}$	Heat, which is a surplus of the system and can be used as district/process
heat	
<i>Renew</i>	Renewable Fuels for Advanced Powertrains
<i>r</i>	Ranking number
<i>R&D</i>	Research and Development
<i>resp.</i>	respectively
<i>RG</i>	Raw Gas
<i>Ru</i>	Ruthenium
<i>SBCR</i>	Slurry Bubble Column Reactor
<i>SE</i>	Secondary Energy
<i>SFB</i>	Stationary Fluidized Bed
<i>SG</i>	Secondary Goal
<i>SMDS</i>	Shell Middle Distillate Synthesis
<i>SMR</i>	Steam reforming
<i>SNG</i>	Synthetic Natural Gas
<i>SP</i>	Starting Point Scenario
<i>SS</i>	Self Sufficient
<i>syngas</i>	synthetic gas for synthesis
<i>TA</i>	Technical Assessment
<i>T€</i>	A Thousand Euro

<i>TFBR</i>	Tubular Fixed Bed Reactor
<i>TUV</i>	Technical University of Vienna (in cooperation with Biomasse Kraftwerk Güssing), Vienna, Austria
<i>UET</i>	Umwelt- und Energietechnik Freiberg GmbH, Choren Industries, Germany
<i>VDI</i>	Verein deutscher Ingenieure - Association of German Engineers
<i>w</i>	Weighing factor
<i>WGS</i>	Water-gas-shift (reactor)
<i>Zn</i>	Zinc
<i>ZnO</i>	Zinc oxide

Units of Physical Magnitudes.

The following units were used for the listed magnitudes.

[<i>m</i>]	kg / h	mass flow rate for solid and liquid fuels
	Nm ³ / h	mass flow rate for gaseous fuels
[<i>LHV</i>]	MJ / kg	lower heating value for solid and liquid fuels
	kWh / kg	
	MJ / Nm ³	lower heating value for gaseous fuels
	kWh / Nm ³	
[<i>P</i>]	MW, kW	Power
[<i>Q̇</i>]	MW, kW	Thermal power
[<i>T</i>]	0 °C = 273.15 K	Temperature
[<i>p</i>]	1 bar = 0.1 MPa	Pressure

Content

Executive Summary.....	65
Concept Profiles and Assessment Method	65
BtL-concepts in the context of XtL.....	66
Assessment Method and Quality	68
Technical Performance of the Concepts	69
Efficiency.....	69
Flexibility.....	72
Development Status	73
Research and demonstration demands.....	75
Time Horizon of BTL-Implementation.....	75
Scale of Future BtL-plants	76
Development Stages and Time Horizon	77
Summary and Conclusions	78
List of Abbreviations and Constants	80
Content.....	86
1 Introduction.....	91
1.1 Background	91
1.2 Aim and Structure.....	92
2 Process Units on Synthetic Fuel Production.....	95
2.1 Pretreatment of Solid Feedstocks	95
2.1.1 Basics	96
2.1.2 Technologies.....	96
2.2 Gasification	98
2.2.1 Basics	98
2.2.2 Technology.....	99
2.3 Gas Cleaning.....	103
2.3.1 Basics	103
2.3.2 Technologies.....	104
2.4 Gas Conditioning.....	105
2.4.1 Basics	105
2.4.2 Technologies.....	106

2.5	Synthesis.....	108
2.5.1	Basics	108
2.5.2	Technologies.....	110
2.6	Upgrading.....	113
2.6.1	Basics	113
2.6.2	Technologies.....	114
2.7	Commercial Process Chains on Synthetic Fuel Production	115
2.7.1	History of GtL/CtL processes	115
2.7.2	CtL/GtL production sites and capacity.....	116
2.7.3	CtL/GtL technology	118
2.7.4	Size and economics of CtL/GtL plants	118
2.7.5	Quality and prospects of GtL/CtL fuels.....	120
2.7.6	Results on commercial Technologies.....	121
3	Concept Description	122
3.1	Scenarios, Inputs and Output Streams.....	122
3.1.1	Scenarios	122
3.1.2	Input and Output Streams	123
3.2	Overview on Concepts Considered	123
3.2.1	Centralised Entrained Flow Gasification for FT-Diesel Production (cEF-D) 125	
3.2.2	Decentralised Entrained Flow Gasification for FT-Diesel Production (dEF-D) 133	
3.2.3	Entrained Flow Gasification of Black-liquor for DME Production (BLEF-DME) 138	
3.2.4	Centralised Entrained Flow Gasification for Ethanol Production (EF-E). 142	
3.2.5	Centralised Autothermal CFB-Gasification for FT-Diesel Production (CFB-D) 148	
3.2.6	Allothermal CFB-Gasification for FT-Diesel Production (ICFB-D)	153
3.2.7	Allothermal CFB-Gasification for Ethanol Production (CFB-E).....	159
4	Basics and Methods of Technical Assessment	165
4.1	Basics of Technical Assessment.....	165
4.1.1	Intention and Procedure.....	165
4.1.2	Terms and Definitions	167
4.2	Method of Technical Assessment and Data Quality	168
4.2.1	Principle of Multicriteria Analysis.....	169
4.2.2	Selected Methods of Multicriteria Analysis	169

4.3	Specification of Technical Assessment	170
4.3.1	Definition of the TA-method.....	171
	Methodical Approach.....	171
	Goals, Modules and Criteria	173
4.3.2	Weighting Factors	174
4.4	Data Quality and Comparability of Concepts.....	176
4.4.1	Available Data	176
4.4.2	Completed Concepts.....	177
5	Comparison of BTL-Concepts based on single criteria.....	179
5.1	Energy Balances and Efficiencies	179
5.1.1	Overall Concept	180
5.1.2	Gasification	189
5.1.3	Gas Cleaning and Gas Conditioning	191
5.2	Evaluation with Industrial Perspective	192
	Flexibility.....	193
	Development Status	194
5.3	Further Evaluation Criteria with Scientific Perspective	195
5.3.1	Maturity	196
5.4	Feedstock and Product Quality	201
6	Target-oriented Multicriteria-Aggregation and Evaluation.....	204
6.1	Overall Plant.....	204
6.1.1	Secondary Goals.....	204
6.1.2	Primary Goals	206
6.1.3	Sensitivity of Primary Goals	209
6.2	Gasification	210
6.2.1	Secondary Goals.....	211
6.2.2	Primary Goals	213
6.2.3	Sensitivity of Primary Goals	214
6.3	Gas Cleaning and Gas Conditioning	216
6.3.1	Secondary Goals.....	216
6.3.2	Primary Goals	219
6.3.3	Sensitivity of Primary Goals	221
6.4	Conclusions on Multicriteria-Aggregation	223
7	Summary and Conclusion	224
7.1	Summary.....	224
7.2	Conclusions.....	226

7.3	Outlook.....	227
8	Sources	229
9	Annex	236
9.1	VDI 3780 (Excerpt).....	236
9.2	Upgrading.....	241
9.2.1	Introduction	241
9.2.2	Approach.....	241
9.2.3	Application to the Incomplete Process Chains of CUTEC, FZK and TUV 242	
9.2.4	Detailed Explanation	243
9.2.5	Calculation of H ₂ -Demand for Mild Hydrocracking.....	246
9.2.6	Calculation of Energy Demand for Upgrading	246
9.2.7	Bibliography of Chapter 9.2.....	251
9.3	Efficiency In-Depth	252
9.3.1	General Definitions.....	252
9.3.2	Definition of System Boundaries	254
9.3.3	Definition of Additional Power Integration	255
9.3.4	Definition of Constants	258
9.3.5	Calculation of Conversion Plant Efficiency	259
9.3.6	Calculation of Primary Energy Based Efficiency	266
9.4	Literature Review on Gas Cleaning and Gas Conditioning	269
9.4.1	Fuel Synthesis.....	269
9.4.2	Gas Cleaning and Gas Conditioning Using Rectisol/Selexol.....	271
9.4.3	Other Fine Cleaning Methods	273
9.4.4	Bibliography of chapter 9.4.....	274
9.5	Indicators for Efficiency	275
9.5.1	Overall Efficiencies and Conversion Rates – Conversion Plant	275
9.5.2	Overall Efficiencies– Primary Energy Based	276
9.5.3	Gasification Efficiencies and Conversion Rates	276
9.5.4	Gas Cleaning and Gas Conditioning Efficiencies and Conversion Rates 277	
9.6	Indicators for Maturity	279
9.6.1	Maturity of the Overall Plant.....	279
9.6.2	Maturity of the Gasification Unit	285
9.6.3	Maturity of the Gas Cleaning and Gas Conditioning Unit.....	287

9.7	Indicators for Feedstock and Product Quality.....	290
9.7.1	Feedstock and Product Quality of the Overall Plant.....	290
9.7.2	Feedstock and Product Quality of the 'Gasification' Unit.....	294
9.7.3	Feedstock and Product Quality of the 'Gas Cleaning and Gas Conditioning' Unit	296
9.8	Ranking Matrices and Weighing Factors.....	297
	List of Figures.....	303
	List of Tables	307

1 Introduction

The use of biogenous energy carrier within the energy system represents an important option at international level to sustainably substitute fossil fuels and thus to reduce the anthropogenic GHG-emissions. Due to its advantages concerning climate relevance and security of supply, biomass is of particular interest within the ongoing discussion on sustainable mobility as well as in context of the European Biofuel Directive.

There is a broad variety of biomass sources available that can be used for energy purposes; especially large technical potentials (e.g. 5.7 EJ/a in EU-28) are based on lignocelluloses. [Thrän, 2005]. On the other hand the energy demand for transportation is continue to increase (within EU-28 approx. 11.65 EJ2005/a) making the conversion of biomass into transportation fuels attractive.

Therefore so called '1st generation biofuels' - biodiesel and bioethanol - have been introduced to the market. These support the local agriculture and forestry and reduce the dependency on politically instable regions. They are also advantageous compared to hydrogen driven fuel cell power trains, since the existing distribution infrastructure can be more or less directly used (blending with conventional fuels is possible). However 1st generation biofuels do not fulfil existing fuel standards DIN EN 590 and DIN EN 288, when blending more than 5 % 1st generation biofuels to conventional fuel, so that existing engines have to be adapted when a higher percentage of 1st generation biofuels should be blended.

Synthetic biofuels like Fischer Tropsch diesel, synthetic natural gas or the gaseous dimethylether are promising alternatives for the existing biofuels out of various reasons: the yield of fuel equivalent per hectare is higher (approx. 3500 lts/ha fuel equivalent vs. 1500 lts/ha fuel equivalent), the quality is better (higher energy density, very low sulphur and aromats content, higher cetane number), more efficient feedstock utilization (the entire plant can be processed for fuel production) and they show less particulate matter emissions than existing 1st generation biofuels [FNR, 2006].

These advantages are very promising for political and scientific communities and result in great expectations on synthetic biofuels. Whether there will be a significant breakthrough of this new technology depends on politics, economics and the process technology itself. The political framework is set on advanced biofuels (the EU has set the target of a 5.75% share of biofuels in the transport sector by 2010 in a so called 'biofuel directive') [EU, 2003, P. 3f]. The new technology seems to be very promising, but the current stage of development is still quite low. Thus, a technical assessment is necessary to identify further focuses and targets of research, funding and support of 2nd generation biofuels, called 'Biomass-to-Liquid' (BtL).

1.1 Background

The paper at hand has been elaborated within the working package 'technical assessment' of the RENEW project (Renewable Fuels for Advanced Powertrains). This project – a European project, supported by the European Commission's 6th Framework Programme and coordinated by Volkswagen – investigates different production routes for synthetic biofuels (BtL) [Renew, 2006].

Thereby aim of the SP 5 is the biofuel assessment. This includes besides the analysis of the biomass potential, the life cycle assessment from well to tank and the economic assessment the analysis of technical aspects of the different options of BtL-production (WP 5.4); for those investigations on production techniques for BtL's, a first draft on technical indicators has been worked out [Vogel 2, 2006].

A variety of different production technologies promises to have high potential for the production of fuels for automotive application from biomass via a synthesis gas. Thereby the techniques to produce and to convert this synthesis gas into a synthetic biofuel differ in a wide range (e. g. with regard to input material, plant size, reactor types, development status). Thus, the BtL-production based on different types of biomass and different conversion processes is examined in detail in Renew-SP 1-4.

These different process technology approaches may not only result in different product characteristics and engine performances (examined in Renew task 5.4.1) but also in advantages and disadvantages of the production route itself (efficiencies, demands of hydrogen, amounts of residues, technical effort etc.). In order to allow conclusions which technology is advantageous in which market niche and to assess the need of further development an overall comparative assessment of the different pathways for different fuels under equal basic conditions is required.

Therefore, an overall paper on scenarios and boundary conditions (Del.5.4.2.1) has been developed by Renew-SP 5 as basis for the development of the most relevant BtL-concepts. Starting from this, production concepts are developed by the specific technology holders in Renew (SP1-4) and technical information and data of these concepts has been provided by SP 1-4 to SP 5. Based on these data, the different BtL-concepts are characterised and assessed in this paper.

1.2 Aim and Structure

Aim. Against this background the main overall objective of the technical assessment is to

- perform a consistent comparison of existing BtL-concepts,
- show both pro's/con's and prospects/risks of the BtL-systems

This assessment has involved different viewpoints and expertise (academic scientists, technology developers, process industry operators) in order to present a clear picture on

- the profiles and characteristics of the different BtL-technologies
- the bandwidths of technical performance (in particular energetic aspects)
- the technical restraints (in particular some aspects of practical industrial realization)
- potential meaningful application fields
- R&D-challenges to be met to secure full industrial and commercial deployment.

To focus on the most important aspects, the technical assessment is structured to answer a selection of key questions in the field of

- concepts profiles / concept cluster
- technical performance of each concept
- industrial implementation perspectives

Method. A transparent (and already applied) method on technical assessment is available. Therefore, the result of the technical assessment will not depend on the method on one hand. On the other hand, a first criteria-set reveal the complexity of technical questions related to BtL's, which shows the influence of the criteria chosen on the results of the technical assessment. To identify the most relevant aspects of BtL concepts, an iterative pre-screening via plausible indicators was done. The method of technical assessment is based on a simple argument balance using pre-screening indicators. The method is described in chapter 4 and in more detail [Vogel 3, 2006].

Characterisation. For a correct assessment, the concepts need to be characterised and 'standardised' to a point, where comparison is possible. Starting from this characterisation, the aims of TA for both parts of evaluation are listed in the following.

Assessment of Simulation Data. The assessment of the simulation data is focussed on the technical performance of the different concepts. This requires to

- check the consistency of concept data (i.e. to check whether the data are reasonable)
- simplify the process information to comparable aspects / criteria
- identify the pros and cons of the system components
- identify the pros and cons of the concepts
- leave the assessment open for new or adapted data and information

Assessment of Prospects of Success / Industrial Applicability. The assessment of the prospect of success is focussed on the concept's technical restraints. This requires to

- compare the concept data with practical results/existing technologies
- assess the development status of system components and identify bottlenecks
- assess the development status of the overall concept
- leave the assessment open for new or adapted data and information

Structure. To achieve these aims of TA the following working steps are worked out:

- explain the basics of the production of synthetic biofuels and the principle of technical assessment (i.e. present the basis for a transparent procedure on technical assessment of BtL-processes), see chapter 2 and 4

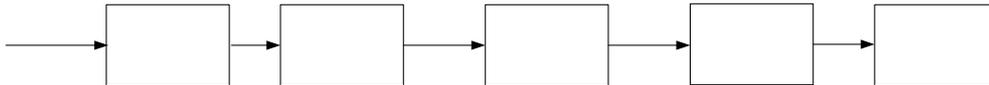
- provide homogenous and coherent description and characterisation of each BTL concept, since they are based on very different principles. This includes a technical description of the process (including size, feedstock and main process steps), block flow diagram, simplified Sankey diagram (energy balance) and the 'philosophy of key technologies' and development status, see chapter 3
- analysis of the concepts in terms of selected criteria from industrial perspective to compare relevant technical aspects, see chapter 5
- perform a target oriented assessment to identify 'pros and cons' of each concept also from scientific viewpoint, see chapter 6
- summarise these technical results and open questions on technical assessment of BTL-processes, see chapter 7

Therewith this paper aims to bundle and summarize different viewpoints and experiences of the SP 5-members responsible for technical assessment (petroleum industry, the automotive industry and academic experts) and the technology holders of the SP1-4 in one common evaluation method.

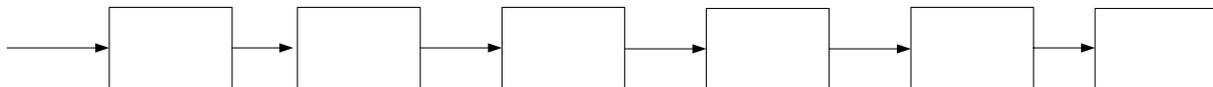
2 Process Units on Synthetic Fuel Production

The basics of XtL (GtL, CtL and BtL) production technologies are object of this chapter. The process chains can be simplified and defined into following basic steps (see Figure 2-1), which will be described in the corresponding chapters:

GtL:



CtL:



BtL:

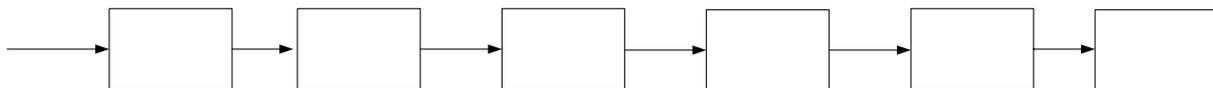


Figure 2-1: Process Chains of GtL, CtL and BtL

For CtL and BtL the solid feedstock is pretreated mechanically, thermally and/or thermochemically (chapter 2.1). The feedstock is gasified into raw gas in the gasification unit (chapter 2.2). Then the raw gas is cleaned from tar, particles and other impurities (e.g. H₂S) (chapter 2.3) and conditioned for synthesis, i. e. the gas composition is adjusted to the synthesis requirements (proper H₂/CO-ratio for synthesis) (chapter 2.4). In GtL processes natural gas is cleaned and then reformed to a product gas, which need to be adjusted, too. From this step on the following steps of XtL-technologies are the same to a large extent. After adjusting the syngas it is converted catalytically into raw products (chapter 2.5). This raw product is finally upgraded to a direct applicable motor fuel (chapter 2.6).

raw coal treatment coal gasification raw gas preliminary purification

2.1 Pretreatment of Solid Feedstocks

The solid feedstocks (coal, biomass) have to be pretreated before feeding into the gasification reactor. The method and effort on pretreatment depends on the gasification technology applied. These methods will be described in the following chapters 2.1.1 and 2.1.2.

biomass treatment gasification raw gas preliminary purification

2.1.1 Basics

To adjust the solid feedstocks to the conditions of the gasifier, various methods are used. They can be classified into mechanical, thermal and thermochemical processes.

Mechanical and Thermal Processes. Part of a mechanical pretreatment is the size adjustment of the solid feedstocks and the separation of impurities. The thermal pretreatment consists of a warming and drying of the solid feedstocks, if the moisture content is too high. This makes sense, since if the moisture content of the solid feedstocks is reduced the fuel power input into the gasifier increases, i.e. the gasification process works more efficient, since the pretreated feedstocks can be gasified right away and does not have to use process energy for evaporating the moisture content of the coal or biomass within the gasifier.

Thermochemical Processes. These processes are pyrolysis, carbonisation or torrefaction. In pyrolysis, the solid feedstocks are converted by thermochemical processes (pyrolytic decomposition) into mainly liquid products [Kaltschmitt, 2003, P. 477ff]. The so called 'flash-pyrolysis' is done by a very fast heating (heating rate ca. 1.000 °C/s) up to temperatures of 450°C and above. During very short retention times (< 1s) various products are formed: pyrolysis gas, pyrolysis oil and char. The goal is to maximize the share of oil (maximum about 75% of dry feedmass). A pumpable suspension is formed after condensing the gas [Kaltschmitt, 2003, P. 481f].

Also a pre-stage or first stage gasification of the solid feedstock is a thermochemical pretreatment. Thereby the feedstock is dried and pyrolytically decomposed in a special reactor at temperatures of about 500 °C. The products are char and a so called low-temperature carbonisation gas containing tar which is fed to the second stage of gasification (see also chapter 2.2.2) [Rudloff, 2004].

Another way of thermochemical pretreatment is torrefaction. The feedstock is slowly heated in an inert atmosphere to a temperature of maximum 300 °C. The product is a fine charcoal like solid material with less moisture content and higher energy content compared to the initial raw material. The process can be called 'mild pyrolysis', with removal of smoke producing compounds and the formation of solid product, retaining about 70% of the initial weight and 90% of the original energy content. For example the electricity consumption for milling torrefied biomass is tenfold lower compared to mill fresh biomass [Zanzi, 2006], [Boerrigter, 2004].

2.1.2 Technologies

The technologies applied for pre-treatment solid feedstocks as biomass will be object of description in this section. Pretreatment can be done centrally or decentrally and further distinguished between mechanical, thermal and thermochemical pretreatment.

Mechanical and Thermal Pretreatment. Mechanical pretreatment is done by drying and chipping the solid feedstock and separating impurities from the resulting gasification media. Drum dryers, steam dryers, natural convection air dryers and conveyer dryers are applied for drying often using waste heat of the plant. Chipper and hammer mills are applied for chipping up the raw material. Impurities like metals are removed by a metal separator, especially when pretreating biomass if the chopped feedstock is pelletised before gasification. For torrefaction, only lab units are available. This kind of pretreatment can be done centrally at the plant itself.

After pretreatment solid gasification media is stored in buffers and bunkers and brought into the gasification unit by a feeding system, e. g. snail systems and lock hoppers.

Thermochemical Pretreatment - Pyrolytical Decomposition. An example for thermochemical pretreatment is a so called 'low-temperature gasifier' (NTV) which is applied as pre-stage or first-stage gasification. This aggregate can be a horizontal cylindrical fixed bed reactor with rotating spindle (for mixing feedstock with hot material). The feedstock is dried and pyrolytically decomposed into pyrolysis gas and char at temperatures of 400 – 500 °C. A hopper system ensures the feedstock pressurisation. The pyrolysis gas is burnt with air or oxygen in the downstream 'high-temperature gasifier' (an entrained flow gasifier) at temperatures of about 1400 °C to supply the heat for the endothermal gasification. The char is milled and blown into the downstream gasifier, where it is gasified (see left picture in Figure 2-2). This kind of pretreatment has to be done centrally at the gasification plant itself. [Rudloff, 2004].

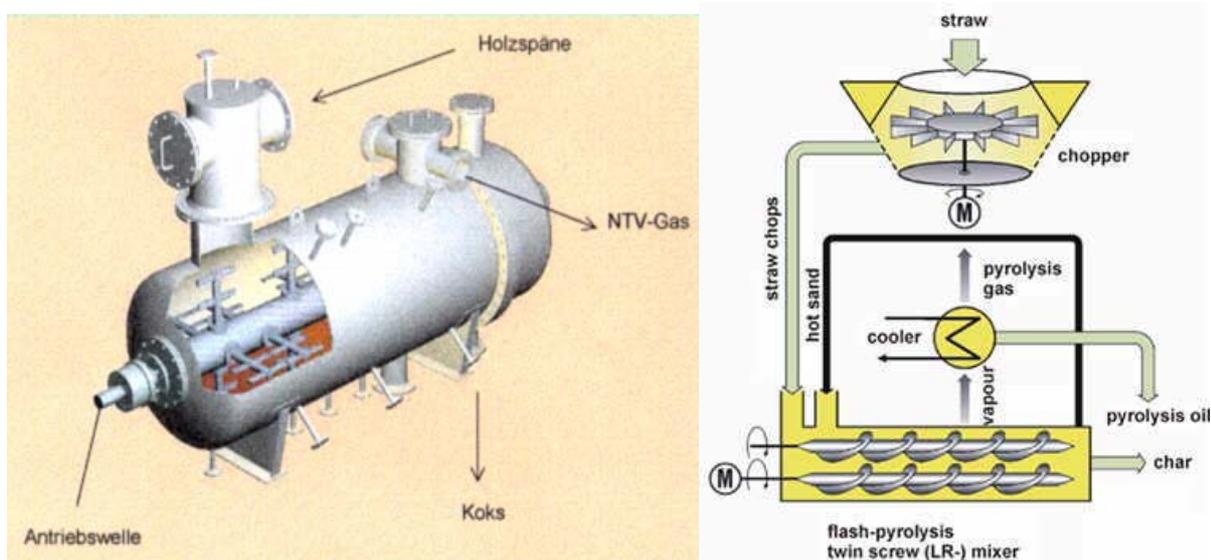


Figure 2-2: Thermochemical Pretreatment - 'Low-Temperature Gasifier' (NTV) (LEFT), Pyrolysis Plant with a Twin Screw Mixer [FZK 1, 2006] (RIGHT); Legend: Holzspäne = Wood Chips; Koks = Char; Antriebswelle = Driveshaft

Thermochemical Pretreatment - Flash Pyrolysis. Another example on thermochemical conversion will be discussed in the following. The use of e. g. straw as feedstock has some main disadvantage: the density and thus the energy content are quite low. This results in a high transport effort, which is not recommendable from an economical and ecological viewpoint. This is the motivation to build small decentral flash pyrolysis plants, where a suspension (pyrolysis oil) is produced. This fluid & gasification media has a higher energy density and the advantage of being pumpable.

After thermal and mechanical pretreatment, the feedstock is converted into a muddy suspension (so called slurry) via 'flash-pyrolysis'. Various reactor types exist whereby the twin screw mixer is the currently most favourable (see right picture in Figure 2-2). Two screws which are counter rotating ensure a proper mixing of feedstock (straw chops) and fluidized sand ($T = 500\text{ °C}$) used as heat carrier. Produced pyrolysis gas is separated from the pyrolysis oil via a cyclone and can be used energetically (heating of the fluidized sand; drying of straw). Pyrolysis oil is mixed with char to become the so called 'slurry', which has a tenfold higher energy density than the initial straw. This pretreatment can be also applied for other kinds of ligno-celluloic biomass materials with similar properties [FZK 1, 2006], [Henrich, 2003].

2.2 Gasification

The gasification of the pretreated solid feedstocks is aimed on the production of carbon monoxide and hydrogen, which presents the so called 'synthesis gas' convertible into motor fuel. The basics of gasification will be the topic of chapter 2.2.1 and the corresponding technologies the topic of chapter 2.2.2.

2.2.1 Basics

Gasification is a thermo-chemical conversion process, where the gasification media (pre-treated solid or liquid fuel) is converted into gaseous fuel, called producer gas, at high temperatures. This is done by a gasification agent under sub-stoichiometric conditions ($\lambda < 1$). The process is basically endothermic; therefore, heat has to be supplied [Kaltschmitt, 2003, P. 272ff]. It can be split into four different parts³.

- 1) Drying; The pretreated solids are heated up and dried at temperatures up to 200 °C .
- 2) Pyrolysis; The dry pretreated solids are pyrolytically decomposed at temperatures in the range of 200 °C to 500 °C . Gaseous hydrocarbons, pyrolysis oil and pyrolysis char are the products.
- 3) Oxidation; During oxidation, the temperature rises up to roughly 2000 °C ; char and part of heavy hydrocarbons are split into small gaseous molecules (CO , H_2 , H_2O , CO_2 und CH_4). This oxidation is an exothermal reaction and supplies the heat for an allothermal gasification mode (see also chapter 2.2.2).
- 4) Reduction; Most of the combustible components of the raw gas are formed by reduction of CO_2 and H_2O whereby the 'Boudouard' reaction (Equation 2-1) and the heterogeneous water-gas-shift reaction take place (Equation 2-2) [Kaltschmitt, 2003, P. 428ff].

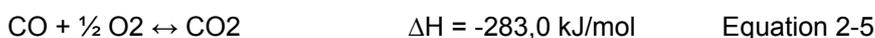
³ Temperature ranges are typical for biomass



Also other reactions take place: the homogeneous water-gas-shift reaction (Equation 2-3), (carbon monoxide reacts with water to carbon dioxide and hydrogen) and the so called 'methane' reaction (Equation 2-4), where carbon and hydrogen react to methane (if pressure is increased, the reaction balance shifts towards methane, i.e. a higher pressure supports the formation of methane) [Kaltschmitt, 2003, P. 430].



The strongly exothermal oxidation of CO to CO₂ (Equation 2-5) and the hydrogen-oxygen reaction (also called 'Knallgas' reaction; Equation 2-6) as well as the oxidation of methane under separation of water is undesired, since they drop the heating value of the raw gas. [Kaltschmitt, 2003, P. 431].



Based on these and further reactions a raw gas is formed which consists mainly of carbon monoxide, carbon dioxide, hydrogen, methane and water vapour and if so nitrogen (small parts from feeding systems; large parts only in case of air as gasification agent). The composition of this raw gas depends strongly on the method of gasification (gasifier design), the gasification agent (type and quantity) and on temperature and pressure of the gasification.

Besides the main products (CO, CO₂, H₂, CH₄, H₂O_{vapour} and if so N₂), the raw gas contains also diverse impurities, which have to be separated from the raw gas stream by application of (sophisticated) gas cleaning methods (see also chapter 2.3) [Kaltschmitt, 2003, P. 428ff], [Knoeff, 2005, P. 13ff & P. 34ff].

2.2.2 Technology

In the past various designs of gasifiers have been developed for different purposes. The requirements on raw gas for power generation are different from the requirements on raw gas for synthesis and synthetic fuels. In general, gasifiers can be classified in several ways, which are described in the following (see also Figure 2-3) [Knoeff, 2005, P. 22ff] [Kaltschmitt, 2003, P. 425ff]:

Gasification Agent. Gasifiers can be classified according to the applied gasification agent, in particular it is type and quantity:

- Air
- Oxygen
- Steam

Using air has the disadvantage of a high inert gas share (especially N₂) in the product gas. For producing synthetic fuels, oxygen or steam (resp. mixtures) are usually the choices.

Pressure. Gasifiers can be classified according to the pressure in the gasifier:

- Atmospheric
- Pressurized

An advantage of the pressurized gasification is that no raw gas compression for gas cleaning is needed, resulting in a lower effort on gas cleaning. But depending on the gasification technology this is connected with a higher technical effort for feeding or feedstock treatment.

Heat Supply for Endothermic Gasification Reactions. Gasifiers can be classified according to the heat supply for gasification.

- Autothermal: heat is provided by partial combustion of the pretreated solids
- Allothermal: heat is supplied from an external source through heat exchanger or indirect process

Gasifier Design. A classification of gasifiers according to their setup and design is shown in Figure 2-3. The ‘fixed bed’ design is a very simple one. The raw gas shows high tar content, which makes it unsuitable for synthetic fuel production. Another disadvantage is the little ‘scale-up’ possibilities, limited by the diameter of the gasifier. The main application field of fixed bed gasifiers is small power and heat generation like it is done in many countries, especially in India. The largest gasifiers built there have around 1MW_{el} power output.

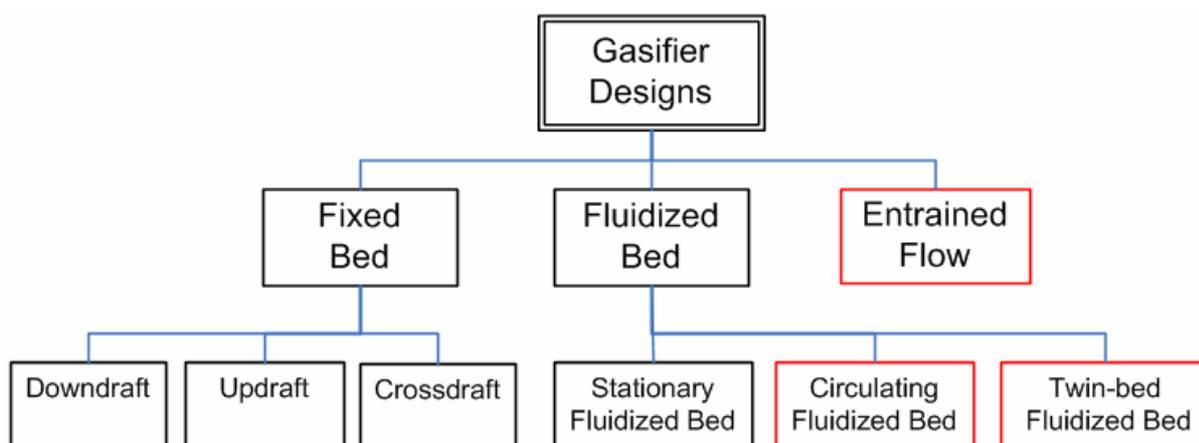


Figure 2-3: Classification of Gasifiers

For synthetic fuel production, the ‘fluidized bed’ and the ‘entrained flow’ types are of higher relevance (marked in red boxes) and will be described more in detail in the following.

Circulating Fluidized Bed Gasifiers. A circulating fluidized bed gasifier contains a bed of fine inert material (silica sand) resting on a perforated plate. The oxidation agent flows through this ‘bed’ and circulates the inert material and the entering feedstock. The difference of the CFB design compared with the fixed bed one is that there is no spacial separation of the single process steps (drying, pyrolysis, oxidation, reduction) but these steps are taking place distributed equally in the entire reactor space.

The main advantage of CFB design is the good inner heat transfer and material transfer properties, which result in lower retention times of the feedstock and thus higher mass flow rates in the reactor. On the other hand, the technical effort is much higher on CFB than on fixed bed gasifier designs. Another disadvantage of CFB gasifiers is the high particle and tar contents in the raw gas (producer gas).

Various types of CFB designs exist. Technically applied are the stationary fluidized bed (SFB), the circulating fluidized bed (CFB) and the internal circulating fluidized bed design (ICFB). These types are explained in the following.

Stationary Fluidized Bed (SFB). In this gasifier design the flow velocity is not as high as in CFBs but maintains the bed material in abeyance. The feedstock mass flow rate is higher compared to fixed bed designs, but lower than with CFBs. Nevertheless, this reactor type is usually not applied for a subsequent fuel synthesis (see Figure 2-4).

Circulating Fluidized Bed. The setup of the CFB design is basically the same as the SFB design. The flow velocity of the gasification agent is higher which increases the mass flow rate of to be converted material through the reactor. Solid parts in the raw gas are separated from the gas stream by cyclones and recycled back to the reactor. Thus the conversion rate of feedstock as well the gasification efficiency increases. Another advantage of the CFB vs. the SFB is the smaller diameter at same fuel power, which is good for further upscaling (see Figure 2-4).

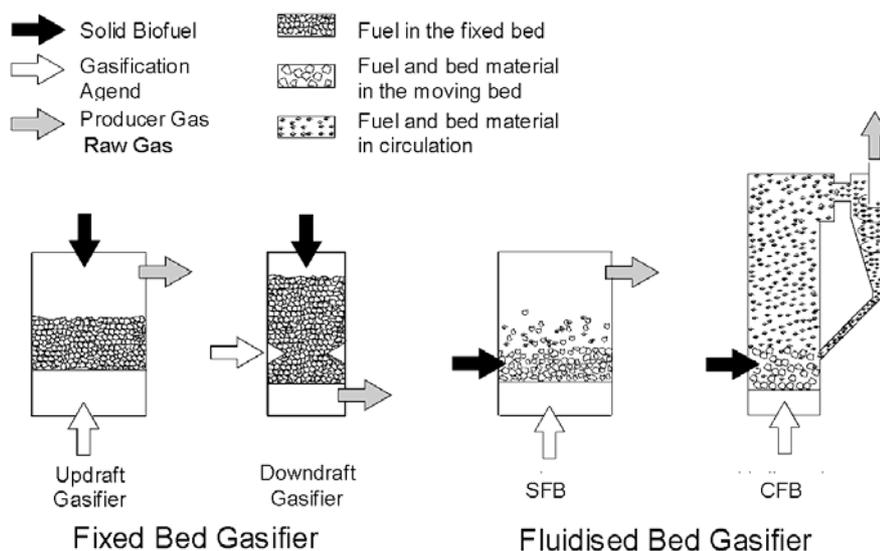


Figure 2-4: Gasifiers in Fixed Bed and Fluidized Bed Design (SFB and CFB)

Internally Circulating Fluidized Bed (also Twin-Bed Fluidized Bed). In the ‘twin-bed’ design, the reactor is split into two fluidized beds, a gasification zone and a combustion zone (see left picture in Figure 2-5). Between both zones a circulation loop of bed material (e.g. sand) acts as heat carrier from the combustion to the gasification zone. Water steam (vapour) can be applied as gasification agent instead of oxygen. The bed material, together with some charcoal, circulates from the gasification zone to the combustion zone. This zone is fluidized with air and the charcoal is partly burned. The exothermic reaction in the combustion zone provides the energy for the endothermic gasification with steam. The flue gas will be removed separately from the raw gas (product gas). Thus the gas produced in the gasification zone (raw gas) is nearly free of nitrogen, which is another advantage of this design.

A disadvantage of this design is its high complexity by integrating two circulating fluidized beds. Nevertheless the effort on raw gas cleaning is reduced by this design, since raw gas (product gas) and flue gas are separated.

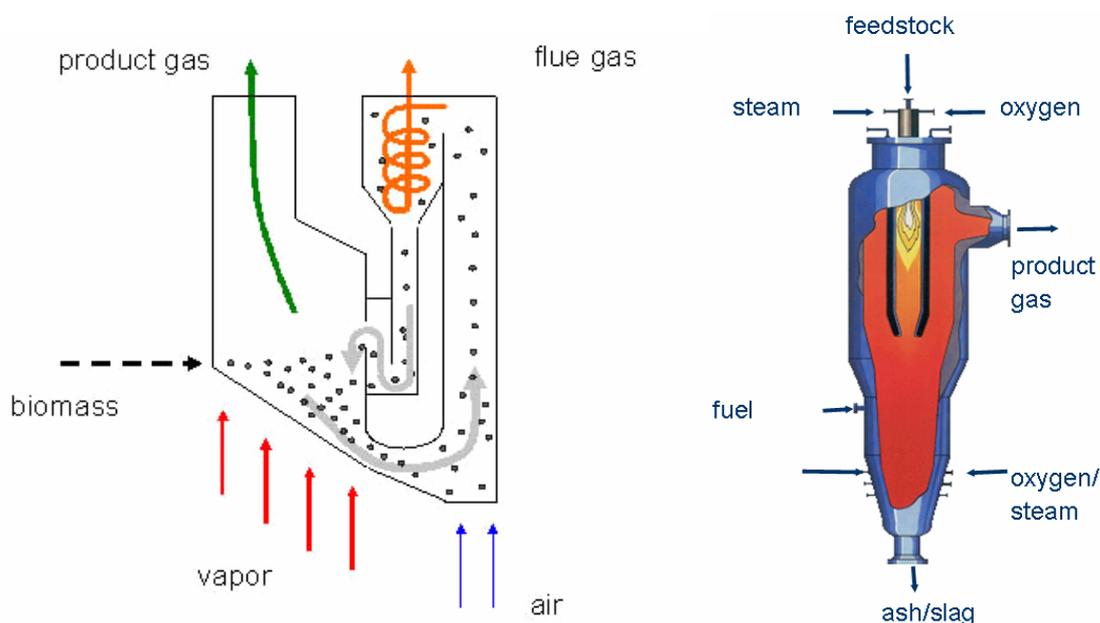


Figure 2-5: Design of a Internally Fluidized Bed Gasifier (Twin-Bed Gasifier) [Hofbauer, 2007] (LEFT), Design of an Entrained Flow Gasifier (EF) (RIGHT)

Entrained Flow Gasifiers. In entrained flow gasifiers (EF gasifiers) the gasification media of small particle size is gasified within seconds at temperature of 1200 – 1500 °C and pressures up to a 100 bars (see right picture in Figure 2-5).

This process parameters allow a reaction operation at equilibrium resulting in the highest carbon conversion rates possible (> 99 %) in gasification systems. EF gasifiers are suitable for many fuels, though they have to be pumpable and a thermochemical pretreatment of the feedstock is necessary. Oxygen is often used as gasification agent. The resulting raw gas is free of tar and has low methane content, vice versa to the CFB design with high tar content and some methane in raw gas (see right picture in Figure 2-5) [Henrich, 2003, P. 12ff], [Rudloff, 2004, P. 2].

The main advantages of EF gasifiers are high carbon conversion rates and a tar-free raw gas. Nevertheless the effort on gasification (production of oxygen for gasification, a thermochemical pretreatment is mandatory) and handling of the extreme process parameters (high temperatures) are clear disadvantages of this design [Kaltschmitt, 2003, P. 431ff], [Knoeff, 2005, P. 13ff], [Henrich, 2005, P. 104].

2.3 Gas Cleaning

The raw gas produced in the gasifier can not be applied directly in synthesis. It contains contaminants, which can block or poison the catalyst downstream. Therefore a further step has to be applied; the cleaning of the raw gas. Other applications beside synthesis like the use of raw gas in a gas engine for combined power and heat production have lower requirements on purity of the gas. For example the clean gas for synthesis may not exceed a tar content of 0.1 mg/Nm^3 , while a gas engine can work with clean gas with tar content up to 50 mg/Nm^3 . The gas cleaning technologies will be the topic of the following chapter [Knoef, 2005, P. 189ff].

2.3.1 Basics

There are many contaminants and impurities in the raw gas depending on the gasification concept chosen. In particular the following impurities may appear in the raw gas:

- condensable hydrocarbons (tars)
- particles (dust, ash, bed material)
- alkali compounds (Na- and K-compounds)
- sulphur compounds (hydrogen sulphide H_2S , carbonyl sulphide COS)
- nitrogen compounds (Ammonia NH_3 , hydrocyanic acid HCN)
- halide compounds (Hydrogen chloride HCl, fluorocarbons HCF)

The gas cleaning technology applied depends on the properties of the particular impurities. They can be distinguished by several aspects: temperature, wet/dry processes and adsorption or absorption.

According to the temperature, the processes are distinguished in hot- and cold gas cleaning technologies. Hot gas cleaning is of advantage for the overall energy balance when a heat exchanger or a tar reformer is applied after the gas cleaning section since these processes require a high inlet temperature. Furthermore clean gas does not coat the areas of the heat exchanger; fouling and slagging of downstream equipment by condensing tars can be avoided. Nevertheless hot gas cleaning is technically more sophisticated than cold gas cleaning and not as developed as standard cold gas cleaning processes.

Another way of characterizing gas cleaning technologies is the distinction in wet and dry processes. Wet processes are scrubbers (with water or oil as solvent). Cyclone-, barriers- and electrostatic filters are applied in dry processes. Gas cleaning processes can be further distinguished in absorptive and adsorptive processes. The absorptive processes are based on the removal of impurities by physical solution without chemical reactions; while the adsorptive processes make use of the adhesive forces of contaminants [Boerrigter, 2003], [Faaji, 2001], [Hamelinck, 2004].

2.3.2 Technologies

Different technologies for gas cleaning are introduced and described briefly in the following. Some technologies are used for both gas cleaning and gas conditioning, i.e. for adjusting the gas to the necessary gas composition for synthesis (see also chapter 2.4). This is also the reason for a combination of gas cleaning and gas conditioning in the following chapters **Fehler! Verweisquelle konnte nicht gefunden werden.** and onwards.

Cyclones remove mainly particles like dust and bed material and also some tar. They can be applied for a wide temperature range. The technology is proven and commercially available at low cost. Cyclones are used often in CFB gasification.

Filters like bag-, ceramic candle- and electrostatic filters show higher separation rates than cyclones (up to 99.99 %) but more expensive than cyclones. Particles, tar and alkalines can be removed by filters. They differ in separation rates, temperature range, technical effort and thus investment costs. Ceramic candle filters can be applied for temperatures up to 1000 °C and suit the requirements of hot gas cleaning.

Tars are on the one hand a threat to downstream equipment but on the other hand they contain a lot of energy. This energy can be used in tar crackers which are applied for thermal decomposition of tar at high temperatures (up to 1200 °C). Part of the raw gas is combusted to generate these high temperatures. This process is called 'thermal cracking' whereby energy is gained for other processes (e.g. heat exchanger) and up to 90 % of tar is converted to CO₂.

Scrubbers are used for the removal of many contaminants (particle, tar, alkalines, sulphur-, nitrogen- and halide components), which are separable by absorption. Water or organic solvents like biodiesel are used as solvents. Scrubbers show very high separation rates. This advantage is also a disadvantage for the solvent disposal. One alternative is the combustion of the dirty biodiesel in the combustion part of the gasifier. Also the rectisol- and selexol processes can be mentioned at this point, which do both gas cleaning and gas conditioning (separation of CO₂). They are described in detail in the gas conditioning chapter 2.4.2.

Adsorptive processes are used for sulphur removal and applied as 'guard beds'. Syngas has to be free of sulphur (like hydrogen sulphide H₂S) since it is poisoning the catalyst. Zinc oxide (ZnO absorber), iron oxide and charcoal can be employed [Faaji, 2001,], [Boerrigter, 2003], [Hamelinck, 2004].

2.4 Gas Conditioning

The term 'gas conditioning' means the adjustment of the clean gas to the conditions of the synthesis. Matched and adopted clean gas is then called 'syngas'. This adaptation is necessary for an optimal synthesis operation and individual for each kind of synthesis process (chapter 2.4.1 and 2.4.2).

2.4.1 Basics

Gas conditioning of clean gas consists of various steps. First, the adjustment of an optimal H_2 / CO ratio in syngas for synthesis is essential. Second, the removal of CO_2 from the gas stream is necessary. Moreover the reforming of hydrocarbons belongs to gas conditioning. These process steps are described below.

An adjustment of the proper H_2 / CO ratio is very essential since this ratio of raw gas of the gasification of biogenous or carbonaceous feedstock is too low in general. Figure 2-6 illustrates that coal and biomass have a molar H/C ratio of under 1, which results in a rawgas which has a H_2/CO ratio of under 1, too. For high FT conversion efficiency, effectively two H_2 molecules are needed per CO molecule, to result in the product diesel.

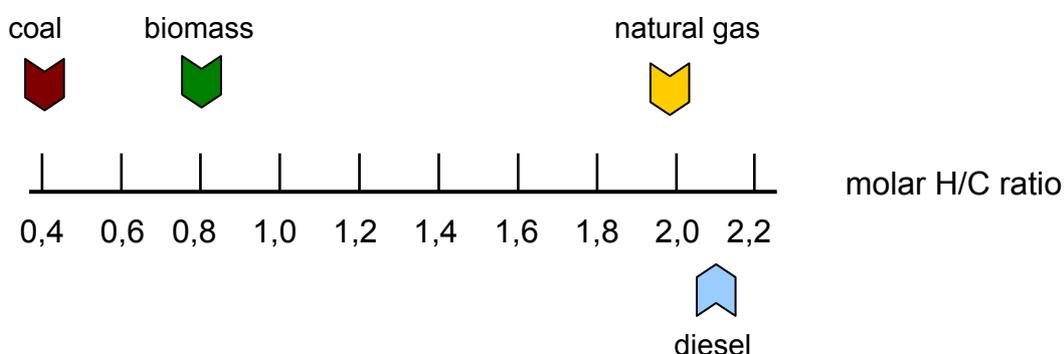


Figure 2-6: Molar H/C ratio of different feedstocks and diesel

To increase the H_2/CO - ratio, either part of the CO can be reformed with water vapour into CO_2 and H_2 (water-gas-shift reaction, **Equation 2-3**) or additional H_2 is added to the gas stream (externally or from pressure swing adsorption, see the following chapter 2.4.2).

Raw gas contains usually a high share of CO_2 , which is increased additionally due to the applied water-gas-shift reaction. A too high share of CO_2 can be disadvantageous for downstream synthesis, making a separation of CO_2 from the gas stream necessary (see chapter 2.5). Physical absorption technologies are applied for the removal of CO_2 .

Clean gas can contain a considerable amount of methane (CH₄) and other light hydrocarbons (C_nH_m). These components may influence negatively the growth probability of hydrocarbon chains or selectivity of the synthesis and are therefore removed (combustion for heat supply) or reformed (more H₂ and CO for the synthesis) (see also chapter 2.5.2). There are two methods of reforming hydrocarbons: steam reforming and autothermal reforming. In both methods, hydrocarbons are reacting with steam to CO and H₂, which can be used in synthesis or for hydrocracking in the upgrading unit (Equation 2-7). This reaction is highly endothermic [Hamelinck, 2004], [Boerrigter, 2003].



2.4.2 Technologies

Some technologies which are employed in gas conditioning will be presented below.

CO-shift – Adjustment of the H₂/CO-ratio. Water-gas-shift reactors (WGS) are used for increasing the H₂ share of the clean gas by converting part of the CO in the clean gas. They operate at temperatures in the range of 300 °C to 500 °C and pressures up to 30 bars. The applied catalysts are based on Fe₂O₃ / CrO [Faaji, 2001].

Addition of H₂ to the Gas Stream. Another possibility of increasing the H₂ share in the clean gas is the addition of H₂. This can be done from external sources (by electrolysis of water) or internally by separating hydrogen from residual gases from the synthesis or the upgrading unit in a so called ‘pressure swing adsorption’ (PSA).

Pressure Swing Adsorption. In this physical process, the molecules get attached to the adsorbent (hydrocarbon or zeolites) under high pressure and released under low pressure. Beside the separation of H₂, a removal of CO₂ is also possible with this process.

Electrolysis. The electrolysis of water is done for generation of additional H₂ required for synthesis. Electrolysis is powered by electricity. Surplus oxygen can be used in the pretreatment and gasification units. Since the oxygen amount is sufficient for these processes, the air separation unit for oxygen production is not needed.

Removal of CO₂ from the Gas Stream. Two processes are described as an example for CO₂ removal technologies: the ‘rectisol’ process developed by Lurgi and Linde and the ‘selexol’ process developed by Dow Chemical. Both processes are gas-liquid scrubbing processes using different solvents and process conditions. The absorption process of the gas contaminants can be physical, chemical, or a combination of both. They are described briefly in the following and more in detail in the annex in chapter 9.4.

Rectisol Process. Cold methanol (-30 to -45 °C) is used in this process as physical solvent. High pressures are positive for the absorption ability of the solvent, thus pressures of 30 to 60 bars are applied and contaminants like CO₂, H₂S, COS, HCN, NH₃, sulphur compounds and hydrocarbons and others are absorbed. By releasing the pressure, the contaminants are desorbed and undergoing further treatment. During reactivation of the solvent some gases are set free (H₂, CO) which are recycled back to the synthesis unit [Cicero, 2003].

Selexol Process. A special mixture is used in this process as solvent, consisting of 95 % dimethylether (DME) based on polyethylene glycol. The process takes place at pressures of 10 to 30 bars and in a temperature range of 0 to 175 °C. The spectrum of absorbed contaminants is similar to the above mentioned rectisol process. Raw gas and solvent are brought into contact in a counter flow absorption column whereby impurities like H₂S or CO₂ are absorbed. Subsequent these impurities are desorbed by pressure release in an expansion vessel. Residue CO and H₂ can be recycled back to the synthesis unit [Cicero, 2003].

Both processes – rectisol and selexol – are highly sophisticated, yet their big advantage is the removal of many other impurities beside CO₂ from the gas stream favouring them as scrubber process.

Reforming of Hydrocarbons. Often some valuable gas and light components (C₂-C₈) are left over after synthesis. To make use of them or to reduce high methane contents of syngas, the reforming of hydrocarbons is used. There are two types: steam reforming (SMR) or autothermal reforming (ATR). Both methods are based on the same endothermic reaction (Equation 2-7) but differ in the heat supply for this reaction.

Steam Reforming (SMR). Reforming is driven by steam addition over a nickel catalyst. The heat is supplied externally by steam.

Autothermal Reforming (ATR). A way to avoid external heat supply is the so called 'autothermal reforming' (ATR). It combines partial oxidation in the first part of the reactor with steam reforming in the second part and integrates thus the heat flows optimally.

The result after all gas cleaning and conditioning processes is a clean syngas, which is aligned to the synthesis requirements [Boerrigter, 2003], [Hamelinck, 2004], [Linde, 2006].

A conclusion of the gas cleaning chapter 2.3 and the gas conditioning chapter 2.4 is an overlapping of the two process steps due to technology. Some gas cleaning technologies are also conditioning the gas (scrubbers) and vice versa (reforming of hydrocarbons, scrubbers).

As a consequence, both process steps cannot be separated in process description and evaluation and will be combined to a 'gas cleaning and gas conditioning' unit in the following chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** and onwards.

2.5 Synthesis

Generally there are various ways of producing motor fuel of syngas ($m \text{ CO} + n \text{ H}_2$). They can be in liquid (Fischer-Tropsch diesel, ethanol, methanol, etc.) or in gaseous form (Dimethylether (DME), synthetic natural gas (SNG), hydrogen (H_2), etc.). The production of FT-Diesel, Ethanol and DME will be the focus in the following chapters.

2.5.1 Basics

Fischer-Tropsch-Synthesis. The Fischer-Tropsch-Synthesis (FT-synthesis) is a polymerisation process whereby syngas (consisting basically in H_2 and CO) is converted into hydrocarbon chains of different length according to the general reaction equation (Equation 2-8). It can be modelled as a chain grow reaction of H_2 and CO on the surface of a cobalt or iron catalyst (Equation 2-9). This reaction is strongly exothermic, about 25% of the chemical energy is converted into heat and has to be removed and used somewhere else to maintain high efficiency and optimum catalyst life.



Several $\text{--CH}_2\text{--}$ chain links form longer hydrocarbons. The main performance parameter of the FT synthesis is the 'chain growth probability' or 'liquid selectivity' which is the chance that a hydrocarbon chain grows with another $\text{--CH}_2\text{--}$ 'building stones', instead of terminating. It is described by the Anderson-Schulz-Flory (ASF) distribution; a simple statistical model predicting a linear relation between the logarithm of the molar amount of a paraffin and its carbon number. The constant α expresses this probability, which influences the composition of the FT synthesis raw product. The molar yield of a hydrocarbon can be calculated according to Equation 2-10 with

α = chain growth probability

n = length of hydrocarbon

C_n = fraction of hydrocarbons having length n

$$C_n = n(1-\alpha)^2\alpha^{n-1} \quad \text{Equation 2-10}$$

The higher α , the longer the respective hydrocarbon chains. A raw product spectrum is built out of light hydrocarbons ($C_1 - C_4$), gasoline fraction ($C_5 - C_{10}$), diesel oils ($C_{11} - C_{20}$) and waxes (C_{21+}), whereby classification of the chain lengths are a varying in literature. This can be derived from Figure 2-7.

This selectivity, the distribution of raw products, depends on α and is determined by several parameters like temperature, pressure, applied catalyst, reactor type and H_2/CO -ratio of the syngas. The following applies in general: α increases by decreasing H_2/CO -ratio, decreasing reactor temperature and increasing pressure.

FT processes are distinguished into high temperature processes (HTFT; temperatures of 300 to 350 °C) and low temperature processes (LTFT; temperatures between 200 and 240 °C). Higher temperatures reduce the average chain length and support the formation of methane, light hydrocarbons and aromatics. Therefore, the low temperature processes are preferred for Diesel production.

The operating pressure of FT synthesis ranges generally from 20 to 40 bars. Higher pressure leads to higher selectivity. Further details may be taken from literature [Boerrigter, 2003], [Tijmensen, 2002].

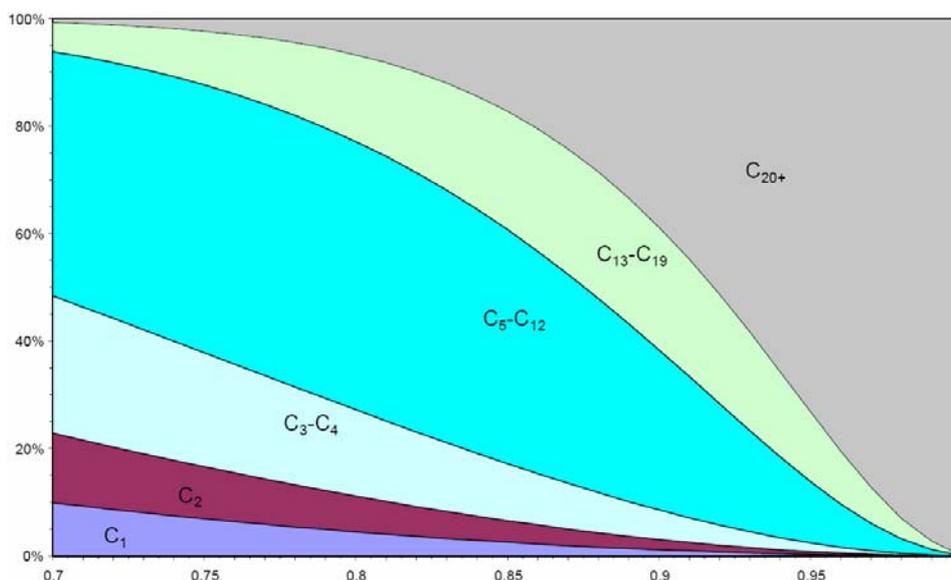


Figure 2-7: FT Product Distribution (Product Weight Fraction [% wt]) for Different α , Calculated Using Equation 2-10 [Boerrigter, 2003]

The impact of the catalyst depends on various parameters like kind, doping and age of the applied catalyst. Nickel (Ni) and Ruthenium (Ru) show very good results besides iron (Fe) and cobalt (Co). Ruthenium is the most active, working at the lowest temperatures (150 °C) and scientifically most attractive. However its high price and limited resource exclude industrial application. Iron catalysts are the most inexpensive and have water gas shift activity (**Equation 2-3**), a favourable feature for FT synthesis with a high share of CO in syngas. Cobalt catalysts have this feature only marginally. Yet they are more active (thus more attractive for FT synthesis) but also much more expensive than iron catalysts. In general, all catalysts are very sensitive on sulphide compounds and can have problems with sintering due to high temperatures in the reactor [Boerrigter, 2003], [Dry, 2002], [Espinoza, 1999], [Iglesia, 1997].

The required H_2/CO -ratio depends mainly on the catalyst chosen. It should be higher than 2 if a cobalt catalyst is applied (optimum 2.15). For iron catalysts a H_2/CO -ratio of 0.6 is sufficient, the optimum is 1.35 since this catalysts performs also the water-gas-shift reaction, whereby H_2 is gained. [Boerrigter 2, 2004], [Hamelinck, 2004], [Tijmensen, 2002], [Bolhàr-Nordenkamp, 2003], [Hofbauer, 2003].

Ethanol-Synthesis. Once the syngas has been pressurised, the syngas can be converted to alcohol in a catalytic reactor. For ethanol synthesis it is known that temperature has an important effect on the alcohol selectivity and product distribution. On the other hand, high pressures are typically required to ensure the production of alcohols. Although MoS₂ catalysts are efficient Fischer-Tropsch catalysts at ambient or low pressures, significantly raising the pressure helps to shift the pathways from hydrocarbon production towards alcohol production. Minimum operating pressure is 69 bar, while maximum pressure value is 690 bar. However, compression requirements for achieving these pressures can be quite substantial. Thus, targeting a catalyst that achieves optimal performance at lower pressures can potentially provide significant cost savings. Basically, the catalyst consists of molybdenum (free or combined) as active metal, iron, cobalt or nickel (sulphides) as co-catalyst and an alkali metal or alkaline earth metal for the reaction in a basic medium. Minimum operating temperature value is 200°C, but it is preferable to operate in the 240 – 325°C range.

Details can be taken from literature [Lodgson, 1994], [Syntec, 2006], [Garcia, 2007].

Dimethylether Synthesis. The synthetic production of Dimethylether (DME) is possible in two ways: it can be produced directly via synthesis or by the intermediate step methanol. For large-scale production, it has been shown that the integration of the two process steps, methanol and DME synthesis, is very advantageous and the best choice for DME production in terms of efficiency. The methanol synthesis takes place according to **Equation 2-11** and **Equation 2-12**: Hydrogen, CO₂ and CO are converted into methanol; water is a by-product. The operating pressure of methanol synthesis ranges from 45 to 100 bars and temperatures of about 220 to 280 °C. Catalysts based on copper (Cu), zinc (Zn) and aluminium oxide (Al₂O₃) are applied [Ekbom, 2005].



Then methanol is converted to DME whereby water is separated chemically. (Equation 2-13). The reaction takes place at temperatures of about 250 to 300 °C.

This three reactions (Equation 2-11, Equation 2-12 and Equation 2-13) are exothermal and the heat can be further used, e.g. for steam production [Ekbom, 2005] [Ekbom, 2003].



2.5.2 Technologies

Some selected technical implementations of the processes described in the previous chapter will be explained in this section.

Fischer-Tropsch Synthesis.

Operation mode. There are two operation modes applied in FT synthesis reactors:

- 'full-conversion' operation
- 'once-through' operation

In 'full-conversion' operation mode, unconverted syngas is looped back to the syngas stream which is increasing the overall syngas to FT raw product conversion rate. Also hydrogen and CO from reforming of light hydrocarbons (described in chapter 2.4.2) can be looped back (recycled) to the FT reactor input.

Such a sophisticated looping is not done in 'once-through' operation mode, where the surplus- and unconverted gas streams are used for heat and power generation in a gas and steam cogeneration plant [Vogel, 2003].

Reactor Design. Two reactor types are applied for low temperature FT synthesis (LTFT) [Vogel, 2003] [Boerrigter, 2003]:

- Tubular Fixed Bed Reactor (TFBR) and
- Slurry Bubble Column Reactor (SBCR)

Tubular Fixed Bed Reactor (TFBR). The TFB reactor consists of a vessel with long thin tubes which are vertically aligned in bundles (left picture in Figure 2-8). The syngas is entering on top of the reactor and flowing very fast through the tubes to create high turbulence which is good for an efficient conversion. The liquid raw products are withdrawn from the bottom of the reactor. On the outside of the tubes the reaction heat is withdrawn by generating steam which can be used in the plant.

Advantageous is the fact that catalyst poison can be adsorbed at the entrance of the reactor avoiding its deactivation. A clear disadvantage is the long standstill periods of the reactor while the catalyst is renewed. This results in a big maintenance effort. Furthermore the investment costs of TFB reactors are higher than of the SBC reactor.

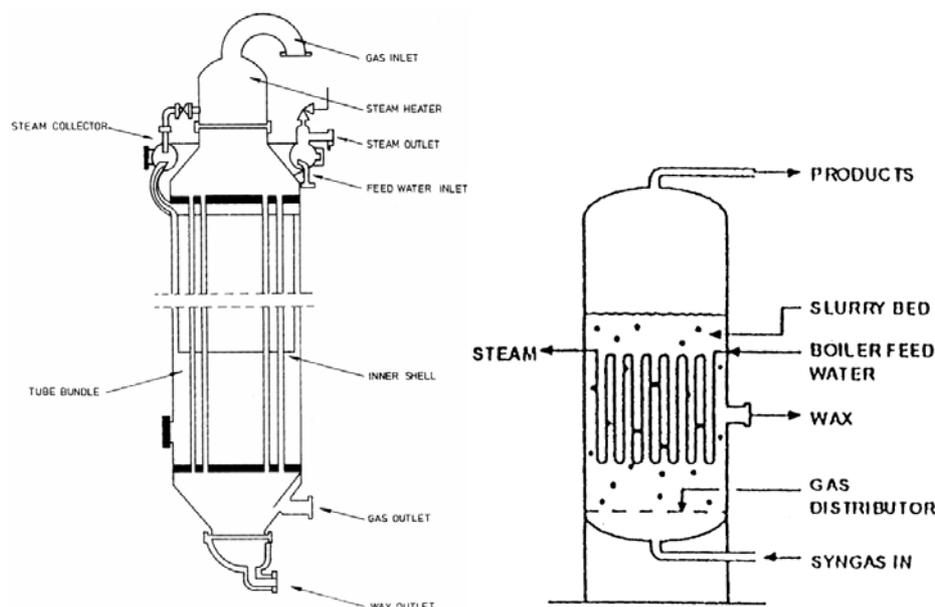


Figure 2-8: Tubular Fixed Bed Reactor [Dry, 2002] (LEFT) vs. Slurry Bubble Column Reactor [Dry, 2002] (RIGHT)

Slurry Bubble Column Reactor (SBCR). The SBC reactor is built of a reactor coat which contains a cooling coil (right picture in Figure 2-8). Syngas is fed in at the bottom of the reactor and 'bubbles' through a suspension (wax and catalyst particles). Unconverted syngas, light hydrocarbons and water are withdrawn at the top of the reactor body. Like in TFB reactors, surplus heat is withdrawn by steam generation for further use in other processes. The catalyst is in the suspension and can be exchanged during operation.

This exchangeability of the catalyst results in lower standstill times of the reactor, which is an advantage of the SBC reactor. Further advantages are lower investment costs and high conversion rates in 'once-through' operation mode.

A disadvantage of this reactor type is the hazard of catalyst deactivation by the entrance of a catalyst poison in the syngas stream. Hence the SBC reactor requires very clean syngas quality for a safe operation. Further the separation of waxes and catalyst particles is sophisticated, which is another disadvantage of this reactor type.

More details on reactors may be taken from literature [Boerrigter, 2003], [Dry, 2002], [Vogel, 2003], [Hamelinck, 2004], [Bolhár-Nordenkamp, 2003], [Hofbauer, 2003].

Dimethylether Synthesis. In this section relevant technical aspects of the DME production will be described. The most common types for methanol synthesis and catalytical dehydration of methanol (DME synthesis) are presented in the following.

A typical reactor type for methanol production is the so called 'ICI-Quench-Reactor' shown in Figure 2-9 (left picture). The adiabatic reactor consists of a pressurised vessel (B) where the syngas is fed in (C). The cooling is done by an internal quench (fast cooling by injection of condensate) with fresh syngas. The reaction heat is withdrawn at the exit of the reactor, which is at the bottom. Several openings are there for reactor maintenance and change of catalyst (A, D). The conversion of methanol to DME where water is chemically separated is done in a DME reactor shown in Figure 2-9 (right picture). Fixed bed reactors are used for this purpose. First, methanol is heated to a temperature of about 250 °C (e.g. by a heat exchanger) before entering the reactor. Inside, an exothermic reaction takes place at temperatures of 250 to 300 °C and DME is formed. After the reactor the effluents are cooled down and DME is separated from unconverted methanol and water. The conversion rate of raw methanol to DME ranges from 86 to 88 %. The 12 to 14 % losses are unconverted methanol (7 to 8 %), water (3 to 4 %) and CO₂ (2 %) adsorbed in DME [Faaji, 2001], [Thuijl, 2003], [Ekbom, 2005], [Ekbom, 2003], [Rauch, 2002].

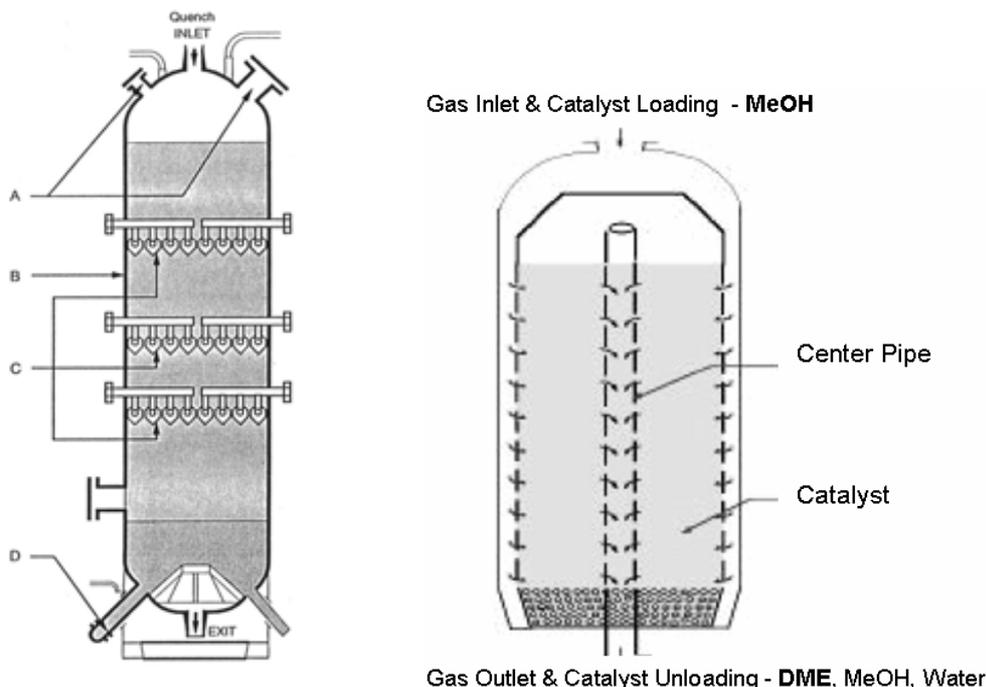


Figure 2-9: ICI quench reactor [Cheng, 1994] (LEFT) vs. Fixed Bed Reactor for MeOH/DME synthesis [Mii, 2001] (RIGHT)

2.6 Upgrading

The products of synthesis are raw products, i.e. they can usually not be applied directly as motor fuel. Depending on the previous synthesis and the desired final motor fuel, there are several upgrading steps to take. Some of these steps are explained in the following. A chapter with further information on upgrading can be found in the annex in chapter 9.2.

2.6.1 Basics

Subsequent the basics of synthetic fuel upgrading of FT raw products and DME are discussed.

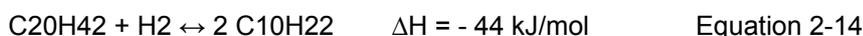
Fischer-Tropsch Products. The FT raw products consist of a wide spectrum of gaseous and liquid hydrocarbons and as well water. The liquid hydrocarbons have to be separated from the gaseous ones and water before they can be further upgraded.

The synthesis reaction parameters can be tuned to maximise the raw products yield by increasing the chain growth probability α to approximately 1 theoretical (0,9 under practical conditions). Then the spectrum of raw products is shifted towards higher hydrocarbons (see chapter 2.5.1, basics of synthesis) Nevertheless some light hydrocarbons ($C_1 - C_4$) are produced in synthesis and as an undesired by-product. They have to be separated from the liquid raw products.

Then the light hydrocarbons are either reformed to H₂ and CO and recycled or looped back to the synthesis ('full-conversion' operation mode) or energetically used for heat and/or power production ('once-through' operation mode) (see also chapter 2.5.2). Water which is a further by-product of synthesis has to be separated as well from liquid raw products.

After the separation of by-products the liquid raw products are distilled in different fractions: naphtha (C₅ – C₁₀), the main product FT diesel (C₁₁ – C₂₀) and waxes (C₂₁₊). Naphtha is a gasoline fraction of minor value; a resource for the petrochemical industry. It can be upgraded to motor applicable gasoline among other things by isomerisation.

The upgrading of waxes (C₂₁₊) is done by hydrocracking; it can be also done for smaller fractions (C₅₊). In this catalytic oil refinery process, long chained hydrocarbons are split into the desired diesel- and middle distillates by C-C bond breaking in presence of hydrogen. The hydrocracking reactions are exothermal (Equation 2-14). The reaction heat can be used in other processes [Ekbom, 2005].



Hydrogen is used to saturate the open C-C bonds and fed into the hydrocracker at pressures of about 30 to 200 bars. The reaction temperatures range between 350 to 500 °C. Nickel is applied as catalyst. To increase the anti-knock and cold flow properties further isomerisation has to be done [Hamelinck, 2004], [Ekbom, 2005], [Tijmensen, 2002].

Ethanol-Synthesis. The outlet stream from the synthesis reactor is composed of unconverted syngas (mainly CO, H₂) and reaction products, namely water, methanol, ethanol, higher alcohols (n-propanol, n-butanol, n-pentanol) and CO₂, CH₄. The first step in the separation process can be carried out in a flash drum, obtaining H₂, CO, CO₂ and CH₄ as gas and alcohols as liquid. Gas is recycled and alcohols are sent to a separation train. Details can be taken from literature [Lodgsdon, 1994], [Syntec, 2006], [Garcia, 2007].

Dimethylether. The effort on upgrading of DME raw products is much less than for FT raw products. Raw DME contains some water, dissolved gases and little amounts of higher ethers, which have to be withdrawn by distillation.

2.6.2 Technologies

A short description of technologies applied for synthetic fuel upgrading will be given in the following; in particular technologies for FT and DME raw products upgrading as described in the previous chapter.

Fischer-Tropsch Products. The gaseous hydrocarbons in the FT raw products are volatile and therefore easy to separate. Water is separated conventionally by a condensate trap. The separation of the particular fractions is done via rectification (repeated distillation) in various columns.

Cracking of long chained hydrocarbons is done in a hydrocracker. Due to extreme reaction parameters (high temperature, high pressure), expensive special hardened steel is used. For the sake of FT products upgrading, Shell has developed a so called 'heavy paraffin conversion' process (HPC) which combines the hydrocracker with an isomerisation unit over the same catalyst. Both processes run simultaneously [Ekbohm, 2005], [Hamelinck, 2004], [Tijmensen, 2002].

Dimethylether. The separation of the dissolved gases from DME can be done in a low pressure atmosphere where the solubility decreases and the solved gases can be drawn off. Then distillation follows, where DME is cleaned intensively. Methanol, higher alcohols and water are separated from DME.

2.7 Commercial Process Chains on Synthetic Fuel Production

Gas to liquids (GtL) or Coal to liquids (CtL) are refinery processes to convert natural gas or coal into longer-chain hydrocarbons for synthetic (liquid) fuel production. In both cases the first step is the synthesis gas production and conditioning to enable the subsequent fuel synthesis. Concerning fuel synthesis GtL and CtL use similar technique but the synthesis gas production and motivation is different.

2.7.1 History of GtL/CtL processes

CtL technology in industrial scale was developed during the II Wold War to make the German liquid fuel production independent of crude oil resources. In the 1950s South Africa started the production of caol based liquid fuels and improves CtL technology which becomes more importance during the later trade embargoes against the apartheid regime. The South African company Sasol currently operates the world's only commercial CtL facility at Secunda, South Africa, with a capacity of 150,000 barrels a day. Synthesis gas production is made by coal gasification followed by an extensive gas cleaning and upgrading necessary to achieve the required synthesis gas quality.

The development and application of GtL technology is more economic based. One of the main goals of GtL processes is to monetize remote or "stranded" gas resources often in conjunction with crude oil exploitation. These gas resources are often far away of the end users and piping of gaseous fuels is distance limited and expensive. Similar to CtL technology the first step is the synthesis gas production which is mainly steam reforming or partial oxidation with oxygen or air. Many companies enrooted in the oil industry have developed GtL processes (at the pilot plant or commercial stage) include Shell, Exxon, BP, Mobil, Statoil, Rentech and Syntroleum. Worldwide commercial GtL plant capacity is estimated to 160,000 barrels per day with increasing tendency /SYNGAS Refiner 2005/.

2.7.2 CtL/GtL production sites and capacity

Existing and planned CtL/GtL production sites and their production capacity are exemplary summarized in Table 4.3.1.

Location, Company	Capacity	Remarks
CtL	barrel/day (b/d)	
Secunda, South Africa, Sasol	Sasol I II III 150,000 b/d since 1955	Sasol III, Slurry Phase Destillate Reactor, Fe-based catalyst /Erdöl Erdgas Kohle 2001/
GtL		
Mossgas, South Africa	23,000 b/d since 1993	/Erdöl Erdgas Kohle 2001/
Bintulu, Malaysia, Shell	12,500 b/d since 1993	SMDS Shell Middle Destilate Synthesis, fixed bed, Co based Catalyst /Erdöl Erdgas Kohle 2001/
Ras Laffan, Qatar, Sasol/Qatar petroleum	ORYX I, 34,000 b/d since 2006 ORYX II, 65,000 b/d planned	ORYX project is a joint venture of Qatar petroleum and Sasol. In a further project 130,000 b/d are planned /SYNGAS Refiner 2005/
Pearl, Qatar, Shell	Pearl 2 x 70,000 b/d planned 2009	/SYNGAS Refiner 2005/
Escravos, Nigeria, Chevron/Sasol	34,000 b/d under construction	/SYNGAS Refiner 2005/

Table 4.3.1 Existing and planned (closed to operation) CtL/GtL production sites

Figure 2-10 shows an overview of the worldwide existing XtL plants with a capacity of more than 1000 barrels per day.

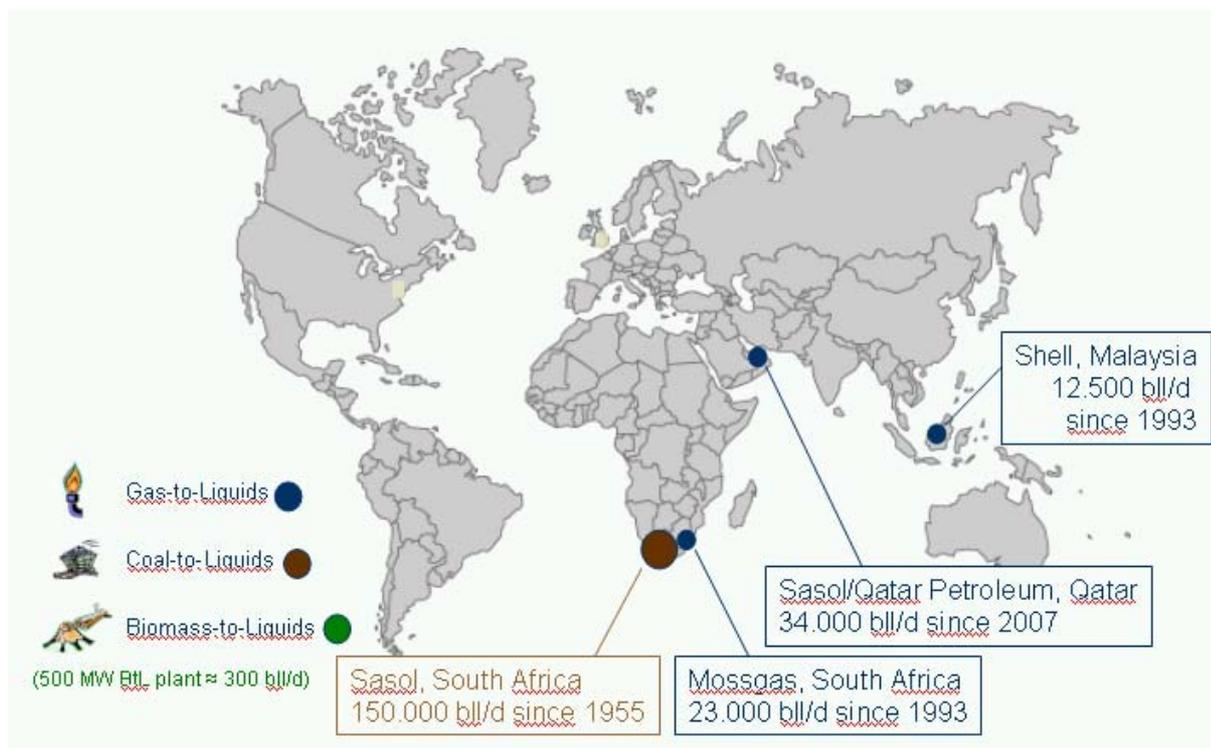


Figure 2-10: Experiences of commercial syngas technologies, existing plants > 1000 barrels per day (bll/d)

Nearly all leading oil companies announced GtL projects located around the world with an expected production capacity of 1 million barrel per day in 2010 /Oilfield Review 2003/. Many of the announced projects are located in Qatar which will become the world leader in GtL production exploiting the “North field” offshore gas reservoir between Qatar and Iran.

Beside the oil industry there are many other companies offering their special know-how linked with CtL/GtL technology, like catalysts, air separation units, gas cleaning and conditioning equipment, product upgrading and more. Some of these companies operated their own pilot or demonstration plants to produce certain amounts of synthetic fuel. Exemplary two of these activities are mentioned beneath.

Syntroleum, an US company has produced over 400,000 gallons of diesel and jet fuel from the Fischer-Tropsch process at its demonstration plant near Tulsa, Oklahoma. Using natural gas as a feedstock, the ultra-clean, low sulfur fuel has been tested extensively by the US Department of Energy, the Department of Transportation, and most recently, the Department of Defense, which utilized the fuel in a flight test of a B-52 bomber at Edwards Air Force Base, CA. Syntroleum is working to commercialize its proprietary Fischer-Tropsch technology via coal-to-liquid plants in the US, China, and Germany, as well as gas-to-liquid plants internationally.

A small US-based company, Rentech, is currently focusing on converting nitrogen-fertiliser plants from using a natural gas feedstock to using coal or coke, and producing liquid hydrocarbons as a by-product.

2.7.3 CtL/GtL technology

As mentioned above CtL and GtL are multi-stage processes which concerns mainly synthesis gas production gas cleaning and conditioning, fuel synthesis and product upgrading. Synthesis gas is the main intermediate product of both CtL and GtL processes. Depending on the envisaged fuel synthesis (mostly Fischer-Tropsch for liquid fuel) the synthesis gas ideally consists of H_2 and CO in the ratio of 2:1 and nothing else. In reality different feedstock and conversion technique produce a broad range of synthesis gas quality. The gasification of coal or biomass produces a “dirty” raw synthesis gas which contain - beside inert components N_2 , CO_2 , H_2O - a lot of impurities H_2S , NH_3 , tar and minerals which origin from the fuel. In the case of solids gasification huge effort on gas cleaning and conditioning is necessary to achieve synthesis gas quality required for fuel synthesis which is described in Annex 10.4.

For gaseous feedstock steam reforming or partial oxidation with oxygen or air is used for synthesis gas production. Depending of the feed gas quality (remote or stranded gas) the gas cleaning and conditioning effort is lower than that of solid feedstock. Nevertheless gas impurities e.g. catalyst poisons has to be removed before catalytic process steps. One can assume that stranded or remote gas varies in quality (CH_4 content, inert gas, impurities) what implies gas cleaning and conditioning measures before fuel synthesis. The effort depends on the one hand on feed gas quality (the higher the heating value the better) and on the other hand on the envisaged fuel synthesis, catalyst and the reactor type.

For Fischer-Tropsch synthesis mainly iron or cobalt based catalyst in combination with different reactor types are used (compare Chapter 2.5). A comprehensive overview on catalysts and reactor type development is given in /Spath & Dyton 2003/. There, the key properties of FT catalyst are mentioned as:

- Lifetime (oxidation, carbon deposition, poisoning, etc.)
- Activity
- Product selectivity
- Costs

2.7.4 Size and economics of CtL/GtL plants

In 2001 /Bakhtiari 2001/ published a provocative article entitled: “Gas to liquids: much smoke, little fire” based on economical data of first and second generation plants. There one can find specific investment costs which are summarised in Table 4.3.3

Plant	Capacity	Specific investment costs
	barrel/day (b/d)	Investment/daily capacity barrel \$/ (b/d)
Mossel Bay, South Africa, Sasol	27,500 b/d since 1993	127,000 \$/(b/d)
Bintulu, Malaysia, Shell	12,500 b/d since 1993	125,000 \$/(b/d)
Ras Laffan, Qatar, Sasol/Qatar petroleum	34,000 b/d Since 2006	23,500 \$/(b/d) estimated in 2001
Escravos, Nigeria, Chevron/Sasol	34,000 b/d under construction	23,500 \$/(b/d) estimated 2001

Table 4.3.3: Reviewed and estimated specific investment costs of GtL plants /Bakhtiari 2001/, /Cornitius 2005/

In various Literature one can find estimated future specific investment cost values for GtL plants in the range of 34,000 to 20,000 \$/(b/d) (Investment/daily capacity barrel) where 20,000 \$/(b/d) is often mentioned as economic threshold. Table 4.3.4 cites an estimated cost breakdown of capital investment for a typical second generation GtL complex with a capacity of 50,000 b/d (barrels per day) /Bakhtiari 2001/.

Facilities and major units	Capital investment
<i>Inside battery limits</i>	<i>\$ million</i>
Gas treating unit	120
Air separation units	230
Syngas units	180
Fischer-Tropsch reactors	220
Products' separation units	190
<i>Outside battery limits</i>	
Utilities and common facilities	360
Total depreciable cap. inv.	1,300
Licensee fees	75
Initial catalyst and chemicals	60
Commissioning and startup	40
Total initial cap. inv. (TICI)	1,475
Contingency (@ 15% of TICI)	225
Total capital investment	1,700
Capital investment/daily capacity barrel: \$1,700,000,000/50,000 b/d = \$ 34,000 \$/b	

Table 4.3.4: Cost breakdown of capital investment for a typical second generation GtL complex with a capacity of 50,000 b/d (barrels per day) /Bakhtiari 2001/.

The cost breakdown is not in that detail, but it gives an impression how the total investment cost is distributed. One can see that auxiliary units (air separation unit), which are often underestimated in terms of cost, takes 20 % of the core installation.

Efficiency, process performance. Concerning economics efficiency plays a mayor role, but there are several definitions of efficiency (refer Annex 10.3 Efficiency In-Depth). The aim here is to give an impression how much of the remote or stranded gas is at least converted to liquid fuel or more general to product. On energy basis (LHV) the theoretical max conversion of methane to paraffins is 78%. In reality the feed gas is no pure methane and many process steps lose irreversible energy. In large scale plants a high process integration (e.g. steam recycling from F-T synthesis to reforming, electricity generation from waste heat, etc.) can improve thermal efficiency. For the GtL process (e.g. SMDS Shell Middle Distillate Synthesis) thermal efficiency in the range of 62-65% and carbon conversion efficiency of 78-82% is reported in literature. For Sasols slurry phase process thermal efficiency is about 60% and carbon conversion of about 75% /Spath & Dayton 2003/.

Economics. The question, if a GtL/CtL plant is economic or not, depend strongly on the frame conditions as there are:

- Process performance, efficiencies, plant size, investment cost
- Feedstock, quality, availability, cost
- Products, market situation, competing crude oil products
- Political situation, taxes, credits

To estimate for example the price of the produced liquid fuel a set of frame conditions has to be fixed and therefore the gained results are very specific. Taking the basic process data given in the tables above and a set of individual frame conditions one can estimate his own fuel prices and decide weather they are economic or not.

2.7.5 Quality and prospects of GtL/CtL fuels

Many of the beneficial properties of Fischer-Tropsch fuels in comparison to petroleum based fuels are based on the following outstanding attributes:

- Very low (no) sulphur content
- Low content of aromatics
- High cetane number

These properties result in superior combustion characteristics with significant decreases in vehicle emissions (except CO₂). Within the RENEW project this is a separate topic and therefore not discussed in detail here. The beneficial properties not only appear with neat fuels but also in blends with conventional fuels. This opens a wide range of future prospects for the whole product spectrum produced with Fischer-Tropsch synthesis.

2.7.6 Results on commercial Technologies

Within this chapter it was shown, that up to now only GtL and CtL plants are running in a commercial scale. Comparing the processes, BtL technology shows a lot of similarities to CtL technology (solid feedstock, process sequence etc.). A main difference between BtL and CtL/GtL exists regarding plant size. From a logistical point of view it is not possible to exceed such large plant sizes as they are for CtL and GtL.

3 Concept Description

At present the production of synthetic biofuels is under discussion for various options of biomass treatment, kind of gasification and gas cleaning up to the different options of synthesis and product upgrading. Further on, it could be realised in different scales under usage of different types of solid biofuels. Starting from this variety, the most relevant options of BtL-production will be evaluated within this TA. Therefore, input and output streams of this assessment are described in the following the scenarios (chapter 3.1). Based on this, an overview on the BtL-concepts considered in this Renew TA is presented (chapter 3.2) [Renew, 2006].

3.1 Scenarios, Inputs and Output Streams

For the analysis of BtL concepts and its comparability in this TA, respective frame conditions have been defined within the deliverable 'Scenario and Boundary Conditions' [Boundary, 2005]. In the following, an overview on this frame conditions is given. Further details on scenario description, biofuel properties and further conditions such as 'conditions of biomass at plant gate', 'requirements on emission reduction' or 'waste water', etc. can be found in this document [Boundary, 2005].

3.1.1 Scenarios

Starting Point. The starting point describes different production routes for biofuels as they are described today by their developers based on expert-guess and the current frame conditions for biofuel production. This approach establishes a starting point for scenario 1 and scenario 2. The abbreviation used in this document for this scenario is SP.

Scenario 1 and 2. A decision was taken to build up and organize all different biofuel supply chains to be commissioned in 2020. Until that date, further research and development will be done in the process design and optimisation and the different industries involved in the supply chain will experience significant improvements: agriculture, biomass and biofuel logistics, energy industry.

Scenario 1: Maximized Biofuel Production. The supply chain is supposed to produce as much as possible biofuel from the biomass input. One of the highest criteria in evaluation of biofuels is the ratio of biofuel production referred to the required surface area for biomass production. Additional conventional energy input to the production system is accepted. The abbreviation used in this document for this scenario is MF.

Scenario 2: Self-Sufficient Biofuel Production. The supply chain is supposed to be as independent as possible from non-biomass energy sources. One of the highest criteria in evaluation is the ratio of biofuel production to the used non-biomass resources.

For each scenario (incl. starting point), the biofuel supply chains are virtually scaled up to 500 MW biomass input. This can be realized by one or several plants. The decision whether one 500 MW-plant or several smaller plants will be realised is taken by the respective technology developer. The physical lifetime of the plant is set to 20 years, the annual operating time to 8000 h/year.

3.1.2 Input and Output Streams

Input. Investigated standard Biomass according to 'boundary conditions':

- Willow-Salix is investigated as standard woody biomass input.
- Miscanthus is investigated as standard herbaceous biomass input.

Only in those cases where the investigated BtL-process is not able/not designed to convert the listed biomass input to BtL other biomass inputs are investigated (e.g. wheat straw).

Output. Main biofuel products:

- Fischer-Tropsch Diesel
- Di-Methyl-Ether (DME)
- Bio-Ethanol

3.2 Overview on Concepts Considered

Figure 3-1 shows the different concepts under different scenarios, their main in- and outputs and the foreseen system components as well.

The system components are distinguished in

- mechanical/thermal pretreatment (chipping, sieving or drying of biomass delivered free plant gate),
- thermochemical pretreatment (downstream pyrolytical decomposition; pyrolysis or torrefaction of the biomass)
- gasification (conversion of the gasifier feedstock into a raw gas)
- gas cleaning (separation of trace components to produce a clean gas)
- gas conditioning (adaptation of the gas composition according to synthesis demands)

- synthesis (production of a synthesis raw product)
- upgrading (conversion of the raw product into a motor fuel)

Further on, the abbreviations of each concept and the partners responsible for data provision can be taken from the legend of Figure 3-1.

The bandwidth of principle options for BtL-production will be assessed by analysing these different technical options. For such an analysis, the different concepts are described in the following. Here, the concept descriptions are reduced to some extent as a result of process simplification and standardisation and confidential agreements. This applies as well for the Sankey diagrams developed for each concept. A more detailed energetic comparison of the concept's process data is done in chapter 5.1.

Concept	cEF-D			dEF-D			BLEF-DME			EF-E			CFB-D			ICFB-D			CFB-E								
Scenario	SP	MF	SS	SP	MF	SS	SP	MF	SS	SP	MF	SS	SP	MF	SS	SP	MF	SS	SP	MF	SS						
willow			eq.SP						eq.SP			eq.SP			eq.SP			eq.SP			eq.SP						
straw			eq.SP			eq.SP									eq.SP												
miscantus																		eq.SP									
Biomass input power [MW]	500															50	500										
Pretreatment - mech. / thermal	drying			drying						drying			drying + pelletising			drying											
- thermochemical	carbonisation			pyrolysis			residue: black liquor (pulp mill)*			torrefaction																	
- location	plant			decentral			plant																				
Gasification	EF									CFB																	
	chemical quench**									quench									autothermal			allothermal					
Gas cleaning / conditioning	conventional physical absorption:									dedicated technologies									conventional physical absorption:								
	Selexol			Rectisol			Selexol												Selexol								
Synthesis	TFBR, Co			SBCR, Co			MeOH, DME			no information			TFBR, Fe			SBCR, Fe			no information								
Upgrading	Distillation, Hydrocracking									Distillation			Distillation			external upgrading (refinery)						Distillation					
Plant product	FT-Diesel									DME			Ethanol			FT-raw-product						Ethanol					
Data provision by	UET			FZK			CHEMREC			ABENGOA			CUTEC			TUV			ABENGOA								

LEGEND

General	Biomass input	Synthesis	BtL output
c central	willow	TFBR	DME
d decentral	straw	SBCR	E
BL Black Liquor	miscantus	MeOH, DME	FT-D / D
		Fe, Co	Dimethylether
		Ferrum - Iron, Cobalt	Ethanol
Scenario	Gasification		Fischer-Tropsch Diesel
SP starting point	EF Entrained Flow		Fischer-Tropsch raw-product
MF maximum biofuel	CFB Circulating Fluidized Bed		
SS self sufficient	ICFB Internally CFB		
eq. equal			

* no explicit thermochemical conversion step: residue of pulp mill
 ** temperature reduction via injection of char (primarily endothermic gasification reactions)

Figure 3-1: BtL-Concepts Considered within the Technical Assessment

The concept descriptions and Sankey diagrams (shown below) are based on the information and data provided by the respective Renew-partners (concept developers) (mentioned in Figure 3-1). Here, the fact has to be considered that production chains differ in terms of provision of an applicable motor fuel:

- The concepts cEF-D, dEF-D, BLEF-DME, EF-E and CFB-E provide a main product that can be directly applied as motor fuel
- The concepts CFB-D and ICFB-D provide a main product that has to be upgraded to FT-Diesel in an external refinery

To achieve a unification and comparability of all concepts in terms of efficiency, the required upgrading from raw product to motor fuel is estimated within this report (respectively taken from other sources; see chapter 9.2). However, the concepts themselves will be evaluated as they are delivered by the technology providers, i.e. without external upgrading.

In this context, it has to be considered that the provided concepts do not match 100% with the defined scenario conditions. This appears also in Figure 3-1; for most of the concept providers (SP1-4) the starting point scenario (year 2004) has been equated with the self sufficient scenario (year 2020).

3.2.1 Centralised Entrained Flow Gasification for FT-Diesel Production (cEF-D)

The production of FT-Diesel via entrained flow gasification of willow and straw is described by the cEF-D concept. Beside this main product also naphtha and electricity is produced. The biomass input power of this concept is 500 MW (over the fence of the overall plant). The information and data basis for this subsection was provided by UET (Choren Industries) [Choren 1, 2005], [Choren 2, 2006], [Choren 2, 2006], [Rudloff, 2005], [Rudloff, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario, the biomass (willow salix or wheat straw) is converted into FT-Diesel without auxiliary energy. Thus, this scenario is equal to the self sufficient scenario. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. The stored biomass is dried to the conditions of downstream processes by hot air ($T \approx 100 \text{ }^\circ\text{C}$, air is preheated by low pressure steam) and fed to the lock hopper of the pyrolytic decomposition.

Thermochemical Pretreatment. A so called ‘low-temperature gasifier’ (NTV) is applied for pyrolytic decomposition of biomass. This aggregate, a horizontal cylindrical fixed bed reactor with rotating spindle (for mixing feedstock with hot material) is operated at 400 – 500 $^\circ\text{C}$ and under a gasification pressure of 35 bar. A hopper system ensures the feedstock pressurisation. To reach the decomposition temperature, biomass is partly oxidised by technical oxygen. As product, a so called low-temperature carbonisation gas (tar-containing) and char is feed to the downstream gasification.

Gasification. The carbonisation gas (with tar) is fed into the combustion chamber of a so called ‘high-temperature gasifier’ (an entrained flow reactor). Tar is reduced in the combustion chamber at high temperatures ($T \approx 1400 \text{ }^\circ\text{C}$; $p = 35 \text{ bar}$). The gasification agent is technical oxygen (produced at site by an air separation unit). A so called ‘Chemical quenching’ is done by blowing cooled and milled char into the hot gases downstream the combustion chamber. The endothermic gasification of the char causes a drop in gas temperature to 800 $^\circ\text{C}$.

The hot tar-free raw gas is then cooled in the heat exchanger producing high pressure steam ($p = 40 - 45$ bar) and low pressure steam ($p = 5$ bar) for power generation and other process parts. Ash particles and unconverted char are separated from the raw gas in the deduster. These are recycled back into the combustion chamber where it builds slag, which is removed from the bottom of the entrained flow reactor.

Gas Cleaning and Gas Conditioning. The main gas cleaning unit contains of two scrubbers. In the first scrubber, contaminants like chlorine and sulphur are washed out by acidic water. The second scrubber is a clear water scrubber, which is separating residual particles and washing agents (from first washer) from clean gas.

Adjusting the right H_2/CO -ratio is done by CO-conversion in the water-gas-shift reactor. The CO_2 in the clean gas is separated physically by a selexol washer. The fine gas cleaning (removal of O-, S- and Cl-traces) is ensured by a physical adsorption (e.g. ZnO), which is acting as a security guard for the synthesis reactor.

Further on, different gases from synthesis are looped back to the gas cleaning and gas conditioning unit; hydrogen is feed from this unit to synthesis and upgrading. For this conversion purpose, the upgrading technologies steam reforming (SMR) and pressure-swing-adsorption (PSA) are foreseen.

FT-Synthesis. A cobalt catalyst is applied in a Tubular-Fixed-Bed reactor (TFBR) for Fischer-Tropsch synthesis. Main products of the synthesis are long chain paraffins and wax for upgrading in the downstream hydrocracker. Beside this, naphtha (gasoline fraction of minor value) is produced as by product (for application as fuel, an additional isomerisation would be required). The reaction enthalpy of the synthesis is used for producing middle-pressure steam ($p = 15$ bar).

Upgrading. The long chain paraffins and waxes are cracked into smaller chains of the diesel fraction in a H_2 -cracking process and simultaneously transformed into adequate isomers by isomerisation. The separation of the FT-raw products into the desired compositions is done in the distillation unit. The main product is FT-Diesel (BtL).

Auxiliary Units. The electrical consumption of the overall process is produced in an internal steam turbine. The steam is generated by superheating of unused process steam via surplus gas and small amounts of natural gas combustion (for optimized superheating). Surplus electricity is fed into the grid. Technical oxygen is produced by an air separation unit (ASU). Effluents of the process are handled in the water treatment and led into the sewage system. Surplus process water is used in the cooling tower to increase its cooling power.

The different process steps are shown in Figure 3-2 for the starting point scenario.

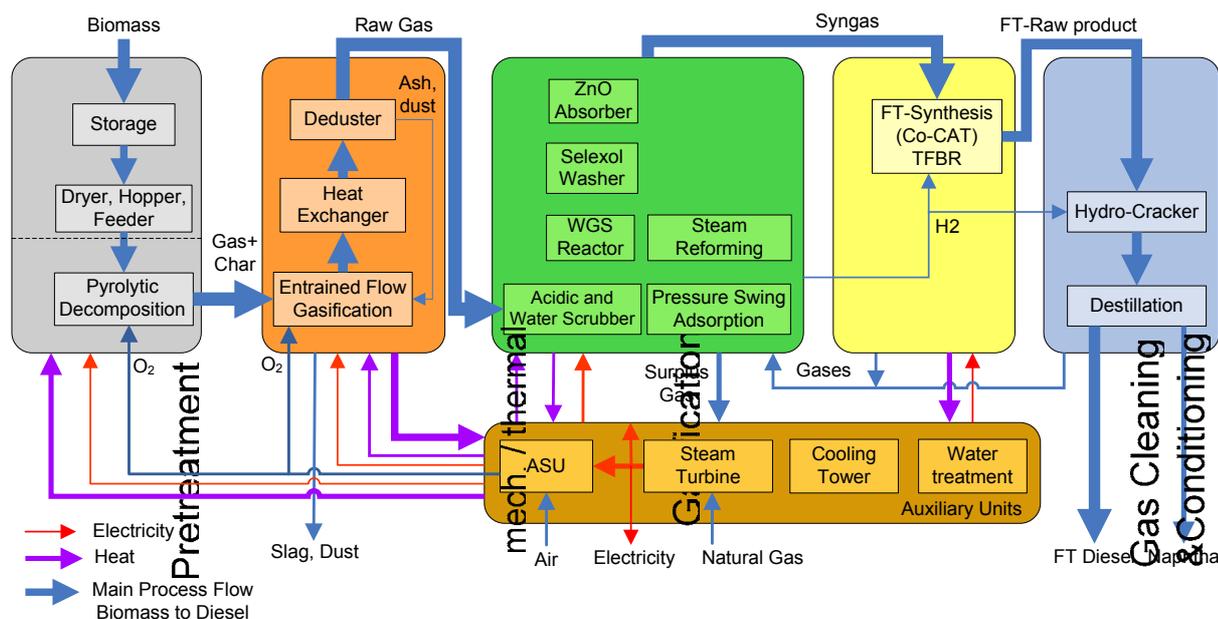


Figure 3-2: Simplified Process Flow of the cEF-D-Concept (Starting Point)

In Figure 3-3, the main energy flows including heat transfer (steam, water, etc.) of the cEF-D-Concept (Scenario Starting Point, willow) are shown.

the thermo-chemical

Process Description – Scenario ‘Maximum Biofuel’. The biomass used in this scenario is willow salix. The process is the same as in the scenario ‘Starting Point’ except the following differences:

- To achieve a higher carbon conversion and therewith higher fuel quantities, additional hydrogen is produced via electrolysis. The hydrogen is used in the synthesis unit and thus, no CO-Shift (WGS reactor) is required in the gas conditioning.
- All CO₂ will be converted in the synthesis process. Hence, the selexol washer is not necessary.
- The oxygen from electrolysis is used in the pretreatment and gasification units. Since the oxygen amount is sufficient for these processes, no air separation unit is needed. Surplus oxygen is foreseen for external use and credited as electricity for internal consumption in the assessment.

Concept Background and Intension. Beside these technical information for assessment, the data source and its quality is of high importance. The data quality can also be assessed by the fact whether investment costs can be provided or not. This and further information on the background and intension of the described concepts are summarised in Table 3-1. The aim of this overview is to provide a ‘condensed picture’ of concept specific differences.

Data Quality. The data quality and information provided by the concept developers (SP1-4) in Renew depends on many sources. To give an overview on the origin and basis of the concept developments, the most important sources are summarised in Table 3-1: Concept Background and Intension of the cEF-D-concepts

System component	information basis
Mech./thermal preparation	<ul style="list-style-type: none"> - simulation of the preparation processes based on literature data on power and heat consumption - investment costs have been summarised based on manufacture offers
Thermochemical preparation	<ul style="list-style-type: none"> - design of the process based on experiences from pilot plant and test campaign with 15 MW unit operated under pressure - design of the 30 MW reactor based on the 1 MW/15 MW test results - investment costs have been summarised based on manufacture experiences and β-plant procurement within the company group
Gasification	<ul style="list-style-type: none"> - design of the process based on the design of the 45 MW-demonstration plant (under construction and start-up) operated in part load test campaign - simulation of a pressurised gasification processes (250 MW) with a software tool evaluated by the data from 1 MW-pilot plant and the β-plant test campaign) - investment costs have been summarised based on manufacture experiences and β-plant procurement within the company group
Gas cleaning & Gas conditioning	<ul style="list-style-type: none"> - design of the gas cleaning based on the experiences of the 1 MW-pilot plant (long term operation of synthesis processes) and the detailed engineering/optimization for the β-plant together with FT-technology supplier and catalysts specialist - simulation based on the above mentioned information - investment costs have been summarised based on manufacture experiences within the company group, β-plant procurement and manufacture offer
Synthesis & Upgrading	<ul style="list-style-type: none"> - design on the experiences of the 1 MW-pilot plant (long term operation of synthesis processes) and the engineering for the β-plant together with FT-technology suppliers - simulation based on the above mentioned information - investment costs: upscaling of β beta cost, crosschecking with downscaling Bintulu/Katar GTL costs
Auxiliary units	<ul style="list-style-type: none"> - power generation data based on process simulation (applying commercial/standard steam turbine data) - electrolysis data (scenario 1) taken from manufacture offer

Table 3-2: Data Quality of the cEF-D-concepts

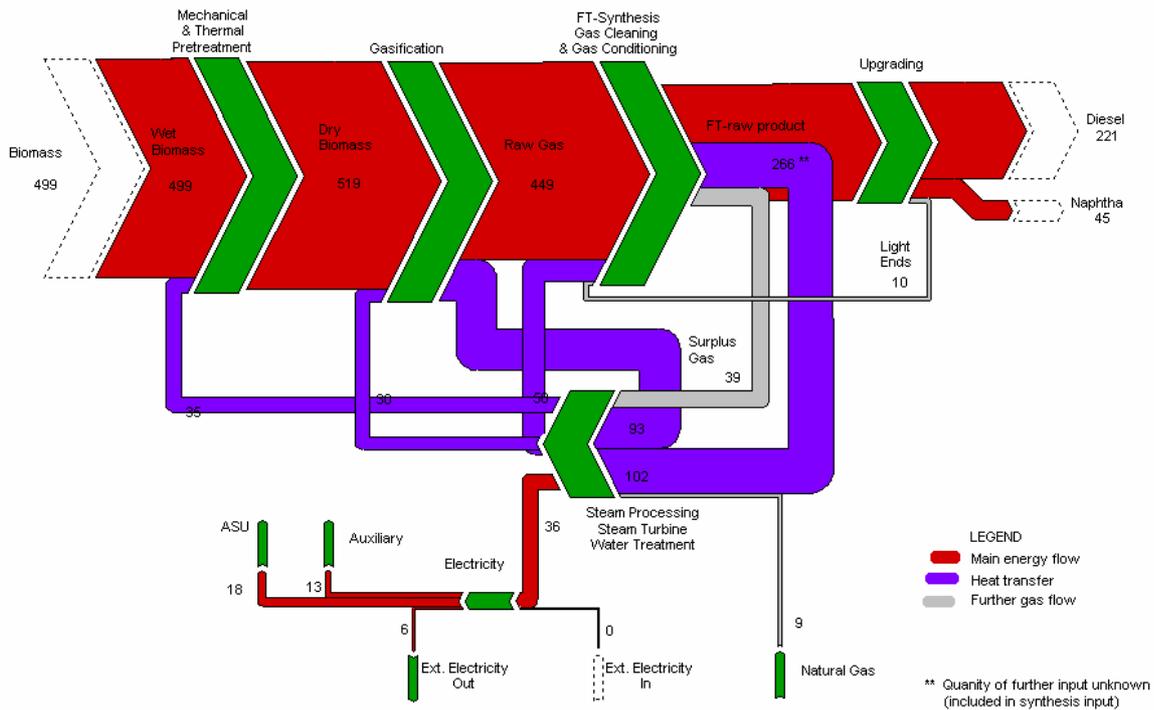


Figure 3-3: Simplified Sankey Diagram of the cEF-D-Concept (Starting Point, willow); Figures in MW

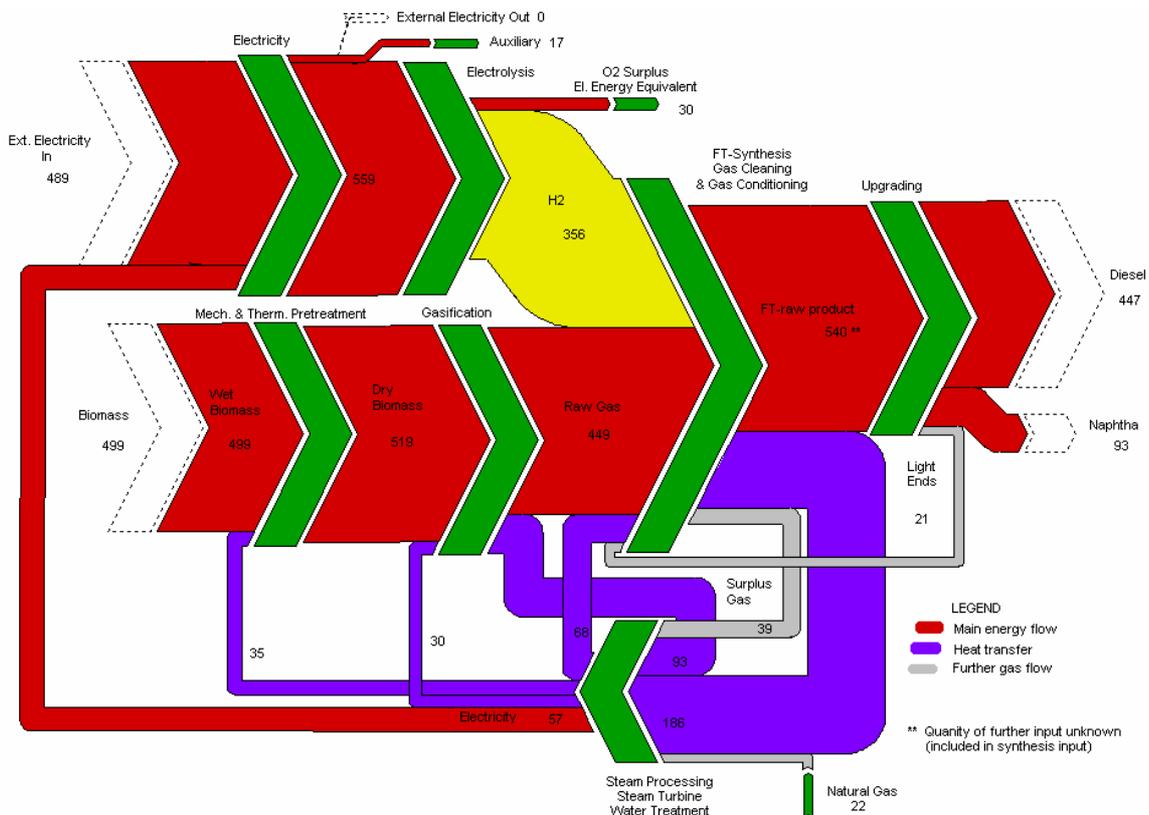


Figure 3-4: Simplified Sankey Diagram of the cEF-D-Concept (Maximum Biofuel, willow); Fig. in MW

Concept developer/data provider:	UET, Freiberg, Germany
Basic purpose of the concept	
<ul style="list-style-type: none"> - technology able to convert a wide spectrum of solid biofuels (via pretreatment) - fuel production for an existing market/infrastructure (focus on Diesel market) - integrated processes for high fuel conversion (loop processes) 	
Basic purpose of the concept components	
Preparation	<ul style="list-style-type: none"> - application of entrained flow gasifier requires thermochemical treatment; technical realisation of this treatment as easy as possible - provision of char for 'chemical quench' in the entrained flow gasifier
Gasification	<ul style="list-style-type: none"> - entrained flow gasification for high carbon conversion - low tar and methane content resulting in low gas cleaning and gas conditioning effort - comparable low raw gas temperature (increase of cold gas efficiency by so called chemical quench)
Gas cleaning & conditioning	<ul style="list-style-type: none"> - separation of impurities by a multi staged system approved for engine gas application - Selexol washing system for CO₂-separation - combination of gas cleaning steps promises sufficient gas quality; in contrast to commercially approved rectisol washing processes here a lower energy demand (no low temperature washer) and lower investment costs are aimed
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis and upgrading at central location (high process integration)
Existing technology	
<ul style="list-style-type: none"> - Construction and operation of an 1 MW_{fuel_power} pilot plant ('α-plant') for engine operation (1998-2001) - Construction and operation of synthesis process (about 1,000 operating hours methanol (2003) and about 10,000 operating hours FT-Fuel (2003 to 2005)) - Construction and operation of a commercial plant ('β-plant') (under construction since 2003), status: <ul style="list-style-type: none"> - one 15 MW_{fuel_power} and one 30 MW_{fuel_power} fuel preparation lines (NTV) - one 45 MW_{fuel_power} entrained flow gasifier - 300 bpd SMDS unit (barrels per day; shell middle distillate synthesis) - Commission (state of the art in 12/2006): <ul style="list-style-type: none"> o biomass storage, treatment, transport: ready, o gasifier: cold commissioning, hot planned for spring 2007 o FT: start in summer 2007 	
Working field/partners development	
<ul style="list-style-type: none"> - Basic engineering of conversion plants; detailed engineering of gas production - Production of components and strategy development within the company group 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - Starting point scenario: based on engineering of a 600 MW plant; thus SP and SS scenario are equal - Maximum biofuel scenario: only additional Hydrogen input simulated; further measures for an efficiency increase are technically possible but not considered in the scenario analysis 	

Table 3-1: Concept Background and Intension of the cEF-D-concepts

System component	information basis
Mech./thermal preparation	<ul style="list-style-type: none"> - simulation of the preparation processes based on literature data on power and heat consumption - investment costs have been summarised based on manufacture offers
Thermochemical preparation	<ul style="list-style-type: none"> - design of the process based on experiences from pilot plant and test campaign with 15 MW unit operated under pressure - design of the 30 MW reactor based on the 1 MW/15 MW test results - investment costs have been summarised based on manufacture experiences and β-plant procurement within the company group
Gasification	<ul style="list-style-type: none"> - design of the process based on the design of the 45 MW-demonstration plant (under construction and start-up) operated in part load test campaign - simulation of a pressurised gasification processes (250 MW) with a software tool evaluated by the data from 1 MW-pilot plant and the β-plant test campaign) - investment costs have been summarised based on manufacture experiences and β-plant procurement within the company group
Gas cleaning & Gas conditioning	<ul style="list-style-type: none"> - design of the gas cleaning based on the experiences of the 1 MW-pilot plant (long term operation of synthesis processes) and the detailed engineering/optimization for the β-plant together with FT-technology supplier and catalysts specialist - simulation based on the above mentioned information - investment costs have been summarised based on manufacture experiences within the company group, β-plant procurement and manufacture offer
Synthesis & Upgrading	<ul style="list-style-type: none"> - design on the experiences of the 1 MW-pilot plant (long term operation of synthesis processes) and the engineering for the β-plant together with FT-technology suppliers - simulation based on the above mentioned information - investment costs: upscaling of β beta cost, crosschecking with downscaling Bintulu/Katar GTL costs
Auxiliary units	<ul style="list-style-type: none"> - power generation data based on process simulation (applying commercial/standard steam turbine data) - electrolysis data (scenario 1) taken from manufacture offer

Table 3-2: Data Quality of the cEF-D-concepts

3.2.2 Decentralised Entrained Flow Gasification for FT-Diesel Production (dEF-D)

The production of FT-Diesel via entrained flow gasification of decentrally produced slurry (5×100 MW biomass input power) is described by the dEF-D concept. Beside this main product also naphtha and electricity is produced. The information and data basis for this subsection was provided by FZK (Forschungszentrum Karlsruhe) [FZK 1, 2006], [FZK 2, 2006], [FZK 3, 2006], [FZK 3, 2006], [Stahl, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario, the biomass (wheat straw) is converted into FT-Diesel without auxiliary energy. Thus, this scenario is equal to the self sufficient scenario. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. The input material straw is pretreated decentralised at 5 pyrolysis plants with a biomass input of 100 MW. Therefore (after storing and drying by ventilation air), straw is crushed in a hammer mill and a chipper and fed to a conveyer dryer.

Thermochemical Pretreatment. A so called ‘fast pyrolysis LR-mixer reactor’ is applied for pyrolytic decomposition of biomass. This aggregate, a double-lead screw mixer reactor (for mixing feedstock with hot fluidized sand) is operated at 600 °C. Straw is thereby decomposed and char is separated from the 500 °C hot gas stream by a cyclone. The gas is split into pyrolysis oil and pyrolysis gas. After heat exchange, the gas is used in a gas burner to supply heat to the heat transfer medium (sand). Char, organic liquids and water form the so called ‘slurry’; it is expected that the water will remain in the slurry (i.e. no phase separation occurs before supply free gasification plant gate).

Gasification. The slurry is taken from 5 fast pyrolysis plants and transported to one syngas plant, where it is mixed and preheated for gasification up to a temperature of 125 °C. The hot slurry is fed to an entrained flow gasifier (pressurised to $p = 80$ bar). The tar-content is limited by high gas temperatures ($T \approx 1200$ °C). The gasification agent is technical oxygen (imported from outside ‘over-the-fence’). The cooling of the raw gas is done via heat exchanger (producing steam of 600 °C) and a water quench.

Gas Cleaning and Gas Conditioning. Ash and particles are separated from the 500 °C hot raw gas in a water scrubber. A two-stage rectisol process is used for further gas cleaning and gas conditioning. In the first stage, impurities like H₂S and COS but also CO₂ are separated from the raw gas. In the second step, the clean gas stream is split: one part goes directly to synthesis; the other part is used for adjusting the right H₂/CO-ratio.

This is done by CO-Conversion in the water-gas-shift reactor. The resulting CO₂ in this second part of the clean gas is separated physically by the second-stage of the rectisol washer.

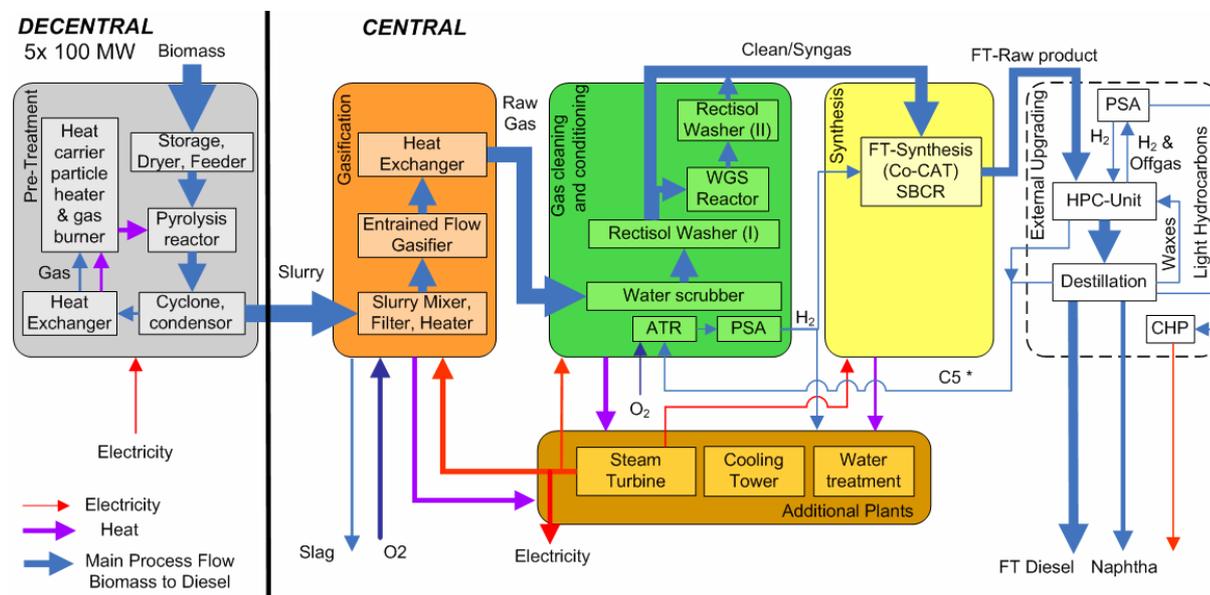
Further on, light hydrocarbons (C5) from the synthesis along with light ends from the distillation and from the hydrocracker are converted by an autothermal reforming process (ATR) into CO and H₂. Hydrogen is separated by a pressure-swing-adsorption unit (PSA) and used in the synthesis and steam generation.

FT-Synthesis. A cobalt catalyst is applied in a low temperature slurry bubble column reactor (SBCR) for Fischer-Tropsch synthesis. Main products of the synthesis are long chain paraffins and wax for upgrading in the HPC-unit (a hydrocracker). Beside this, naphtha (gasoline fraction of minor value) is produced as by-product (for application as fuel, an additional isomerisation would be required). The reaction enthalpy of the synthesis is used for producing steam (T = 200 °C).

Upgrading. The light hydrocarbons (C5) are separated from the FT-raw product in the work-up rectification unit. The remaining raw product is left for upgrading as supplemented in chapter 9.2 'Upgrading' by the TA-working group.

Auxiliary Units. The electrical consumption of the overall process is produced in an internal steam turbine. The steam is generated by superheating of unused process steam via surplus gas from the PSA-unit. Surplus electricity is fed into the grid. Technical oxygen is imported from outside. Effluents of the process are handled in the water treatment and led into the sewage system.

The different process steps are shown in Figure 3-5 for the starting point scenario.



* C5 recycle into the syngas is part of this concept but not yet included in the process calculation; here C5 is used in the external upgrading

Figure 3-5: Simplified Process Flow of the dEF-D-Concept

In Figure 3-6, the main energy flows including heat transfer of the dEF-D-Concept (Starting Point, straw) are shown. For further information on upgrading, see chapter 9.2.

Process Description – Scenario ‘Maximum Biofuel’. The biomass used in this scenario is wheat straw. The process is the same as in the scenario ‘Starting Point’ except the following differences (see also Figure 3-7):

- To achieve a higher carbon conversion and therewith higher fuel quantities, additional hydrogen is produced via electrolysis. The hydrogen is used in the synthesis unit and thus, no CO-Shift (WGS reactor) is required in the gas conditioning
- All CO₂ will be converted in the synthesis process. Hence, the 2nd stage of the rectisol washer is not necessary
- The oxygen from electrolysis is used in the gasification unit. Since the oxygen amount is sufficient for these processes. No external oxygen has to be imported over the fence, but surplus oxygen is foreseen for external use and credited as electricity for internal consumption in the assessment.

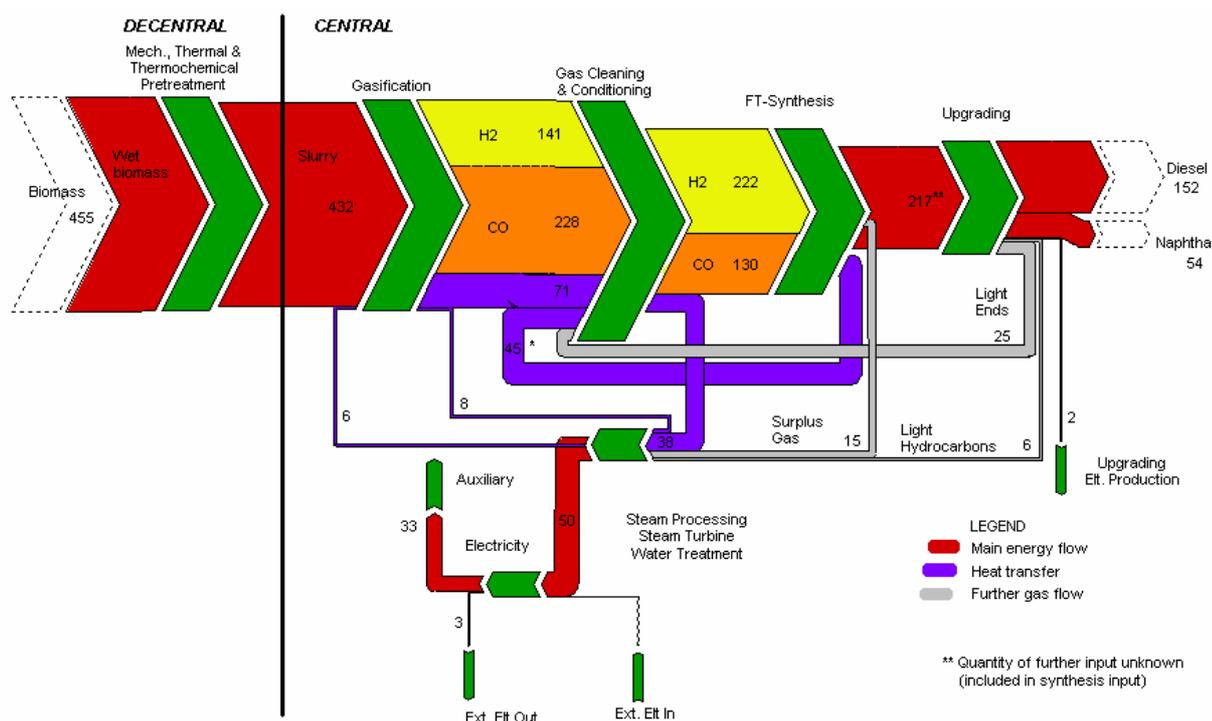


Figure 3-6: Simplified Sankey Diagram of the dEF-D-Concept (Starting Point, straw); Figures in MW

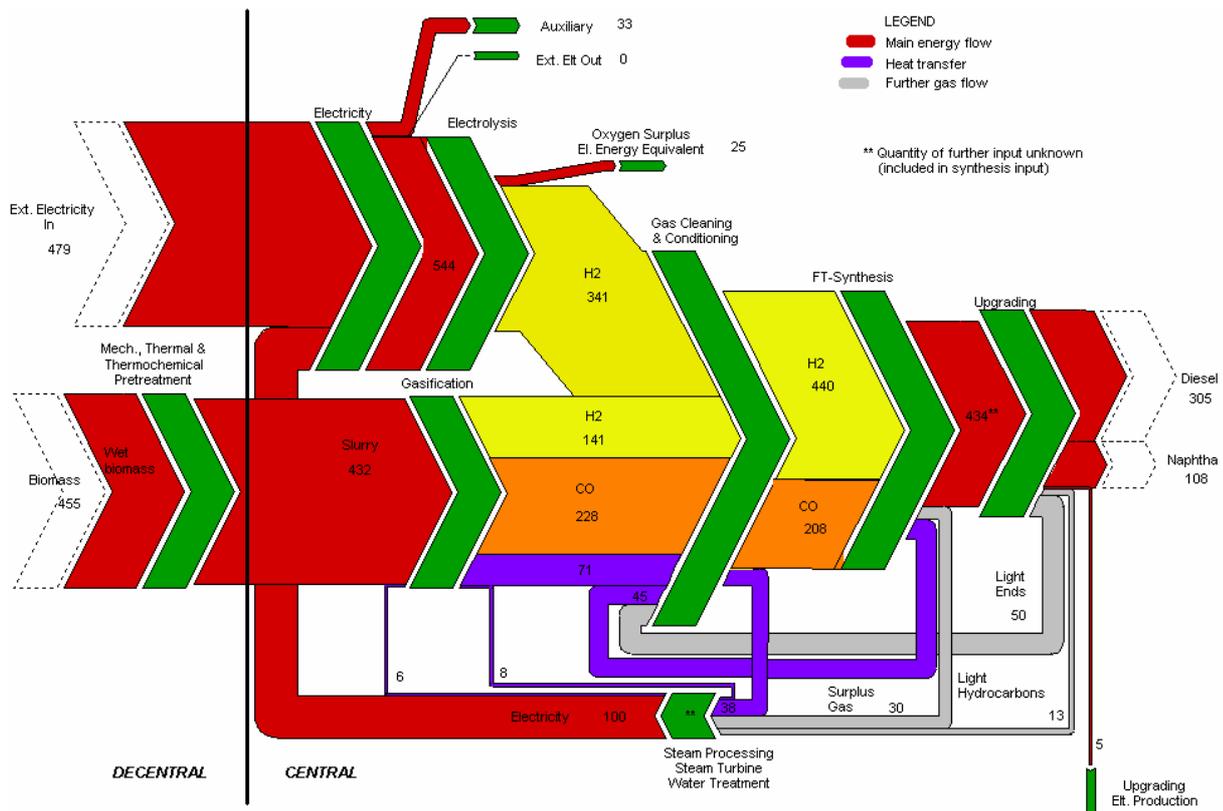


Figure 3-7: Simplified Sankey Diagram of the dEF-D-Concept (Maximum Biofuel, straw); Figures in MW

Concept Background and Intension. Information on the background and intension of the described concepts are summarised in Table 3-3. The aim of this overview is to provide a 'condensed picture' of concept specific differences.

Concept developer/data provider:	Forschungszentrum Karlsruhe; co-operation with Future Energy, Freiberg, Germany
Basic purpose of the concept	
<ul style="list-style-type: none"> - technology able to convert a wide spectrum of solid biofuels (via pretreatment) into a pumpable feedstock (slurry) for entrained flow gasification (decentral) - the focus is the conversion of residues as straw - gasification of slurry (central) for fuel production; application of the concept on large scale - fuel production for an existing market/infrastructure (focus on Diesel market) - loop processes foreseen in the concept but not included in the process calculation yet 	
Basic purpose of the concept components	
Preparation	<ul style="list-style-type: none"> - decentral feedstock production to enlarge the catchment area - to lower the transport effort, a high heating value (higher energy density) of the feedstock is aimed - production of a pumpable feedstock for entrained flow gasification
Gasification	<ul style="list-style-type: none"> - entrained flow gasification for high carbon conversion - low tar and methane content resulting in low gas cleaning and gas conditioning effort - application of a commercial applied entrained flow gasifier (so called GSP-gasifier)
Gas cleaning & conditioning	<ul style="list-style-type: none"> - separation of impurities by commercially approved gas cleaning technology (rectisol) - two-stage rectisol washing system for syngas preparation (gas cleaning, CO-Shift and CO₂-separation)
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis and upgrading at central location (high process integration)
Existing technology	
<ul style="list-style-type: none"> - Construction and operation of a small scale pilot plant (10 kg/h) for fast pyrolysis of straw (2002-2005) - Construction of a pilot plant (500 kg/h) for slurry production - Operation of a 3-6 MW_{th} pilot plant entrained flow gasifier at FUTURE ENERGY, Freiberg 	
Working field/partners development	
<ul style="list-style-type: none"> - R&D in the field of pyrolysis, basic oriented research - development of syngas production concepts 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - starting point scenario: development focussed on large scale concepts (GW-Scale); thus, the Renew-scenario definition does not match with the process developments of FZK and is defined equal to the SS-scenario - Maximum biofuel scenario: only additional Hydrogen input simulated 	

Table 3-3: Concept Background and Intension of the dEF-D-concepts

Data Quality. The data quality and information provided by the concept developers depends on many sources. To give an overview of the origin and basis of the concept developments, the most important sources are summarized in Table 3-4.

System component	information basis
Mech./thermal preparation	- simulation of preparation processes based on literature data about power and heat consumption
Thermochemical preparation	- investment costs: reference on literature data - design of the process based on experiences from 10 kg/h pilot plant and 3-5 MW pilot plant
Gasification	- simulation of a 100 MW-plant based on data from 10 kg/h-pilot plant - investment costs: reference on literature data - design of the process based on the design of the 3-6 MW-pilot plant at Future energy Freiberg - simulation of a pressurised gasification processes (500 MW) based on chemical equivalent (and/or data from the 3-6 MW-pilot plant) - investment costs: reference on literature data
Gas cleaning & Gas conditioning	- description of the main gas cleaning and gas conditioning components based on the commercial process steps - balancing of the CO-conversion process based on chemical equilibrium - investment costs: reference on literature data
Synthesis & Upgrading	- estimation based on SMDS process - investment costs: reference on literature data
Auxiliary units	- rough estimation of heat and power consumption - electrolysis data (scenario 1) taken from literature

Table 3-4: Data Quality of the dEF-D-concepts

3.2.3 Entrained Flow Gasification of Black-liquor for DME Production (BLEF-DME)

The production of DME via entrained flow gasification of black liquor is described by the BLEF-DME concept. The biomass input power of this concept is 500 MW (over the fence of the overall plant). The information and data basis for this subsection was provided by Chemrec [Ekbom, 2005], [Ingman 1, 2006], [Ingman 2, 2006], [Gebhard, 2006], [Chemrec, 2005], [Chemrec, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario the gasification of black liquor is combined with a DME(Di-Methyl-Ether)-synthesis. Thereby the black liquor is taken from a pulp mill; i. e. the DME-production is an additional process of this mill but integrated in the mass and energy flows: Instead of using black liquor in a boiler (like it is done in commercial pulp mills) it is gasified and green liquor is recirculated to the mill. The original heat and power production via the black liquor boiler is compensated via biomass combustion in two separate boilers. This power of the ‘compensation boiler’ corresponds to a power of 500 MW. Neither electricity nor district heat is imported or exported ‘over the fence’, i.e. the BtL-plant including pulp mill is self sufficient. Hence, this scenario is reflects also the self sufficient scenario. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. The stored biomass is dried and chopped to the conditions of combustion processes in a modern circulating fluidized bed boiler. Despite this feedstock for the boiler, the gasification media black liquor from the mill is filtered and heated up to a temperature of 120 °C for downstream gasification.

Gasification. Preheated black liquor is fed into four entrained flow gasifiers pressurised to $p = 32$ bar, with a capacity of each 167 MW ($4 \times 33\% = 133\%$ of full load). Necessary for this plant scale would be the usage of three reactors; one additional reactor is set up to increase the availability of the plant. Thus, if one reactor fails, a stand-still of the pulp mill can be avoided. The tar-content is limited by high flame temperatures in the entrained flow gasifier. The gasification agent is technical oxygen (produced at site by an air separation unit). Quenching is done by spraying condensate into a quench pipe tube, and after the quench smelt droplets and the raw gas are separated. The smelt droplets dissolve in the liquid forming green liquor, which is fed back to the pulp mill after cooling. The quench causes a drop in gas temperature to 220 °C.

Gas Cleaning and Gas Conditioning. The saturated raw gas is then cooled and cleaned in the 'combined cooling and washing system'. Particulates water and small amounts of organic material are removed from the raw gas via cooling the raw gas in a counter current condenser producing steam ($p = 10$ and 4 bar pressure). This steam is feed to the pulp mill. The BLEF-DME concept is considering a two-stage rectisol process. In the first stage traces of tars are removed followed by H_2S and COS but also CO_2 . In the second step, the clean gas stream is split: one part goes directly to synthesis; the other part is used for adjusting the right H_2/CO -ratio.

This is done by CO-conversion in the water-gas-shift reactor. The resulting CO_2 in this second part of the clean gas is separated physically by the second-stage of the rectisol washer.

DME/Methanol-synthesis. DME is produced conventionally from the intermediate product Methanol. The syngas is compressed from 30 to 90 bar before entering the first reactor. Two reactors are used: a methanol reactor and a DME reactor. In the methanol reactor, CO, CO_2 and H_2 are converted into MeOH and H_2O and the water-gas-shift reaction takes place. The DME raw product is produced preliminary from MeOH by separation of water in the DME-Reactor. The reaction enthalpy of the synthesis is used for producing high-pressure steam ($p = 50$ bar).

Upgrading. Dissolved light gases are separated from the DME raw product at low pressure in a separator. The distillation of the raw product is done in a three-stage distillation unit. The first separates the by-products and send it to the boiler. The second separates methanol for recycle and the third produces pure DME and process water (which is send to the waste water treatment plant).

Auxiliary Units. Biomass is imported to the mill site in order to produce steam and electricity to make the pulp mill and the BtL plant self-sustained. Technical oxygen is produced by an air separation unit. Effluents of the process are handled in the water treatment and led into the sewage system.

The different process steps are shown in Figure 3-8 for the starting point scenario.

In Figure 3-9, the main energy flows including heat transfer (steam, water, etc.) of the BLEF-DME Concept (Scenario Starting Point) are shown.

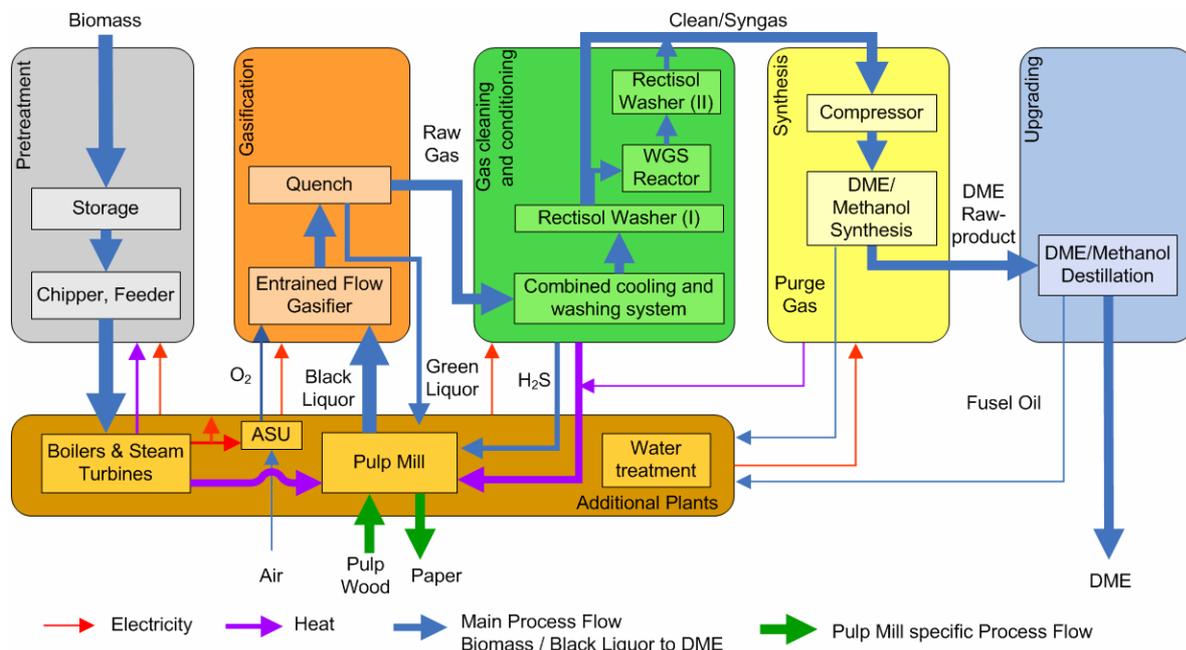


Figure 3-8: Simplified Process Flow of the BLEF-DME-Concept; Figures in MW

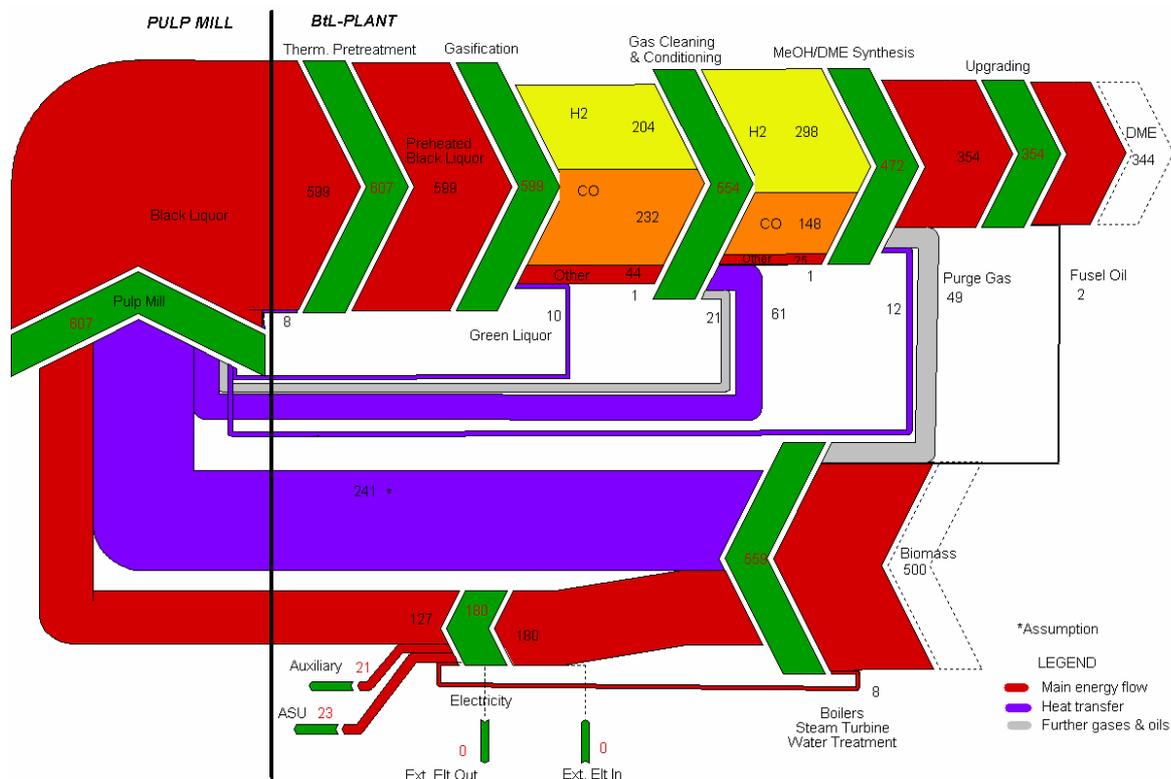


Figure 3-9: Simplified Sankey Diagram of the BLEF-DME Concept

Concept Background and Intension. Information on the background and intension of the described concepts are summarised in Table 3-5. The aim of this overview is to provide a ‘condensed picture’ of concept specific differences.

Concept developer/data provider:	Chemrec AB, Stockholm, Sweden
Basic purpose of the concept	
<ul style="list-style-type: none"> - BtL-production from black liquor (residue of pulp mill) - fuel production as an alternative (new infrastructure and usage systems needed) for Diesel market - integrated processes for high fuel conversion (energetic integration in pulp mill) 	
Basic purpose of the concept components	
Preparation	<ul style="list-style-type: none"> - biomass combustion used for steam and power generation enables wide spectrum of solid biofuels - comparable low effort on upgrading of gasifier feedstock (black liquor) for entrained flow gasification which is used for DME production
Gasification	<ul style="list-style-type: none"> - gasification of residue black liquor; green liquor production - entrained flow gasification high carbon conversion - low methane content resulting in low gas conditioning effort
Gas cleaning & conditioning	<ul style="list-style-type: none"> - separation of impurities by commercial approved gas cleaning technology (rectisol) - two-stage rectisol washing system for syngas preparation (gas cleaning, CO-Shift and CO₂-separation)
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis and upgrading at central location (high process integration) - high efficiency of syngas conversion by DME-synthesis - easy upgrading of DME-raw product to motor fuel compared to FT-synthesis
Existing technology [CHEMREC, 2006]	
<ul style="list-style-type: none"> - Construction and operation of pilot plants and demonstration plants since 1987: - Atmospheric pilot plant, 3 tDS/24h (0.5 MWth) SKF, Hofors, 1987 - Booster demonstration plant, 75 tDS/24h (11 MWth), AssiDomän, Frövi, 1991 - Pressurized air-blown pilot plant, 6 tDS/24h (1 MWth), Stora Enso, Skoghall, 1994 - Commercial Booster plant, 300 tDS/24h (50 MWth), Weyerhaeuser, New Bern, 1996 - Pressurized oxygen-blown rebuilt pilot, 10 tDS/24h (1.5 MWth), Stora Enso, Skoghall, 1997 - Rebuilt 2nd generation commercial Booster plant, 300 tDS/24h, Weyerhaeuser, New Bern, 2003 - Pressurized oxygen-blown development plant, DP-1, 20 tDS/24h (3 MWth), Kappa Kraftliner, Piteå, 2005 - DP-1 plant – operation for more than 120 hours by May 2006 	
Working field/partners development	
<ul style="list-style-type: none"> - Basic engineering of conversion plants (BLGMF – Black Liquor Gasification with Motor Fuels Production; BLGCC – Black Liquor Gasification Combined Cycle) - Practical experiences on large scale gas cleaning (for firing systems) - Large scale black liquor gasification 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - Integrated concept (based on frame conditions of pulp and paper mill); thus only one optimised concept (no further, time-related optimisation) foreseen 	

Table 3-5: Concept Background and Intension of the BLEF-DME-concept

Data Quality. The data quality and information provided by the concept developers depends on many sources. To give an overview of the origin and basis of the concept developments, the most important sources are summarized in Table 3-6.

System component	information basis
Mech./thermal preparation	<ul style="list-style-type: none"> - simulation of the preparation processes based on external engineering - investment costs have been summarised based on manufacture offers
Thermochemical preparation	<ul style="list-style-type: none"> - design of the process based on the design of the ... MW-demonstration plant (under construction and start-up) - simulation of a pressurised gasification processes (167 MW) based on engineering data - investment costs have been summarised based on manufacture offers
Gasification	<ul style="list-style-type: none"> - simulation of preparation processes based on external engineering - investment costs have been summarised based on manufacture offers
Gas cleaning & Gas conditioning	<ul style="list-style-type: none"> - based on information and data of Haldor Topsoe (catalyst and technology company) [Topsoe, 2007] - investment costs have been summarised based on manufacture offers
Synthesis & Upgrading	<ul style="list-style-type: none"> - power generation data based on process simulation (applying commercial/standard steam turbine data)
Auxiliary units	-

Table 3-6: Data Quality of the BLEF-DME-concepts

3.2.4 Centralised Entrained Flow Gasification for Ethanol Production (EF-E)

The production of Ethanol via entrained flow gasification of willow is described by the EF-E concept. Beside this main product, also methanol, propanol and electricity are produced. The biomass input power of this concept is 500 MW (over the fence of the overall plant). The information and data basis for this subsection was provided by Abengoa [Abengoa 1, 2006], [Abengoa 3, 2006], [Abengoa 4, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario, biomass (willow salix) is converted into Ethanol without auxiliary energy. Thus, this scenario is equal to the self sufficient scenario. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. The stored biomass is dried to the conditions of downstream processes by a direct steam dryer (mid pressure steam; T= 309 °C; p = 12 bar).

Thermochemical Pretreatment. As part of the preparation for downstream gasification, the biomass is fed to a torrefaction unit and milled to char dust afterwards. A hopper system ensures the feedstock pressurisation ($p = 40$ bar). Compressed CO_2 inert gas is used for the pneumatic transport and feeding.

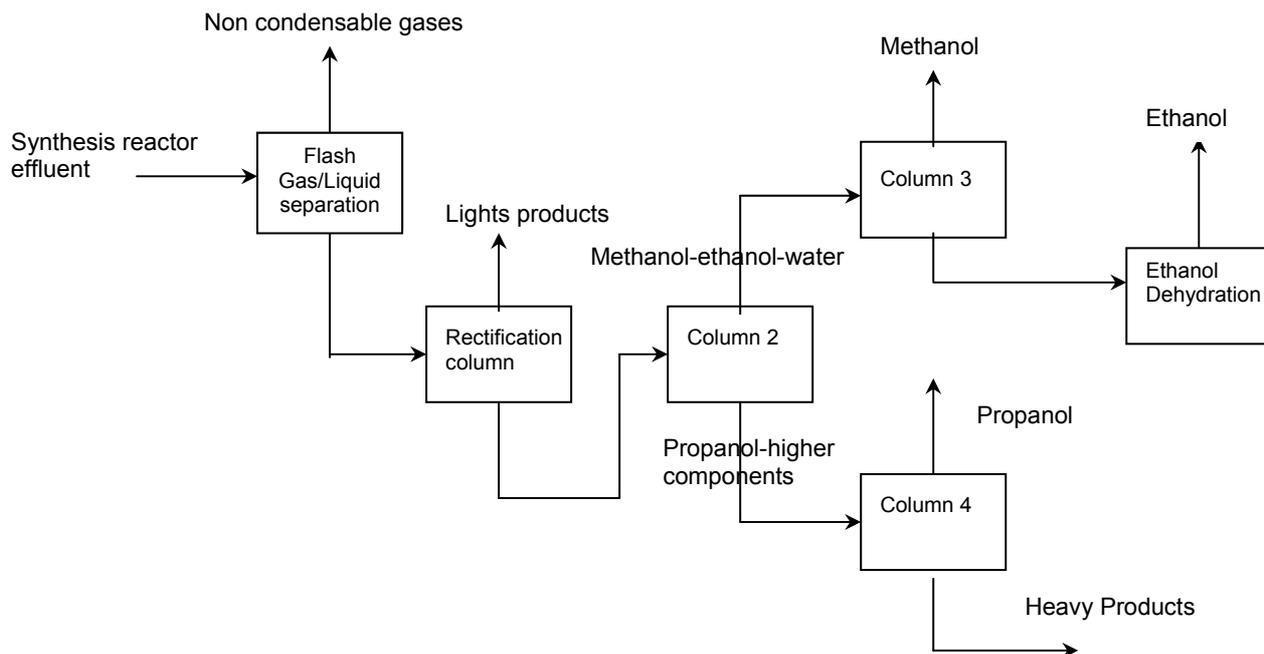
Gasification. The char dust is fed to an entrained flow reactor pressurised to $p = 40$ bar. The tar-content is limited by the high gas temperatures ($T \approx 1300$ °C). The gasification agents are technical oxygen (produced at site by an air separation unit), CO_2 (from gas washing system) and high pressure steam ($p = 40$ bar).

Gas Cleaning and Gas Conditioning. The hot tar-free raw gas is then cooled down to 65 °C in the heat exchanger producing high pressure steam ($T = 537$ °C; $p = 55$ bar) for power generation and other process parts. H_2S is separated from the raw gas in the so called LO-CAT[®]-unit (unfortunately the data provider did not supply specific information about the function of this catalyst unit) and a ZnO-adsorber.

Adjusting the right H_2/CO -ratio is done by CO-conversion of a part of the raw gas stream in the water-gas-shift reactor. Downstream of the CO-Shift-reactor, the water is removed from the joint stream by reducing the temperature to 50 °C. Then, the gas is fed directly to the selexol washer for CO_2 removal. Before entering the synthesis reactor, the syngas is compressed to 70 bars which is the pressure required by the downstream synthesis reactions.

Ethanol-Synthesis. An alcohol synthesis reactor is used for syngas synthesis ($T = 300$ °C, $p = 70$ bar). The main product of the synthesis is ethanol. By-products are methanol, propanol, methane, ethane, butanol, pentanol, CO_2 and water. The reaction enthalpy of the synthesis is used for producing high pressure steam ($p = 55$ bar) from high pressure water.

Upgrading. A gas/liquid separator is used to separate reactants, CO_2 and light hydrocarbons (methane) from the raw product. Further, light products, methanol, propanol and heavy products are separated from ethanol in four rectification columns. Finally, water is separated from ethanol in a dehydration unit.



Auxiliary Units. The electrical consumption of the overall process is produced in an internal gas turbine by combustion a part of the gases from gas/liquid separation. The steam from the power generation unit is used within the process (e.g. for distillation). Surplus electricity is fed to the grid. Technical oxygen is produced by an air separation unit. Effluents of the process are handled in the water treatment and led into the sewage system. The concept provider did not specify in which processes the high pressure steam generated in the heat exchanger after the gasifier and the synthesis reactor is used.

The different process steps are shown in Figure 3-10 for the starting point scenario. In Figure 3-11, the main energy flows including heat transfer (steam, water, etc.) of the EF-E-Concept (Scenario Starting Point, Biomass input wood) are shown.

Process Description – Scenario ‘Maximum Biofuel’. The biomass used in this scenario is willow salix. The process is the same as in the scenario ‘Starting Point’ except the following differences (see also Figure 3-12):

- recycled syngas from ethanol synthesis is converted by a steam reforming process (SMR) into CO and H₂ and fed back to the clean gas
- the heat for the steam reforming unit is supplied by natural gas
- the electricity for compressing syngas, O₂ and CO₂ is taken from the grid, the gas turbine is not necessary

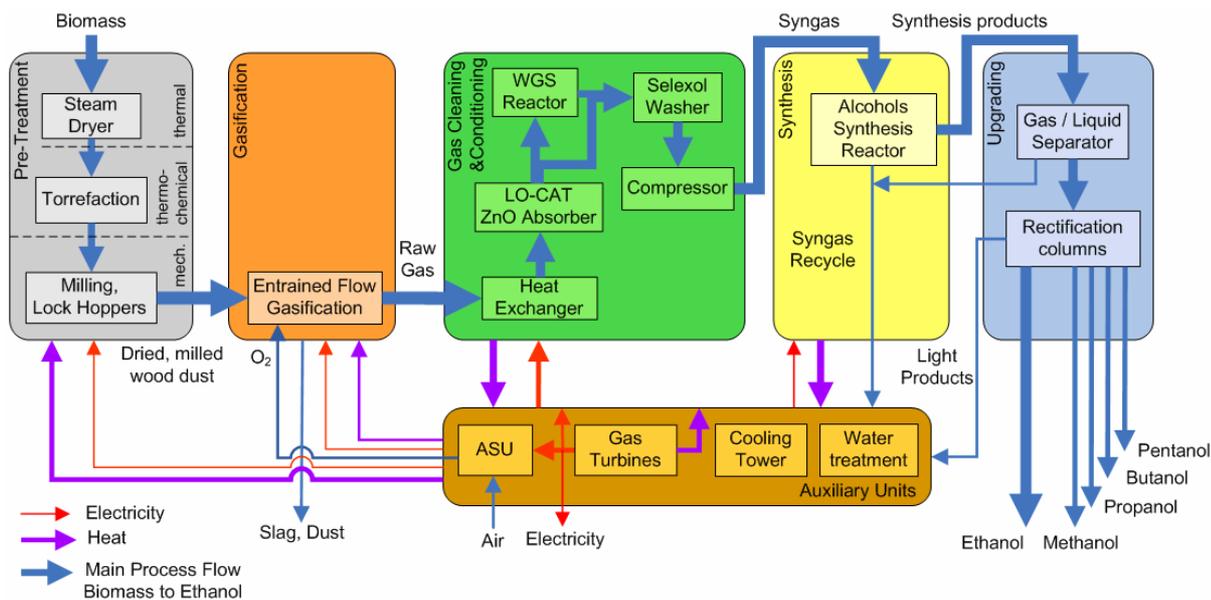


Figure 3-10: Simplified Process Flow of the EF-E-Concept (Starting Point)

Concept Background and Intension. Information on the background and intension of the described concepts are summarised in Table 3-7. The aim of this overview is to provide a ‘condensed picture’ of concept specific differences.

Concept developer/data provider:	Grencell, Abengoa, Sevilla, Spain
Basic purpose of the concept	
<ul style="list-style-type: none"> - technology able to convert a wide spectrum of solid biofuels (via pretreatment) - alternative for 1st generation ethanol production (focus on gasoline market) 	
Basic purpose of the concept components	
Preparation	<ul style="list-style-type: none"> - application of entrained flow gasifier requires thermochemical treatment; technical realisation of this treatment by torrefaction and milling of biomass to reach a high gasification efficiency
Gasification	<ul style="list-style-type: none"> - entrained flow gasification for high carbon conversion - low tar and methane content resulting in low gas cleaning and gas conditioning effort
Gas cleaning & conditioning	<ul style="list-style-type: none"> - separation of H₂S by a LO-CAT and a ZnO absorber; low investment effort - Selexol washing system for CO₂-separation - in contrast to commercially approved rectisol washing processes here a lower energy demand (no low temperature washer) and lower investment costs are aimed
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis and upgrading at central location - low upgrading effort compared to FT-synthesis
Existing technology	
<ul style="list-style-type: none"> - construction and operation of biodiesel plants and enzymatic produced bioethanol - basic oriented research on Ethanol-catalysts 	
Working field/partners development	
<ul style="list-style-type: none"> - basic and detailed engineering of conversion plants 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - theoretical concept developed for comparison of Ethanol production with other synthetic biofuels 	

Table 3-7: Concept Background and Intension of the EF-E-concepts

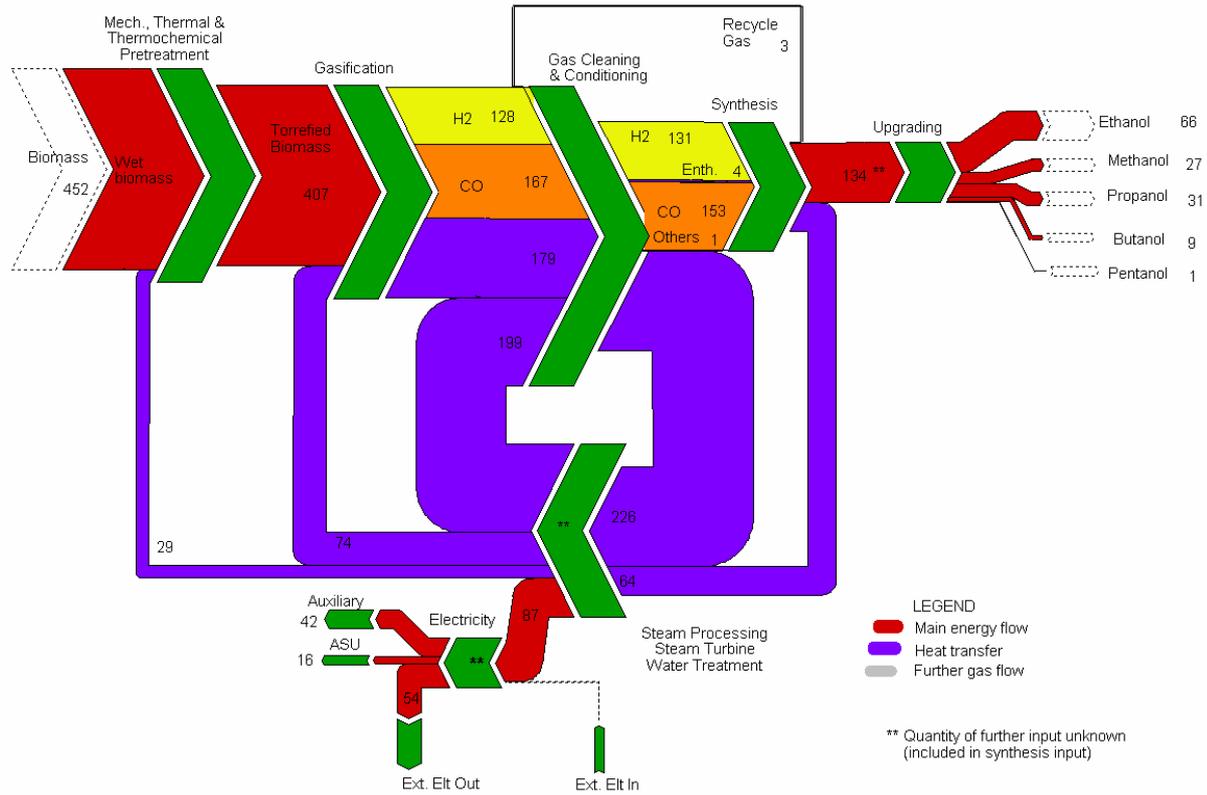


Figure 3-11: Simplified Sankey Diagram of the EF-E-Concept (Starting Point); Figures in MW

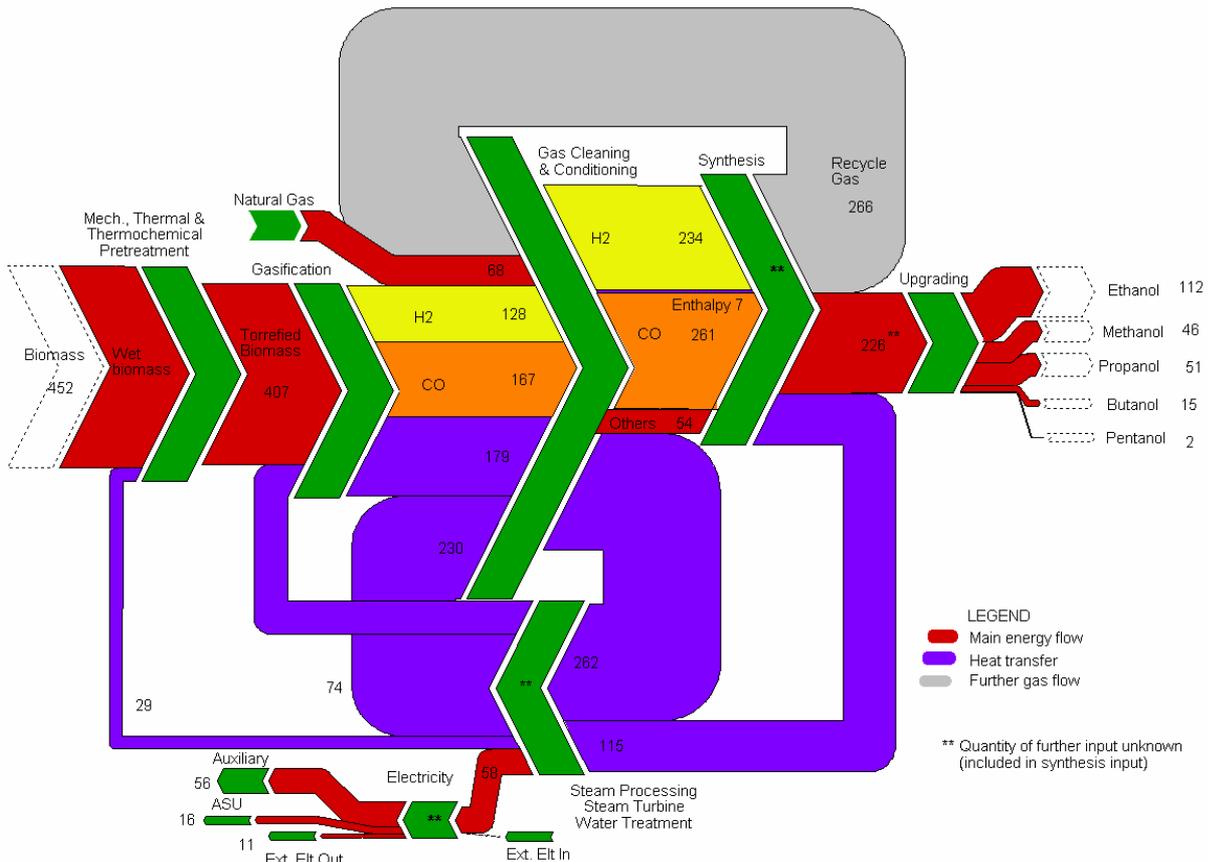


Figure 3-12: Simplified Sankey Diagram of the EF-E-Concept (Maximum Biofuel); Figures in MW

Data Quality. The data quality and information provided by the concept developers depends on many sources. To give an overview of the origin and basis of the concept developments, the most important sources are summarized in Table 3-8.

System component	information basis
Mech./thermal preparation	- simulation based on literature data - no information on investment costs
Thermochemical preparation	- simulation based on literature data - no information on investment costs
Gasification	- simulation based on literature data - no information on investment costs
Gas cleaning & Gas conditioning	- simulation based on literature data - no information on investment costs
Synthesis & Upgrading	- simulation based on literature data and catalyst experiments on lab scale - no information on investment costs
Auxiliary units	- power generation data based on process simulation (applying commercial/standard gas turbine data) - electrolysis data (scenario 1) taken from literature

Table 3-8: Data Quality of the EF-E-concepts

3.2.5 Centralised Autothermal CFB-Gasification for FT-Diesel Production (CFB-D)

The production of FT-Diesel via CFB gasification of willow and straw is described by the CFB-D concept. Beside this main product also naphtha is produced. The biomass input power of this concept is 500 MW (over the fence of the overall plant). The information and data basis for this subsection was provided by the CUTEC-Institute [Cutec 1, 2005], [Cutec 2, 2005], [Cutec 3, 2006], [Schindler, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario, the biomass (willow salix or wheat straw) is converted into FT-Diesel without auxiliary energy. Thus, this scenario is equal to the self sufficient scenario. In the scenario with willow salix as biomass input, surplus electricity is fed to the grid. In the scenario with wheat straw as biomass input, external electricity is imported ‘over-the-fence’. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. The delivered biomass is chipped and dried in a conveyer dryer. In case of wood as input material additionally metals are removed by the metal separation unit. Then chipped straw is further prepared for gasification in the pelletiser. Afterwards, the wood chips or straw pellets are stored and fed to the gasifier.

Thermochemical Pretreatment. No thermochemical pretreatment is needed in this concept.

Gasification. The dry chipps (or pellets) are fed to five circulating fluidized bed gasifier with a capacity of each 100 MW (5x20%), i.e. they are operated in parallel. The heat for gasification is supplied by oxidation of part of the biomass (autothermal concept). The gasifier works at temperatures of 950 °C and atmospheric pressure. The gasification agent consists of technical oxygen (produced at site by an air separation unit) and water steam (produced from treated waste water). The bed material is sand. At the exit of the gasifier (two phase stream of raw gas and sand) the solid material is separated from the raw gas in a cyclone and fed back to the gasifier.

Gas Cleaning and Gas Conditioning. A hot gas dedusting (by a battery of ceramic filters) is applied to remove particulates from the raw gas. To reduce the tar and adjust the H₂/CO-ratio a combined reactor is applied. This unit adjusts the right H₂/CO-ratio by CO-conversion in the water-gas-shift part; tar in the raw gas stream is removed by a Ni-catalyst. Afterwards, the raw gas is cooled down to 30 °C in a heat exchanger, producing low pressure steam at 110 °C. The removal of impurities like H₂S and NH₃ is done by absorption in a gas quench and water scrubber. Further tar impurities are dissolved and condensed at low temperature (6 °C) in a biodiesel scrubber. The tar-polluted biodiesel is partially discharged to the gasifier for combustion. The clean syngas is compressed to a pressure of 25 bar, which is necessary for FT-synthesis. The impurity carbonyl sulphide is catalytically converted with the help of hydrogen to CO and H₂S in a catalytical hydrogenation unit. Further, hydrogen sulphide is reduced to pure sulphide in a so called 'oxidizing wash' unit. The CO₂ in the clean gas is separated physically by a selexol washer. The fine gas cleaning (guard bed) is done in a ZnO-adsorber.

FT-Synthesis. A cobalt catalyst is applied in a Tubular-Fixed-Bed reactor (TFBR) for Fischer-Tropsch synthesis (T = 220 – 250 °C; p = 20 – 30 bars). Main products of the synthesis are long chain paraffins and waxes. The reaction enthalpy of the synthesis is used energetically in the process.

Upgrading. The light hydrocarbons (C1-C4) are separated from the FT-raw product in the work-up rectification unit and used within the gas turbine process. The remaining raw product is foreseen to be delivered for upgrading to a commercial refinery. For the calculation of conversion efficiencies, this upgrading is calculated in chapter 9.2 'Upgrading' by the TA-working group; in this chapter also electricity produced in the external refinery is described.

Auxiliary Units. The electrical consumption of the overall process is produced in a gas turbine. Surplus electricity is fed into the grid. Technical oxygen is produced by an air separation unit. Effluents of the process are handled in the water treatment and led into the sewage system. Surplus process water is used in the cooling tower to increase its cooling power.

The different process steps are shown in Figure 3-13 for the starting point scenario (willow salix; for straw electricity has to be imported from the grid).

In Figure 3-14, the main energy flows including heat transfer (steam, water, etc.) of the CFB-D-Concept (Scenario Starting Point, Biomass input wood) are shown.

Process Description – Scenario ‘Maximum Biofuel’. The biomass used in this scenario is willow salix or wheat straw. The process is the same as in the scenario ‘Starting Point’ except the following differences (see also Figure 3-15):

- To achieve a higher carbon conversion and therewith higher fuel quantities, additional hydrogen is produced via electrolysis. The hydrogen is used in the synthesis unit and thus, no CO-Shift (WGS reactor) is required in the gas conditioning
- The oxygen from electrolysis is used in the gasification units. Since the oxygen amount is not sufficient for these processes, air separation unit is still required.

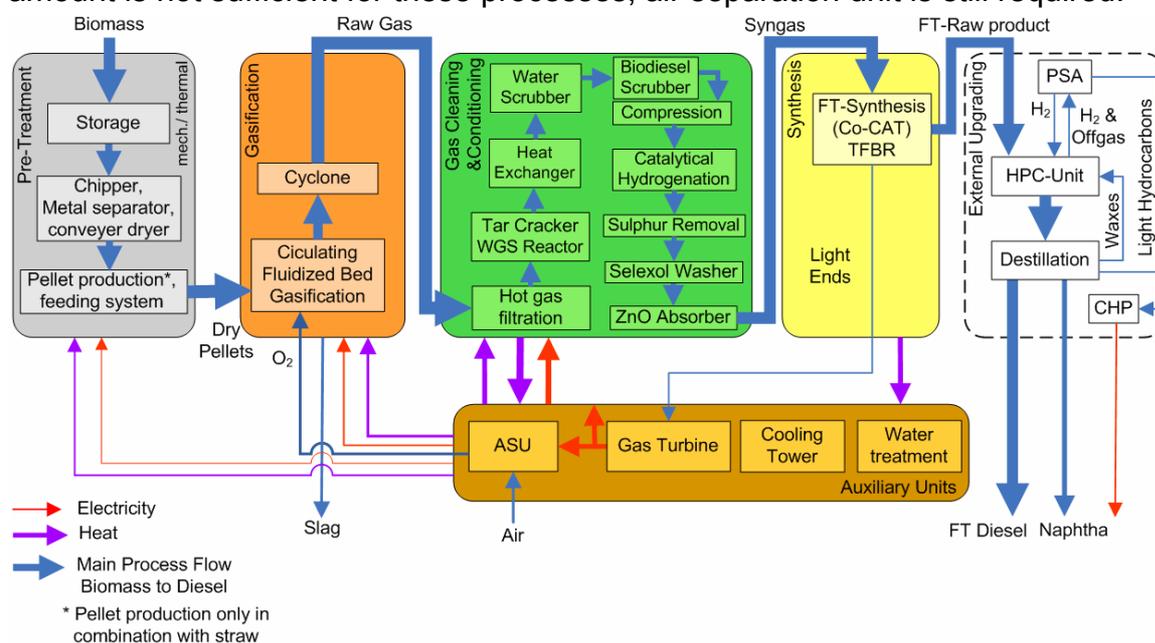


Figure 3-13: Simplified Process Flow of the CFB-D-Concept

Data Quality. The data quality and information provided by the concept developers depends on many sources. To give an overview of the origin and basis of the concept developments, the most important sources are summarized in Table 3-9.

System component	information basis
Mech./thermal preparation	- simulation of the preparation processes based on literature data on power and heat consumption - no information on investment costs available
Gasification	- simulation based on experiences from 400 kW-test facility and literature data - simulation of the gasification processes (100 MW) based on chem.equivalent - investment costs have been summarised based on manufacture offer
Gas cleaning & Gas conditioning	- simulation based on experiences from 400 kW-test facility and literature data - no information on investment costs available
Synthesis & Upgrading	- power generation data based on process simulation (applying commercial/standard gas turbine data) - electrolysis data (scenario 1) taken from literature
Auxiliary units	-

Table 3-9: Data Quality of the CFB-D-concepts

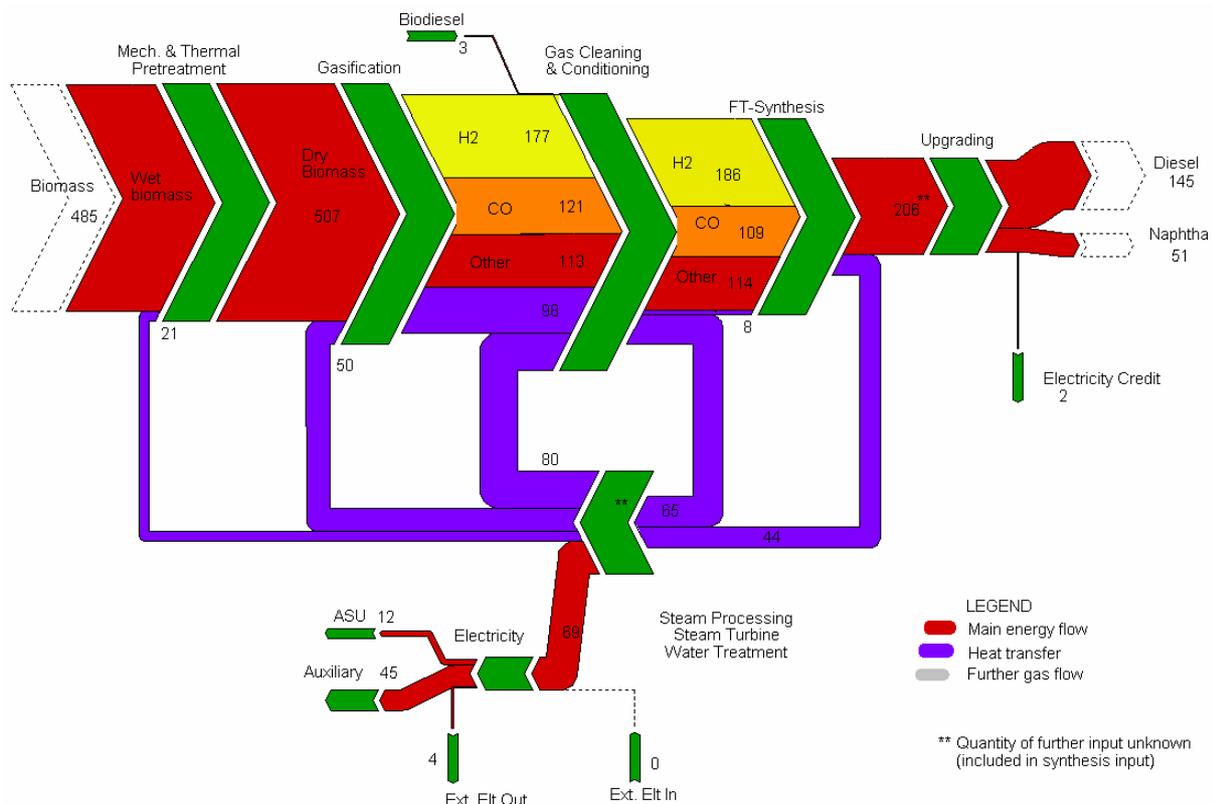


Figure 3-14: Simplified Sankey Diagram of the CFB-D-Concept (Staring Point, willow); Figures in MW

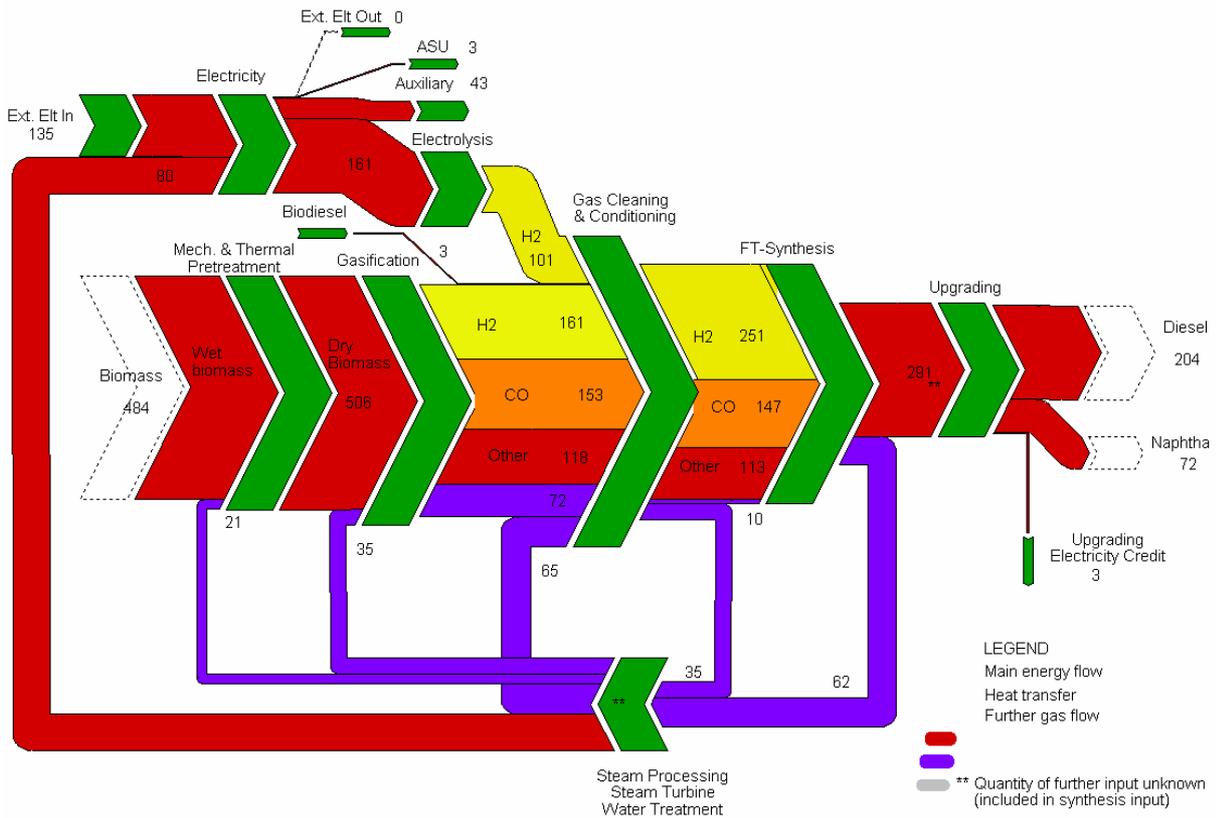


Figure 3-15: Simplified Sankey Diagram of the CFB-D-Concept (Maximum Biofuel, willow); Fig. in MW

Concept Background and Intension. Information on the background and intension of the described concepts are summarised in Table 3-10. The aim of this overview is to provide a ‘condensed picture’ of concept specific differences.

Concept developer/data provider:	Clausthaler Umwelttechnik-Institut GmbH, Clausthal-Zellerfeld, Germany
Basic purpose of the concept	
<ul style="list-style-type: none"> - technology able to convert a wide spectrum of solid biofuels (via additives) - fuel production for an existing market/infrastructure (focus on Diesel market) 	
Basic purpose of the concept components	
Preparation	<ul style="list-style-type: none"> - For the application of a circulating fluidized bed gasification (no thermo-chemical pretreatment) high fuel quality is required; therefore, a conveyer dryer, a metal separator are applied and the chopped biomass is pelletised
Gasification	<ul style="list-style-type: none"> - no thermochemical pretreatment required - CFB as commercially approved reactor type - possibility of gasifier-internal catalyst application (for biomass usage with low ash melting point)
Gas cleaning & conditioning	<ul style="list-style-type: none"> - separation of impurities by a multi staged system - Selexol washing system for CO₂-separation - combination of gas cleaning steps promises sufficient gas quality; in contrast to commercially approved rectisol washing processes here a lower energy demand (no low temperature washer) and lower investment costs are aimed
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis at plant location - upgrading is done decentrally in existing refineries (reduction of technical effort and utilisation of high process integration)
Existing technology	
<ul style="list-style-type: none"> - construction and operation of an 400 kW gasifier (2005) - side stream test and optimisation on gas conditioning and synthesis (side stream of gas cleaning) 	
Working field/partners development	
<ul style="list-style-type: none"> - R&D in the field of gasification, gas conditioning, synthesis and product upgrading (lab and/or technical scale) - basic oriented research in BTL-production 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - Starting point scenario: based on simulation; thus SP and SS scenario are equal - Maximum biofuel scenario: only additional Hydrogen input simulated 	

Table 3-10: Concept Background and Intension of the CFB-D-concepts

3.2.6 Allothermal CFB-Gasification for FT-Diesel Production (ICFB-D)

The production of FT-Diesel via fast internally circulating fluidized bed gasification of willow and miscanthus is described by the ICFB-D concept. Beside this main product also naphtha, electricity and district heat (only in starting point scenario) is produced [TUV, 2006]. The biomass input power differs between the following concepts. The information and data basis for this subsection was provided by the Technical University of Vienna [Rauch, 2005], [Rauch 1, 2006], [Rauch 2, 2006], [Guessing, 2006], [TUV, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario, the biomass input power of 50 MW is taken for tri-generation of FT-Diesel, electricity and district heat. The concepts are based on willow salix and miscanthus. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. Biomass is stored and chipped at site. The woody chips are dried in a drum dryer. Afterwards, the biomass is stored and fed to the gasifier.

Thermochemical Pretreatment. No thermochemical pretreatment is needed in this concept.

Gasification. A so called fast internal circulating fluidized bed gasifier (FICFB) is used in this concept. This reactor is divided into two fluidized beds, a gasification zone and a combustion zone. Between both zones, a circulation loop of bed material acts as heat carrier from the combustion to the gasification zone. Thus, the water steam (produced from treated waste water by waste heat) can be applied as gasification agent instead of oxygen. The bed material, together with some charcoal, circulates to the combustion zone. This zone is fluidized with air and the charcoal is partly burned. The exothermic reaction in the combustion zone provides the energy for the endothermic gasification with steam. The flue gas will be removed without coming in contact with the raw gas. Hence, the gas produced in the gasification zone (raw gas) is nearly free of nitrogen.

Gas Cleaning and Gas Conditioning. The gas cleaning unit contains of two lines: one for the raw gas cleaning and another for the flue gas cleaning. After the gasifier, dust is removed from the raw gas by a hot gas deduster (cyclone) and the gas is cooled by a heat exchanger. Around 30 % of tar is removed from the raw gas stream in fabric filters. Remaining tar is washed out in a biodiesel scrubber (RME). Residues of these gas cleaning units are recycled back to the combustion zone of the gasifier. After a booster compressor and a cooling and condensing unit, the gas is entering a 2-stage compressor, where it is pressurized 35 bars. The fine gas cleaning (removal of H₂S and HCl-traces) is ensured by a HDS-catalyst and a ZnO-absorber, which is acting as a security guard for the synthesis reactor.

Flue gas is treated in the second line of gas cleaning for post-combustion and heat generation. After the combustion zone, dust is separated from the flue gas steam via a cyclone. In the post-combustion, the combustible components of the flue gas are oxidized, generating heat, which is recovered by heat exchangers and used in the ORC plant and the drum dryer.

In this concept, no gas conditioning is considered.

FT-Synthesis. A cobalt catalyst is applied in a slurry bubble column reactor (SBCR) for Fischer-Tropsch synthesis. Main products of the synthesis are long chain paraffins and wax. The separation of the catalyst from the products is done in a sedimentation unit and a filtration unit. Both units are integrated into the FT-synthesis. The remaining raw product is foreseen to be delivered for upgrading to a commercial refinery. For the calculation of conversion efficiencies this upgrading is calculated in chapter 9.2 'Upgrading' by the TA-working group.

Upgrading. The light hydrocarbons (C1-C4) are separated from the FT-raw product in the work-up rectification unit. The remaining raw product is foreseen to be delivered for upgrading to a commercial refinery. For the calculation of conversion efficiencies this upgrading is calculated in chapter 9.2 'Upgrading' by the TA-working group.

Auxiliary Units. The electrical consumption of the overall process is produced internally by a gas turbine (by combustion of recycled syngas) and an organic rankine cycle plant. The ORC plant uses the heat recovered by the heat exchanger in the process. The steam for gasification is generated via waste heat. Surplus electricity is fed into the grid. Surplus heat is used externally as district heat. Because of the scale, the ICFB-D concept is the only concept, which considers heat as output. Effluents of the process are handled in the water treatment and led into the sewage system.

The different process steps are shown in Figure 3-16 for the starting point scenario.

Process Description – Scenario 'Maximum Biofuel'. In the maximum biofuel scenario, the biomass (willow salix or miscanthus) is converted into FT-Diesel without auxiliary energy. Thus, this scenario is equal to the self sufficient scenario. The process is the same as in the scenario 'Starting Point' except the following differences (see also Figure 3-19):

- a) the biomass input fuel power is 500 MW
- b) the aim of the concept is not tri-generation (like in the starting point scenario) but a maximised diesel production with self sufficiency, at this fuel optimised concept on large scale, district heat is not considered as output product
- c) the gasifier is operated under pressure
- d) the gas cleaning is different and additional conditioning is installed (e.g. steam reformer); thus, it will be described in the following
- e) recycled syngas from FT-synthesis is converted by a steam reforming process (SMR) into CO and H₂ and fed back to the clean gas

Gas Cleaning and Gas Conditioning. After the gasifier, dust is removed from the raw gas. Then it is mixed with the recycled syngas from synthesis and converted by a steam reforming process (SMR) into CO and H₂. Now the gas is cooled and impurities are filtered out. A ZnO-absorber is applied for fine gas cleaning (removal of H₂S and HCl-traces). In this concept, no biodiesel scrubber is applied.

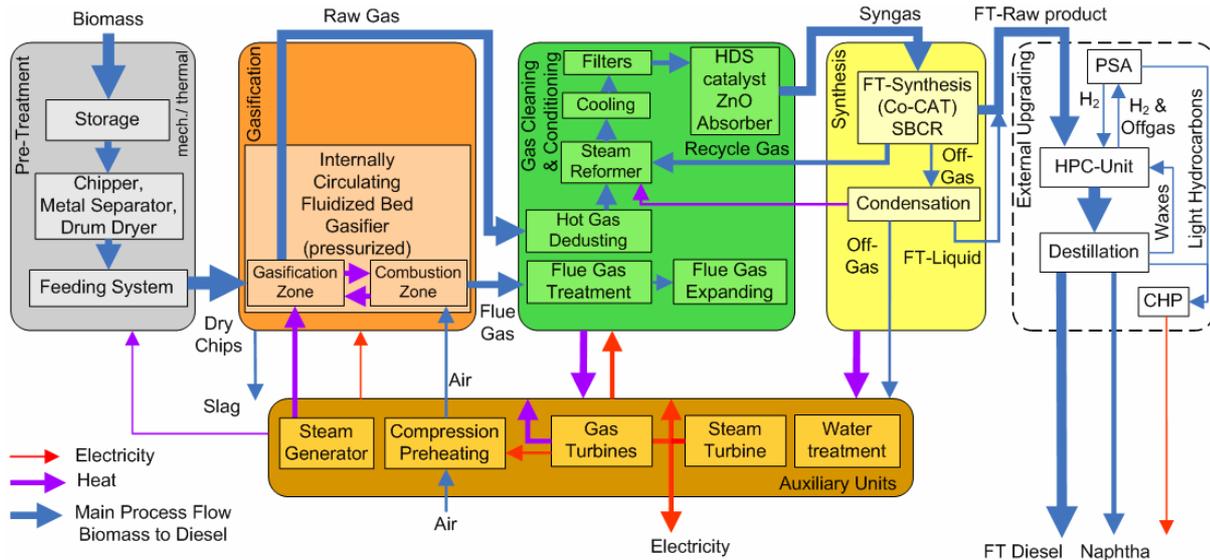


Figure 3-18: Simplified Process Flow of the ICFB-D-Concept (Maximum Biofuel, willow); Figures in MW

In Figure 3-19 the main energy flows including heat transfer (steam, water, etc.) of the ICFB-D-Concept (Scenario Maximum Biofuel, willow) are shown.

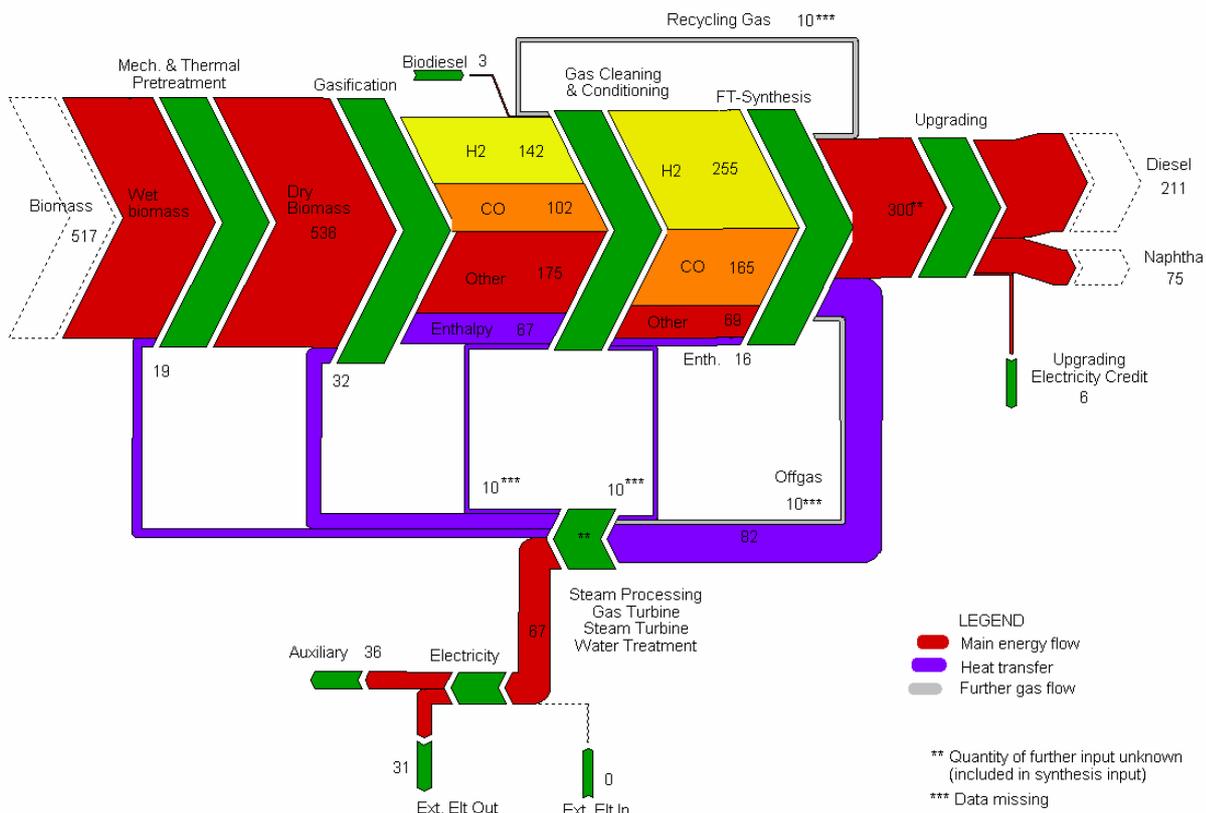


Figure 3-19: Simplified Sankey Diagram of the ICFB-D-Concept (Maximum Biofuel, willow); Fig. in MW

Concept Background and Intension. Information on the background and intension of the described concepts are summarised in Table 3-11. The aim of this overview is to provide a ‘condensed picture’ of concept specific differences.

Concept developer/data provider:	Technical University of Vienna (TUV), Vienna, Austria, in cooperation with Biomasse Kraftwerk Güssing
Basic purpose of the concept	
<ul style="list-style-type: none"> - technology able to convert a wide spectrum of solid biofuels (via additives) - fuel production for an existing market/infrastructure (focus on diesel market) - <i>starting point scenario</i>: tri-generation for maximized biomass utilization - <i>maximum biofuel scenario</i>: integrated processes for high fuel conversion (loop processes) 	
Basic purpose of the concept components	
Preparation	<ul style="list-style-type: none"> - For the application of a circulating fluidized bed gasification standard biomass preparation technology will be applied (drying, chipping)
Gasification	<ul style="list-style-type: none"> - no thermochemical pretreatment required - application of well-proven concept (FICFB) for fuel production - production of nitrogen-free and hydrogen-rich product gas without use of oxygen (no air separation unit needed)
Gas cleaning & conditioning	<ul style="list-style-type: none"> - separation of impurities by a multi staged system approved for engine gas application - combination of gas cleaning steps promises sufficient gas quality; in contrast to commercially approved rectisol washing processes here a lower energy demand (no low temperature washer) and lower investment costs are aimed - utilisation of flue gas for heat generation - maximised biofuel scenario: installation of an gas conditioning (not foreseen in starting point scenario); comparable low gas cleaning effort (no low temperature washing system and no CO₂-separation)
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis at plant location - upgrading is done decentrally in existing refineries (reduction of technical effort and utilisation of high process integration)
Existing technology	
<ul style="list-style-type: none"> - Construction and operation of a 8 MW_{fuel_power} demonstration plant for CHP operation - side stream for gas conditioning and synthesis 	
Working field/partners development	
<ul style="list-style-type: none"> - Basic and detailed engineering of conversion plants for CHP production - Scientific support of demonstration plants 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - Starting point scenario: upgrading of existing CHP-plant for tri-generation - Maximum fuel scenarios: developed on theoretical basis for comparison with other 500 MW concepts in Renew 	

Table 3-11: Concept Background and Intension of the ICFB-D-concepts

Data Quality. The data quality and information provided by the concept developers depends on many sources. To give an overview of the origin and basis of the concept developments, the most important sources are summarized in Table 3-12.

System component	information basis
Mech./thermal preparation	<ul style="list-style-type: none"> - simulation of the preparation processes based on literature data on power and heat consumption - investment costs have been summarised based on manufacture offers
Gasification	<p>Starting point scenario:</p> <ul style="list-style-type: none"> - design of the process based on the design of the 8 MW-demonstration plant (commercial operation since 2001) - investment costs have been summarised based on manufacture offers <p>Self sufficient scenario:</p> <ul style="list-style-type: none"> - simulation of a pressurised gasification processes (500 MW) based on chemical equivalent (and/or data from 8 MW-pilot plant)
Gas cleaning & Gas conditioning	<p>Starting point scenario:</p> <ul style="list-style-type: none"> - simulation based on experiences from 8 MW-demonstration plant and manufacture offer - investment costs have been summarised based on manufacture offer <p>Self sufficient scenario:</p> <ul style="list-style-type: none"> - simulation based on literature data
Synthesis & Upgrading	<ul style="list-style-type: none"> - simulation based on literature data - Investment costs from literature data
Auxiliary units	<ul style="list-style-type: none"> - power generation data based on process simulation (applying commercial/standard steam turbine data) - electrolysis data (scenario 1) taken from literature

Table 3-12: Data Quality of the ICFB-D-concepts

3.2.7 Allothermal CFB-Gasification for Ethanol Production (CFB-E)

The production of Ethanol via circulating fluidized bed gasification of willow is described by the CFB-E concept. Beside this main product, also methanol, propanol and electricity are produced. The biomass input power of this concept is 500 MW (over the fence of the overall plant). The information and data basis for this subsection was provided by Abengoa [Abengoa 2, 2006], [Abengoa 3, 2006], [Abengoa 4, 2006].

Concept Description – Scenario ‘Starting Point’. In the starting point scenario, biomass (willow salix) is converted into Ethanol without auxiliary energy. Thus, this scenario is equal to the self sufficient scenario. In the following, the main steps of the conversion process are described.

Mechanical and Thermal Pretreatment. The stored wood is dried to the conditions of downstream processes by a direct steam dryer (mid pressure steam; $T = 309\text{ }^{\circ}\text{C}$; $p = 12\text{ bar}$). A hammer mill decreases the wood size to the requirements of the fluidized bed gasification.

Thermochemical Pretreatment. No thermochemical pretreatment is needed in this concept.

Gasification. The dried and milled wood is fed to a circulating fluidized bed reactor. The reactor works at $850\text{ }^{\circ}\text{C}$ and 2 bars. Mineral olivine (a magnesium iron silicate) is used as heat transfer media for the endothermic gasification reactions. It is heated by the combustion of unconverted char in an additional char combustor, which is fed with recycled syngas and air (see description of the ICFB-D-concepts). The gasification agent is mid pressure steam ($p = 20\text{ bar}$).

Gas Cleaning and Gas Conditioning. A catalytic tar reformer is applied for destroying methane and ammonia in the raw gas. It is powered by recycled syngas and operating at a temperature of $870\text{ }^{\circ}\text{C}$. The hot tar-free raw gas is then cooled down to $65\text{ }^{\circ}\text{C}$ in the heat exchanger producing high pressure steam ($T = 537\text{ }^{\circ}\text{C}$; $p = 55\text{ bar}$) for power generation and other process parts. H_2S is separated from the raw gas in the LO-CAT[®] (unfortunately the data provider did not supply specific information about the function of this catalyst unit) and a ZnO-adsorber.

Adjusting the right H_2/CO -ratio is done by CO-conversion of a part of the raw gas stream in the water-gas-shift reactor. Downstream of the CO-Shift-reactor the water is removed from the joint stream by reducing the temperature to $50\text{ }^{\circ}\text{C}$. Then the gas is fed directly to the Selexol washer for CO_2 removal.

Before entering the synthesis reactor, the syngas is compressed to 70 bars which is the pressure required by the downstream synthesis reactions.

Ethanol-Synthesis. An alcohol synthesis reactor is used for syngas synthesis ($T = 300\text{ }^{\circ}\text{C}$, $p = 70\text{ bar}$). The main product of the synthesis is ethanol. By-products are methanol, propanol, methane, ethane, butanol and pentanol. The reaction enthalpy of the synthesis is used for producing high pressure steam ($p = 55\text{ bar}$) from high pressure water.

Upgrading. A gas/liquid separator is used to separate reactants, CO_2 and light hydrocarbons (methane) from the raw product. Further, light products, methanol, propanol and heavy products are separated from ethanol in four rectification columns. Finally, water is separated from ethanol in a dehydration unit.

Auxiliary Units. The electrical consumption of the overall process is produced in an internal gas turbine by combustion a part of the gases from gas/liquid separation. The steam from the power generation unit is used within the process (e.g. for distillation). Surplus electricity is fed to the grid. Effluents of the process are handled in the water treatment and led into the sewage system.

The concept provider did not specify in which processes the high pressure steam generated in the heat exchanger after the gasifier and the synthesis reactor is used.

The different process steps are shown in Figure 3-20 for the starting point scenario.

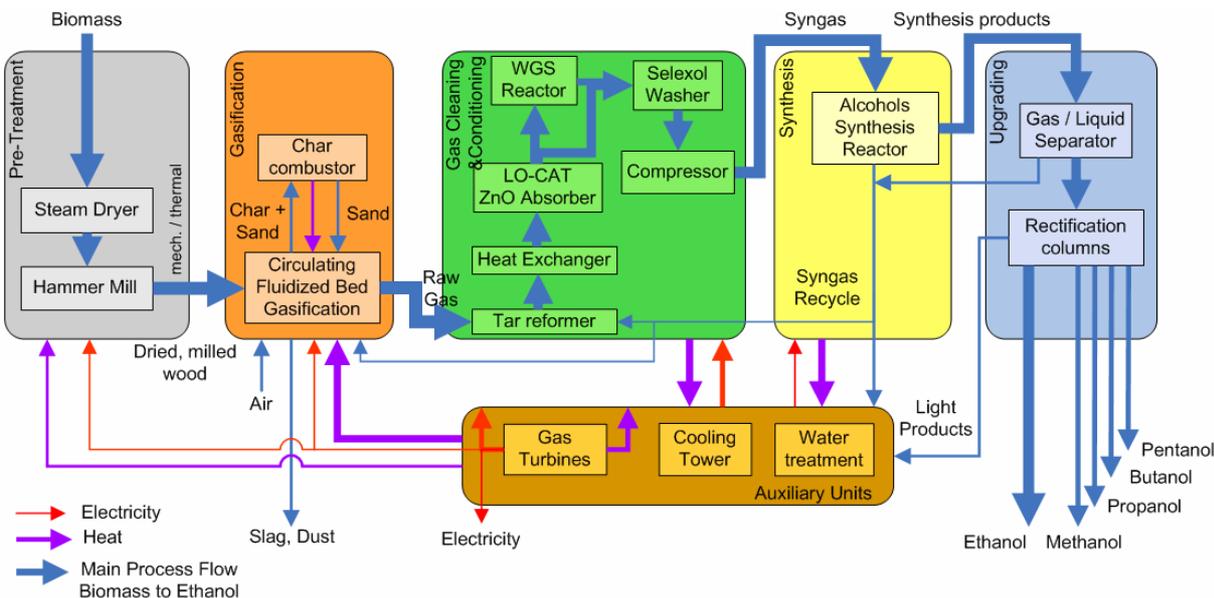


Figure 3-20: Simplified Process Flow of the CFB-E-Concept

In Figure 4-21, the main energy flows including heat transfer (steam, water, etc.) of the CFB-E-Concept (Scenario Starting Point, Biomass input wood) are shown.

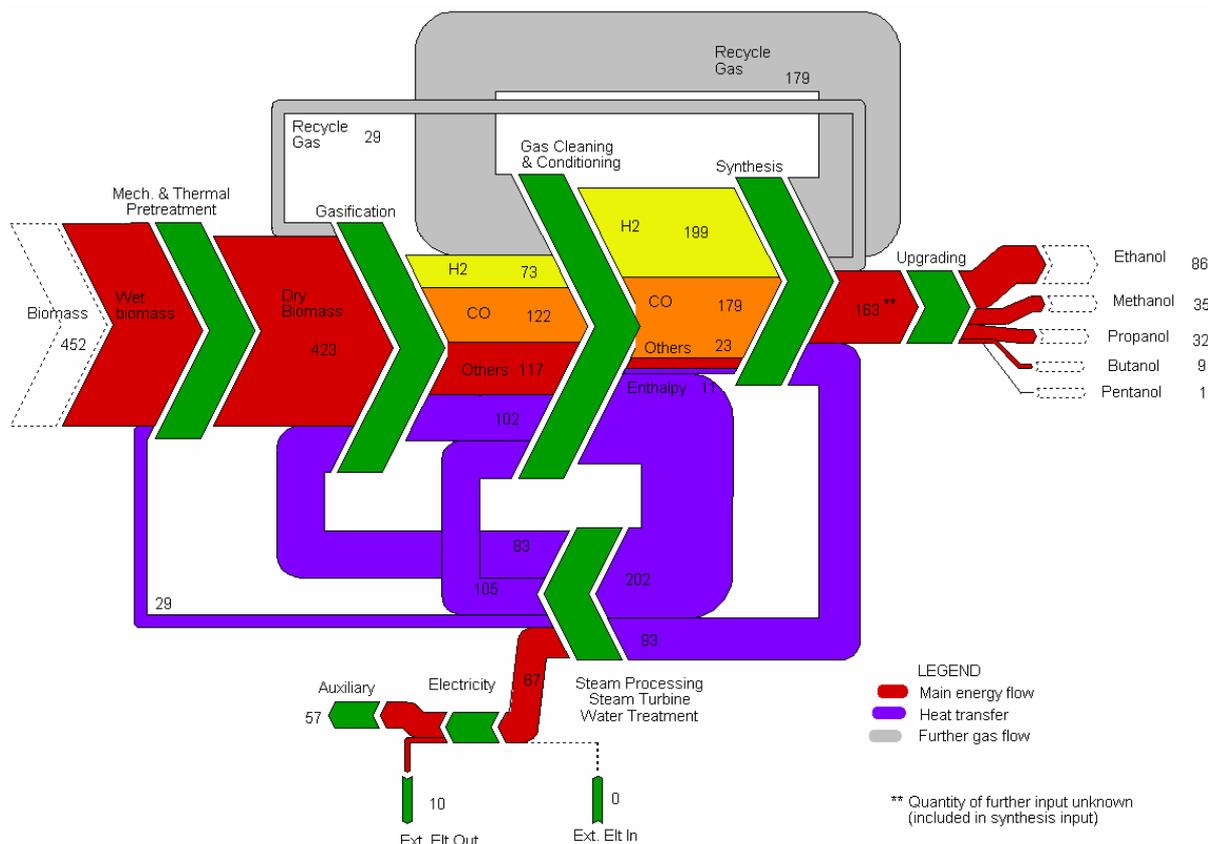
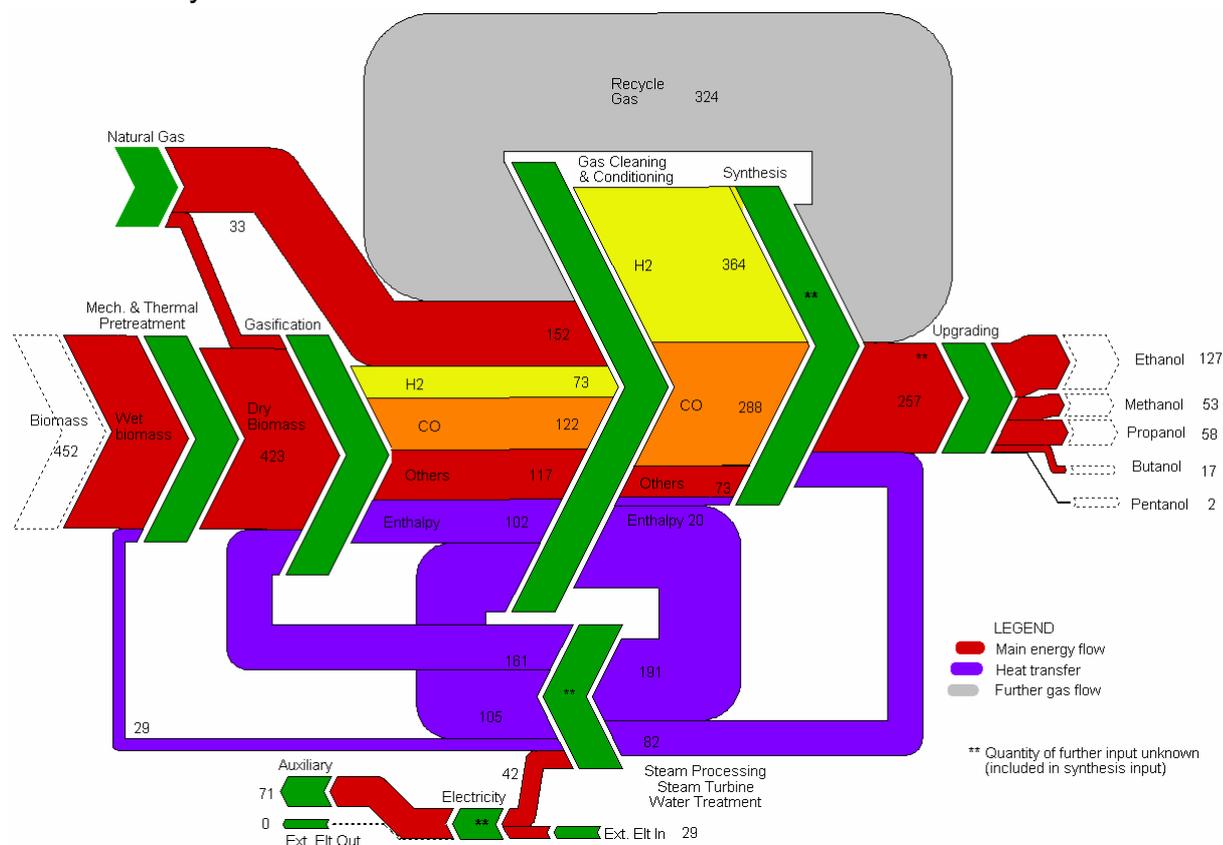


Figure 3-21: Simplified Sankey Diagram of the CFB-E-Concept (Starting Point); Figures in MW

Process Description – Scenario ‘Maximum Biofuel’. The biomass used in this scenario is willow salix. The process is the same as in the scenario ‘Starting Point’ except the following differences (see also Figure 3-22):

- recycled syngas from ethanol synthesis is converted by a steam reforming process (SMR) into CO and H₂ and fed back to the clean gas
- after SMR the converted syngas is led through a heat exchanger, generating high pressure steam
- the heat for the steam reforming unit, the char combustor and the tar reformer is supplied by natural gas
- The electricity for compressing syngas is taken from the grid, the gas turbine is not necessary



Concept Background and Intension. Information on the background and the intension of the described concepts are summarised in Table 3-13. Thereby the aim of this overview is a ‘condensed picture’ of concept specific differences.

Concept developer/data provider:	Grencell, Abengoa, Sevilla, Spain
Basic purpose of the concept	
<ul style="list-style-type: none"> - technology able to convert woody biomass to biofuels - alternative for 1st generation ethanol production (focus on gasoline market) 	
Basic purpose of the concept components	
Preparation	- prepare woody biomass for circulating fluidized bed gasification via drying and milling
Gasification	- high carbon conversion
Gas cleaning & conditioning	<ul style="list-style-type: none"> - use recycled syngas for heat supply of char combustor - separation of H₂S by a LO-CAT and a ZnO absorber; low investment effort - Selexol washing system for CO₂-separation - only catalytical tar reformer before fine gas cleaning (no washing system) to reduce investment costs - in contrast to commercially approved rectisol washing processes here a lower energy demand (no low temperature washer) and lower investment costs are aimed
Synthesis & upgrading	<ul style="list-style-type: none"> - synthesis and upgrading at central location - low upgrading effort compared to FT-synthesis
Existing technology	
<ul style="list-style-type: none"> - construction and operation of conventional bioethanol plants (biochemical conversion) - basic oriented research on Ethanol-catalysts 	
Working field/partners development	
<ul style="list-style-type: none"> - Basic and detailed engineering of biomass conversion plants 	
Compatibility of Process Developments and Renew-Scenarios	
<ul style="list-style-type: none"> - theoretical concept developed for comparison of Ethanol production with other synthetic biofuels 	

Table 3-13: Concept Background and Intension of the CFB-E-concepts

Data Quality. The data quality and information provided by the concept developers depends on many sources. To give an overview of the origin and basis of the concept developments, the most important sources are summarized in Table 3-14.

System component	information basis
Mech./thermal preparation	- simulation of the preparation processes based on literature data - no information on investment costs available
Thermochemical preparation	- simulation of the preparation processes based on literature data - no information on investment costs available
Gasification	- simulation of the preparation processes based on literature data - no information on investment costs available
Gas cleaning & Gas conditioning	- simulation of the preparation processes based on literature data - no information on investment costs available
Synthesis & Upgrading	- simulation of the preparation processes based on literature data and catalyst experiment on lab scale - no information on investment costs available
Auxiliary units	- power generation data based on process simulation (applying commercial/standard gas turbine data) - electrolysis data (scenario 1) taken from literature

Table 3-14: Data Quality of the CFB-E-concepts

4 Basics and Methods of Technical Assessment

In chapter 2 the basics of fuel production have been described. To assess these complex technologies, the basics of technical assessment and methods applicable for this task (theoretical background) are presented in general in chapter 4.1 – 4.3. Furthermore aspects of data quality and the comparability of the concepts are specified in chapter 4.4.

4.1 Basics of Technical Assessment

The assessment of technical systems – and therewith the development of evaluation methods – is as old as technology itself. Considering the development of different evaluation methods also different terms and definitions have been used in the past. Thus, the intention and procedure of a technical assessment as well as its terms and definitions are explained in general in the following.

4.1.1 Intention and Procedure

Intention. According to the VDI guideline 3780 [VDI 3780, 2000], technical assessment means a methodical, systematic, organised process assessing the direct and indirect technical, economic, health, ecological, human, social, and other impacts of this technology and possible systems (i.e. a technology and its alternatives).

This definition allows a broad view on the overall impact of a technology but with regard to the aims of this technical assessment (Chapter 2) it is unspecific. . In the case of SP 5.4, the technical assessment in Renew requires a focus on *technical values* and *goals*, i.e. non-technical and non-economic values and goals should be excluded from the evaluation as far as possible. Therefore the term ‘technical assessment’ in Renew is not defined as a complete assessment based on a broad ‘Technology Assessment (TA)’. It is rather a single assessment of the value *functionality*.

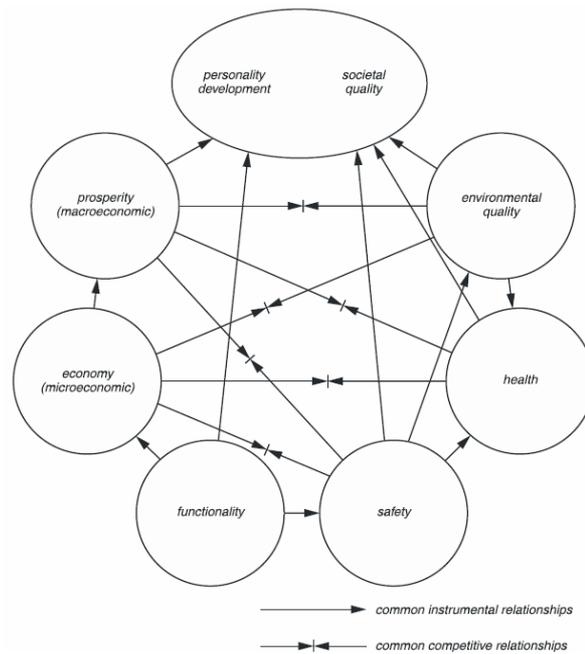


Figure 4-1: Values in Technical Action [VDI 3780, 2000]

As shown in Figure 4-2 the value functionality has an influence on further values like for example environmental quality and microeconomics. These relations have to be considered also within the 'Renew' technical assessment, but only as far as this is relevant to a technical realisation of a BtL-concept. This means that environmental aspects like process emissions or residues are considered but not as detailed as in a Life Cycle Assessment. Economic aspects are as well reduced as far as they are essential for technical aspects, which are projected in the technical *criteria* (efficiency, technical effort, practical realisation, etc.).

Procedure. Independent from type and complexity, every assessment is a methodical, systematic, organised process that can be explained as follows (the term 'system' can be regarded as the same as 'concept'):

If a technical system is not considered as a closed-off stand-alone unit but rather as a media for the realisation of specific goals, 'technical assessment' can be defined as an 'evaluation of a *system* regarding the achievement of *goals*'.

To grasp this evaluation somehow, common *evaluation criteria* have to be defined. Furthermore, for each of these criteria comparable *evaluation numbers* have to be defined (e.g. best concept = 5 points, worst concept = 1 point) to be able to calculate and compare different concepts. Then, these different concepts (systems) are investigated and described; evaluation numbers are determined. Finally, the evaluation numbers are weighted and summarized as *values* and conclusions can be drawn. This general assessment procedure is shown in Figure 4-2 [Ropohl, 2003] [Breiing, 1997].

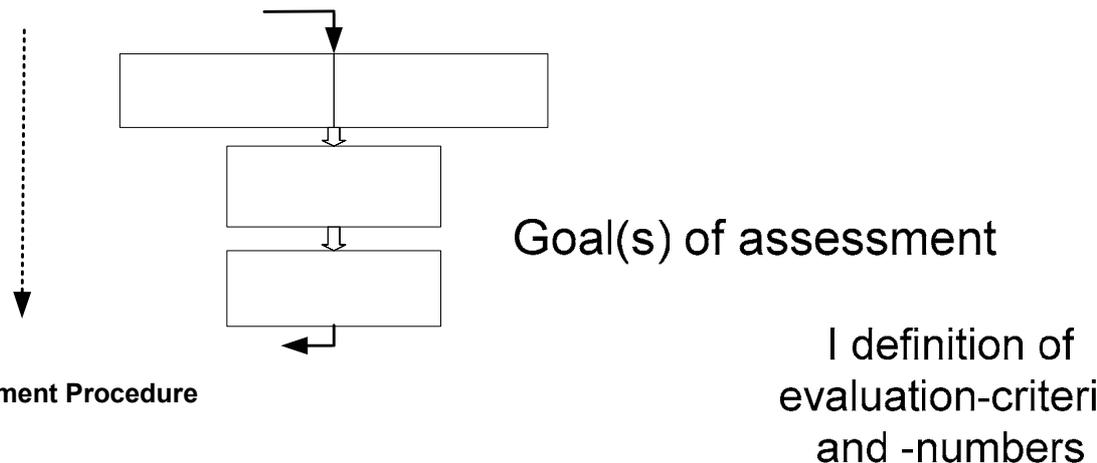


Figure 4-2: General Assessment Procedure

To give a very simple example out of daily life: A new car has to be purchased and two goals may be of importance: high power and low fuel consumption. In *step I* this can result in criteria like e.g. specific power [kW/kg] and fuel consumption [$l_{\text{diesel-equivalent}}/\text{km}$]. For these criteria evaluation numbers can be defined:

- for specific power e.g. 1 point (worst case) = $< 0.035 \text{ kW/kg}$
 up to 5 points (best case) = $> 0.12 \text{ kW/kg}$ whereas for
- fuel consumption e.g. 1 point (worst case) = $> 12 \text{ l/km}$
 up to 5 points (best case) = $< 4 \text{ l/km}$

In *step II* the systems to be assessed needs to be described by comparable data. In the above example this can be: Volkswagen Polo 1.4 TSI (105 kW, 1495 kg, 4.6 $l_{\text{Diesel}}/100 \text{ km}$) and Volkswagen Phaeton V6 TDI (165 kW, 2160 kg, 9.6 $l_{\text{Diesel}}/100 \text{ km}$).

In *step III* evaluation numbers can be determined. If we assume a linear relation of technical data and evaluation numbers (compare chapter 0) this leads to the following results:

- system I (Volkswagen Polo): power: 1.55 points; fuel demand: 4.7 points
- system II (Volkswagen Phaeton): power: 2.94 points; fuel demand: 2.2 points

Step IV (and concluding from this also the assessment result) depends on the weighting of the main goal/intention. If the criterion power has a high priority, system II is advantageous. If not, consequently system I is the 'first choice'. If both criteria have the same weight, still system I is advantageous.

4.1.2 Terms and Definitions

General Terms and Definitions. Since a lot of technical and non technical evaluation methods have been developed in the past, a broad variety of terms and definitions has been generated and can be found in literature. To find a commonly agreed assessment method within the working group and the Renew project a general accepted definition of terms is required.

The choice on terms and definitions is the VDI guideline 3780 - TA, Concepts and Foundations [VDI 3780, 2000]. It is attached in the annex (see chapter 9.1).

Definition of Criteria. As described above, one essential step of technical assessment is the *definition of evaluation criteria*. Thus, the different kinds of criteria are explained in addition to the VDI guideline:

In contrast to an economic assessment (where in most cases the definition of one goal is sufficient, e.g. annuity), a technical assessment requires the consideration of different technical aspects (efficiency, maturity, etc.) and therewith the consideration of several goals (high technical performance, etc.) and criteria. In this way, different pros and cons of the concepts can be identified.

One possibility to distinguish these criteria is the separation in (i) quantitative and (ii) qualitative criteria. The advantage of such distinction is the capture of dimensional parameters in respect to mathematically describable results. Furthermore, (for very complex assessment tasks) it can be of support to distinguish these two kinds of criteria in three further kinds of sub-criteria: (i) deterministic (countable, measurable, weighable and in form of numbers comparable), (ii) linguistic (describable by comparison, observation or estimation) and (iii) probabilistic (repeatable with a respective probability) criteria [Beiing, 1997]. These relations are shown in Figure 4-3. These different characteristics of criteria need to be considered when developing an adapted evaluation method for the actual assessment (see chapter 4.3.1).

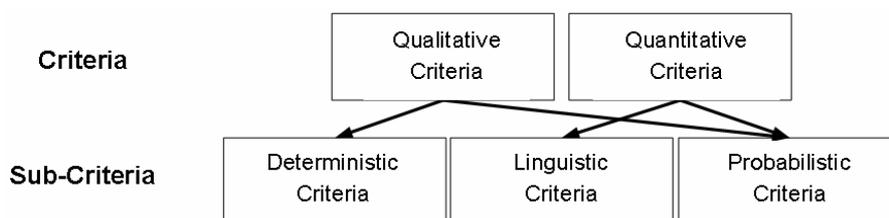


Figure 4-3: Various Kinds of Criteria and Their Relations

4.2 Method of Technical Assessment and Data Quality

Many methods of technical assessment (classic and new approaches) are available in literature [VDI 3780, 2000], [Adams, 1996], [Mild, 2002], [Zangemeister, 1976], [Ludwig, 1995], [Oesterdiekhoff, 1993], [Scheffczik, 2003], [Breiing, 1997]. These shall not be discussed in detail in this assessment but instead, a simple and common method is chosen.

So called 'multicriteria methods' are used broadly and are the most suitable for the purpose of this evaluation. These methods will be described in the following.

4.2.1 Principle of Multicriteria Analysis

Since the criteria have different functional characteristics, they need to be unified by *evaluation numbers* (as also showed within the example above). These evaluation numbers are points or point intervals on a numeric scale (like e.g. from 1 to 5 points).

Furthermore, the relevance of several criteria is also not unique. This can be compensated by the definition of *weighting factors*. The product of *evaluation number* and *weighting factors* results in the so called *value*.

This general procedure is as well defined in the VDI guideline [VDI 3780, 2000], but obviously too general. A procedure mentioned at [Beiing, 1997] seems to fit much better:

1. Definition of the systems to be investigated and evaluated
2. Definition of the multicriteria method to be used
3. Unification of the 'level of description' of the systems to be investigated
4. Definition of evaluation criteria
5. Determination of quantitative data or qualitative properties of the systems for each criterion
6. Determination of evaluation numbers for each criterion
7. Weighting of criteria and definition of weighting factors for each criterion
8. Determination of value for every alternative (product of evaluation number and weighting factor)
9. Discussion of the evaluation results

These steps of evaluation are the basis of most technical assessments and will be used also in this 'Renew' technical assessment. Different methods can be based on this general procedure. The selected methods are described in the following exemplarily.

4.2.2 Selected Methods of Multicriteria Analysis

Argument Balance. This method is the easiest assessment method. It is used for decisions in 'small or easy' scale by argumentative comparison of advantages and disadvantages. A numerical analysis of complex questions is not possible.

Techno-Economic Assessment. This method combines economic (e.g. production costs) and technical criteria (e.g. efficiency). Technical aspects are analysed according to the procedure mentioned above (calculation of values). An ideal process is defined as a standard for the maximum of technical 'value'. The best system results from the highest technical and economic value, i.e. the highest convergence with the predefined ideal process. This multicriteria method requires both technical and economic information.

Preference Matrix. The weighting factors for each criterion are determined by a pair wise comparison of criteria. An equal priority of two criteria is excluded (preference matrix).

Ranking Matrix. The determination of weighting factors by a ranking matrix is similar to the preference matrix (compare Figure 4-6). Three weighting states can be used:

- criteria A is more important than criteria B (e. g. mark '+')
- criteria A is comparable important than criteria B (e. g. mark '0')
- criteria A is less important than criteria B (e. g. mark '-')

The evaluations of the various criteria (a number or the marks '+', '0' and '-') lead to the weighting factor calculation. The advantage of this method is the transparency of the weighting and the possibility to adapt the assessment to another focus or priority.

Value of benefit. The value of benefit uses the description of (sub-)goals whereas these subgoals are used to assess the achievement of an overall goal. The criteria, subgoals and overall goals are structured by a hierarchy and weighted by horizontal and vertical weighting factors. The advantage of the method is the definition and weighting of different hierarchies; the disadvantage is the higher complexity compared to the ranking matrix and therewith a lower transparency.

Now the basics of technical assessments have been described. To develop adopted methods on technical assessment according to the special requirements of the BtL concepts, the concepts themselves have to be described, characterized and somehow simplified to a level where they can be compared with each other. This description and characterisation of the considered BtL concepts will be done in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** Later in chapter 4.4 the desired and defined criteria have to be adjusted and restrained according to the data quality and transparency available.

4.3 Specification of Technical Assessment

The basics and methods of the technical assessment were described in chapter **Fehler! Verweisquelle konnte nicht gefunden werden.** The aim was defined in chapter 1.2. Based on this and the indicators of chapter 4, the TA method and goals are now defined and adopted to the requirements of BtL concepts in chapter 4.3.1. In chapter 4.3.2 the weighing factors are defined and the later applied sensitivity analysis described.

4.3.1 Definition of the TA-method

Methodical Approach

Assessment Approach. Based on the characteristics of BTL-concepts and aims of assessment an approach will be chosen, which enables the distinction in different modules.

The determination of values is based on the methods ranking matrix and value of benefit and shown in Figure 4-4. The determination (calculation) of *secondary goals* is done by assessment and weighting of evaluation criteria. First, each criterion is evaluated. Then it is multiplied with a weighing factor and assigned to a secondary goal. These criteria are connected both to these modules and to the secondary goal. As result the values (rating, valence) of different secondary goals can be compared.

For further assessment the values of secondary goals can be assigned to *primary goals*. This is determined by the method mentioned above (i.e. weighting factor * value of secondary goals = value of primary goal). The relation between criteria, goals and modules is shown in Figure 4-4 and can be displayed by different weightings.

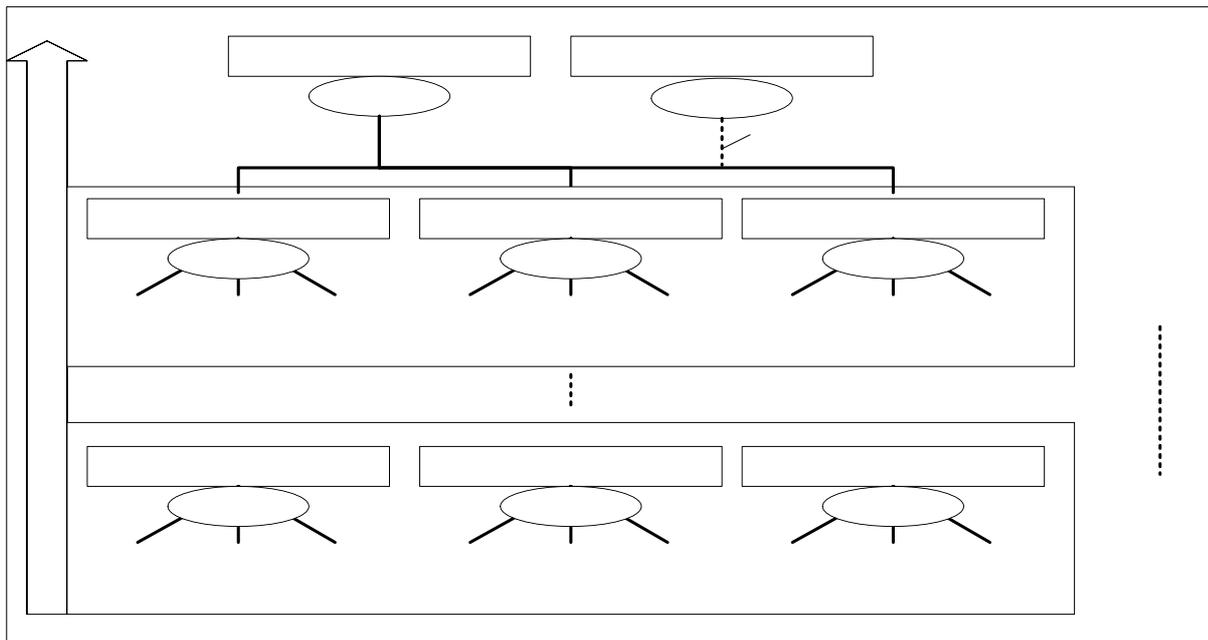


Figure 4-4: Criteria and Goal System as Basis of Technical Assessment

Definition of Evaluation Numbers and Criteria Weighting. To evaluate the criteria evaluation numbers are necessary as well as weighing factors:

Evaluation numbers. The definition of evaluation numbers is explained by the following example:

- first, the best case (e.g. 87 % overall efficiency) of a systems will be assessed by a evaluation number of 5 points
- second, the worse case will be assessed by a evaluation number of 1 point
- then the range is set to evaluate the other cases

As an example the criteria ‘overall efficiency’ of fuel production is shown in Table 4-1. On one hand, the best case of the systems shows 50 % and the worse case 35 %. On the other hand the products of the systems differ in a wide range (diesel, distilled products or FT raw product) and have to be distinguished accordingly.

evaluation number	diesel production	distilled FT-product	FT-raw product
1	35.0%	45.0%	50.0%
2	38.8%	48.8%	53.8%
3	42.5%	52.5%	57.5%
4	46.3%	56.3%	61.3%
5	50.0%	60.0%	65.0%

Table 4-1: Example on Evaluation Numbers for the Criteria ‘Overall Efficiency’

The evaluation numbers shown result from a linear relation of best and worst case. In this way, the evaluation numbers can be calculated very exactly (decimal place like e.g. 2.5 points at an efficiency of 40.7%, see Figure 4-5). Yet other non linear definitions are possible.

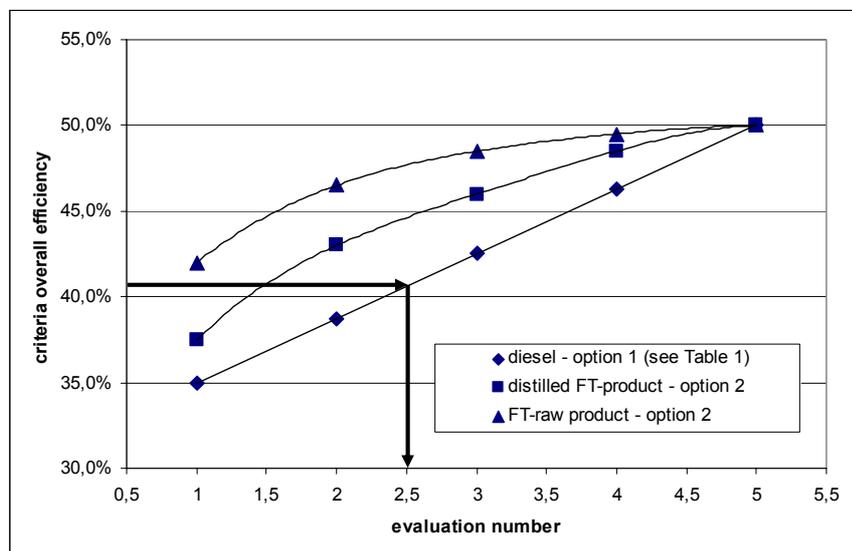


Figure 4-5: Evaluation Numbers of the Criteria Overall Efficiency

Criteria weighting. For the weighting of the criteria (and goals) the method of ranking matrix is applied. Each criterion is compared with each other criteria of the equal module. The following example shows the principal: The secondary goal ‘high gasification efficiency’ should be evaluated.

The criteria 'energetic efficiency', 'cold gas efficiency', 'syngas efficiency', 'H₂/CO-ratio', 'tar content' and 'dust content' are defined as criteria. These criteria are compared (as an example) with each other in Figure 4-6 resulting in different weighting factors (right column).

Criteria for Gasification Efficiency	Energetic Efficiency	Cold gas Efficiency	Syngas Efficiency	H ₂ /CO-ratio	Tar content	Dust content	quantity "+"	ranking numbers r	weighting
Energetic Efficiency	-	-	-	0	-	0	0	7	0,12
Cold gas Efficiency	+	-	0	+	0	+	3	13	0,22
Syngas Efficiency	+	0	-	+	+	+	4	14	0,23
H ₂ /CO-ratio	0	-	-	-	0	+	1	9	0,15
Tar content	+	0	-	0	-	+	2	11	0,18
Dust content	0	-	-	-	-	-	0	6	0,1
quantity "-" (check)	0	3	4	1	2	0	60	1	

Figure 4-6: Example on Weighting of Criteria for Gasification Efficiency

In contrast to the ranking matrix found in literature [Breiing, 1997] (here criteria weighting only by '+', '0' or '-') the weighting is calculated by *ranking numbers r*.

The following weighing definition is used:

- very important '+' 3 points
- important '0' 2 points
- less important '-' 1 points

The weighting factor w_k of a criterion can be calculated by $w_k = r_k / \sum r_k$, whereby the criterion is k ($k = 1 \dots x$), i.e. how much weight does one criterion have compared with the sum of all weighing factors. In this way the criteria balance themselves and are effecting the evaluation according to their weighing.

Goals, Modules and Criteria

Now the goals, modules and criteria which where described in the previous chapter in examples are given and defined in this chapter. The overall BtL assessment is more oriented on linguistic and probabilistic criteria (see chapter 4.1.2).

Definition of Secondary Goals. To calculate the primary goals mentioned above the following secondary goals are used for support (see also theory in chapter 4.1.2).

- (High) Efficiency (qualitative criteria; more focused on PG 1; important to evaluate the technical performance)
- (High) Maturity (quantitative criteria; more focused on PG 2; important to evaluate the state-of-the-art and the practical realisation)

- (High) Feedstock and Product Quality (quantitative criteria; more focused on PG 2; important to assess the possible feedstocks, the market potential and quality of the produced fuels)

Definition of Primary Goals. The secondary goals can be weighted and summarized in different ways. This is done in the primary goals, which are defined here and derived from the concept characterisation of the considered BtL concepts:

- High technical performance – PG 1 (more oriented on technical data)
- Good industrial applicability (close to practical realisation) – PG 2 (more oriented on technical restraints)

Definition of Modules. The following modules have been chosen in this TA:

- Overall Plant
- Gasification
- Gas Cleaning and Gas conditioning

Definition of Evaluation Numbers. The indicator evaluation will be done as follows:

- the best case of the considered concepts will be evaluated with 5 points
- the worst case of the regarded concepts will be evaluated with 1 point
- by a linear relation between these two cases, the other cases will be evaluated accordingly

4.3.2 Weighting Factors

Definition. The weighing factors are defined by application of the ranking matrix method described in chapter 0. They are listed in tables in the annex in chapter 9.8. As an example, the ranking matrix and weighing factors of the secondary goal 'high overall efficiency' are listed in Figure 4-7:

Criteria for Efficiency - Overall Plant -	Overall Efficiency - Main Fuel	Overall Efficiency - All Liquids	Overall Efficiency - CHP-F	PE_equ. Overall Efficiency - Main Fuel	PE_equ. Overall Efficiency - All Liquids	PE_equ. Overall Efficiency - CHP-F	Conversion Rate - Biomass to Main Fuel	Conversion Rate - Biomass to All Liquids	ranking numbers r	Weighting - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	FINAL WEIGHING FACTORS (incl. data security factor)
Overall Efficiency - Main Fuel	+	0	-	0	-	+	+		15	0,13	1	0,134
Overall Efficiency - All Liquids	-	-	-	-	-	+	+		11	0,10	1	0,098
Overall Efficiency - CHP-F	0	+	+	0	-	+	+		15	0,13	1	0,134
PE_equ. Overall Efficiency - Main Fuel	+	+	+	+	0	+	+		20	0,18	1	0,179
PE_equ. Overall Efficiency - All Liquids	0	+	0	-	-	+	+		15	0,13	1	0,134
PE_equ. Overall Efficiency - CHP-F	+	+	+	0	+	+	+		20	0,18	1	0,179
Conversion Rate - Biomass to Main Fuel	-	-	-	-	-	-	+		9	0,08	1	0,080
Conversion Rate - Biomass to All Liquids	-	-	-	-	-	-	-		7	0,06	1	0,063
Sum check									112	1,00		

Figure 4-7: Example for Ranking Matrix and Weighing Factors – Efficiency – Overall Plant

Sensitivity Analysis. The application of the defined TA method will give first results on primary and secondary goals. To increase the result's quality and check their dependency from the weightings and assumptions chosen, a sensitivity analysis will be carried out. Two methods will be used for this purpose, which are explained in the following:

- variation of data security factors (for primary and secondary goals)
- variation of different secondary goals weighing factors (for primary goals)

Definition of Data Security Factors. Data security factors tell how reliable the given data and its evaluation are. They range from 1,00 (data is sure), 0,66 (data is quite sure) to 0,33 (data is uncertain). These factors have been set to a value according to their quality in the ranking matrices having also an influence on the final weighing factors (see chapter 9.8).

Variation of Data Security Factors. For sensitivity analysis, the data quality of all criteria will be varied (e.g. evaluated as sure and set to 1) to note and interpret possible variations.

Variation of Secondary Goals Weighing Factors. The secondary goals are summarized and allocated together in the primary goals by different/alternative weighing. First, the goals are multiplied with the proportional weighing factor (which includes the data security factor already) and second, they are added to represent the final results of primary goals. The comparison of the primary goals (which result from different weighing of secondary goals) is thus a sensitivity analysis by itself.

Comparison of the Combination of Single Results with the Overall Results. Another part of sensitivity analysis could be the comparison of combined single results like gasification and gas cleaning and gas conditioning with the overall result. Since the examined units represent only half of the BtL process chain, this method was not applied in this TA. It would be a recommendable sensitivity analysis method for future technical assessments.

4.4 Data Quality and Comparability of Concepts

In the concept description in chapter Fehler! Verweisquelle konnte nicht gefunden werden., differences in the R&D-intension and the experiences among the concept developers (SP1-4) appeared. These differences show that also the quality of information and data available for concept comparison is not of homogeneous quantity and quality. This aspect is discussed in the following chapters regarding the availability of data and the completeness of concepts in terms of the provision of a motor fuel.

4.4.1 Available Data

The quality of a concept comparison depends mainly on the quality of the original data and information. Therefore, the following questions have to be kept in mind when analysing and interpreting the assessment results:

- how transparent are the available data and information?(data transparency)
- how were the data generated (which data based on the commonly agreed boundary conditions, which not? If there are differences, who significant are they for the result?) (data acquisition)
- how where the indicators calculated? (indicator calculation)
- what kind of further uncertainties exist? (further uncertainties)

Data Transparency. The data and information applied for the following analysis and evaluation origins from different sources (simulation, estimation or detailed engineering from third parties). It is based on different development status (pilot plants, laboratory experiments or literature) - see also the tables ,data quality' in chapter 3.2. These data have been checked in terms of consistency (mass and energy balances) as far as possible. But resulting from the different kind of data generation and invisible data (due to confidential agreements), some data is not a 100% transparent. This is obvious in the incomplete Sankey diagrams for example. Against this background, the analysis has been focused on criteria assessable by transparent data and information. Non transparent data has been indicated in the following.

Data Acquisition (by SP 1-4). Boundary conditions where given as default to ensure a maximum data comparability [Boundary, 2006]. Some parameters for indicator calculations where fixed (e.g. the heating values of feedstock and products).

Despite of this, different calculations and databases have been used by the partners from SP1-4 (see also the tables 'data quality' in chapter 3.2). Due to these different databases, the data used by them varies to some extent which had an influence on their calculations. For example under definition of the same biomass properties, the databases led to different heating values within the simulation tools of SP 1-4. This caused deviations of about $\pm 5\%$. Therefore, also deviations in the heat balance of the concepts appeared, assumed in the same magnitude.

Indicator Calculation (by SP5). As described above, the process designs are heterogeneous to some extent. Therefore, some indicators are difficult to unify, resulting in a deviation in the outcome. That is why the sankey diagrams in chapter 3.2 and the following efficiency calculations and indicators are to be understood as tendencies, not as absolute values. Here, a standardized simulation would be necessary and help out, but to do this, some obstacles are still on the way:

- part of the data is missing
- the data quality for simulation is limited
- (difference between available models / databases and real processes)
- some data are under confidential agreements

Further Uncertainties. Beside these differences in process design and databases, also differences in terms of the level of maturity and the concepts developers 'philosophy' (intention) exists. That is why a detailed concept comparison is not possible for some technical questions. For this purpose, a higher level of process information and more specifically defined plant location conditions would be required. This would demand for a high engineering effort which is not aimed within this assessment.

Also due to this reason, this TA can only be an evaluation of selected and more general questions rather than a comprehensive study. Based on the goals of this evaluation and on the available data quality of current recently developed BtL concepts, this work represents a scientific evaluation of selected concepts; an analysis with the dept of an feasibility study.

4.4.2 Completed Concepts

Beside differences in the data quality, also the design of the concepts leads to different final products. Without doubt, in order to enable a comparability of the concepts in terms of efficiency, unification up to a certain comparable product-quality-level is necessary. As shown in chapter 3.2, not all outputs of the concepts are comparable. Thus, efficiency calculation based on equivalent heating value (e.g. diesel-equivalent) would not lead to comparable results when assessing the concept 'as they are'. To close this gap, a fictive upgrading step is foreseen for two concepts (CFB-D, ICFB-D). This is shown in Figure 4-8. In addition to this, the upgrading is also calculated for the dEF-D concept in chapter 9.2. This is due to the fact that data on hydrogen demand is still missing.

Thereby, it has to be distinguished between calculation of efficiencies and the technical assessment in principal:

- the gap will be closed for the definition and evaluation of efficiency
- the gap will be left open and described for technical assessment in principal; i.e. the concepts CFB-D and ICFB-D, delivered by SP2, will be left 'as they are'.

In chapter 9.2 (**Upgrading**) the completion of the process chain for efficiency calculations is described in detail.

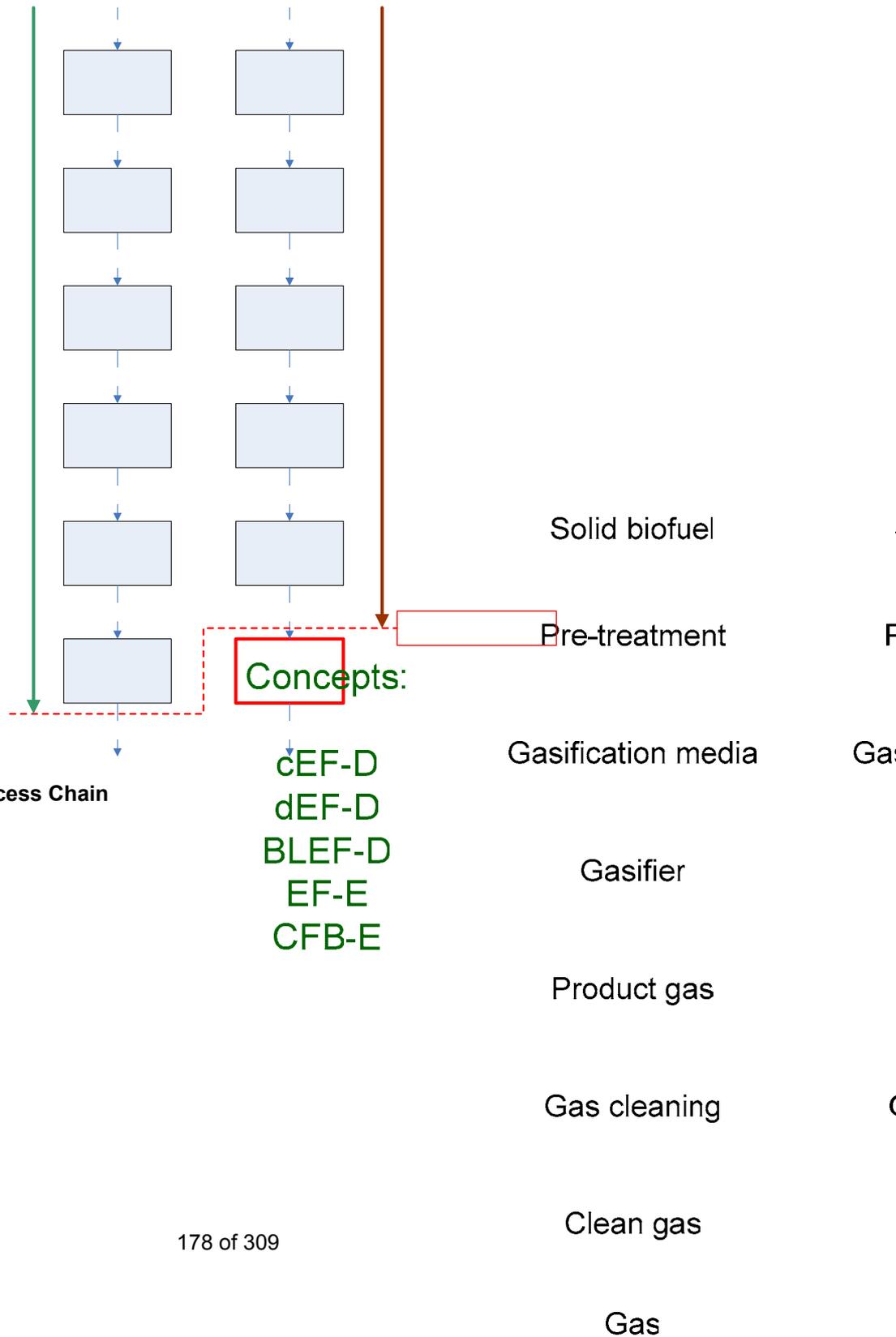


Figure 4-8: Incomplete Process Chain

5 Comparison of BTL-Concepts based on single criteria

In chapter **Fehler! Verweisquelle konnte nicht gefunden werden.**, the concepts to be assessed have been described in terms of applied technology and data sources. In order to compare these concepts more detailed, a common level of comparability has to be established. Therefore, the data have to be checked in terms of quality and completeness. If necessary, the concepts have to be completed in accordance with the concept's developers. This is done in chapter 4.4.

In this TA, efficiency is one of the most important and essential indicators. To satisfy this importance, efficiency will be analysed, discussed and defined separately in an in-depth study in chapter **9.3**.

Beside the indicators of

- a) efficiency (chapter 5.1),
the definition and evaluation of further more or less qualitative indicators is needed.

These indicators are grouped as indicators assessed with

- b) industrial perspective (flexibility and development status of the concepts) (chapter 5.2) and
- c) scientific perspective (analysed for the overall plant, the gasification unit, as well as for the gas cleaning and gas conditioning unit (chapter 5.3)

5.1 Energy Balances and Efficiencies

For the assessment of the qualitative criteria on efficiency in the following chapters, the calculation results are shown and discussed by headwords. Here, it has to be considered that each of these results depends on the definition of efficiencies and the corresponding system boundaries (see chapter 9.3). The database for these calculations and charts are the questionnaires, filled by SP 1-4. The data differ in terms of choice of technology, method and quality (calculations based on theory and practical data from pilot / demonstration plant or some are only based on theory and calculated theoretically/ideally). At some points of the calculations, these differences 'make a difference' and will be explained and discussed in the results. Summarized, not only one single efficiency has to be considered, but several ones. All calculated efficiency values can be found in the annex in chapter 9.5.

5.1.1 Overall Concept

Overall Efficiency – Conversion Plant. One of the main efficiency questions (also with high relevance for economic or environmental issues), is the overall efficiency of the conversion plant. The following overall efficiencies and their specified definitions are shown in Figure 5-1 (upper part):

The coloured staple is the sum of single efficiencies, calculated on the CHP-F method (see definition in chapter 9.3.5.1), whereby the colours are representing the parts listed in the legend of the figure; the sum is the overall efficiency according to the CHP-F method (see

Equation 9-18)

- In contrast to this method, the conventional method is applied for the overall efficiency 'main fuel' (grey column left to the staple) (see **Equation 9-16**, chapter 9.3.5.1) and for the overall efficiency 'all liquids' (black column right to the staple) (see **Equation 9-17**, chapter 9.3.5.1)

For a better comparison of the concept specific differences also the deviations from the average efficiency is shown in Figure 5-1 (lower part).

Depending on the kind of efficiency definition, different viewpoints can be analysed:

1. Energetic Utilisation. Comparing the energetic utilisation of the biomass (by-products considered as credit), different efficiency definitions with different focus can be applied:

- a) 'main fuel' applying the 'Conventional method': here, the focus is on motor fuels applicable without further upgrading
- b) 'all liquids' applying the 'Conventional method': here, the focus is on all fuels that can be applied as motor fuel (with or without further upgrading)
- c) 'all energy outputs' (fuel, electricity, district heat) of the 'CHP-F method': here, the focus is not distinguished regarding different energy products – district heat, electricity and fuel are of equally valued (poly- or tri-generation)

2. Production of Motor Fuels. Comparing different concepts regarding the production of a fuel applicable in combustion engines, the 'main fuel content' of the 'CHP-F method' (chequered staple) is of highest relevance (no by-products are considered as credit).

Based on these definitions the following conclusions can be drawn:

1a: Conventional method – main fuel. The focus of this overall efficiency is on direct applicable motor fuels without further upgrading.

- applying this efficiency calculation an average value of 38 % is achieved by the concepts

- regarding the type of gasification an general effect on the overall efficiency can not be concluded
- regarding the biomass applied no significant differences can be drawn; only the CFB-D concept shows a better efficiency with willow as biomass input vs. straw which results from the additional pelletising unit which is used in the straw scenarios (higher electricity consumption)
- regarding the scenario specific differences in case of electrolysis the maximum biofuel scenarios shows more or less the same efficiency as the starting point / self sufficient scenarios; higher efficiencies can be accomplished by applying an adapted process integration (e.g. additional H₂ generation by reforming of surplus gas)
- regarding the concept specific differences the BLEF-DME concept shows the best efficiency because of process integration (pulp mill); the EF-E (SP), CFB-E (SP) and the ICFB-D (SP) concept obtain the lowest efficiencies because of little main fuel output (Ethanol concepts) and focus on tri-generation (ICFB-D (SP) concept

1b: Conventional method – all liquids. The focus of this overall efficiency is on applicable motor fuels with or without further upgrading.

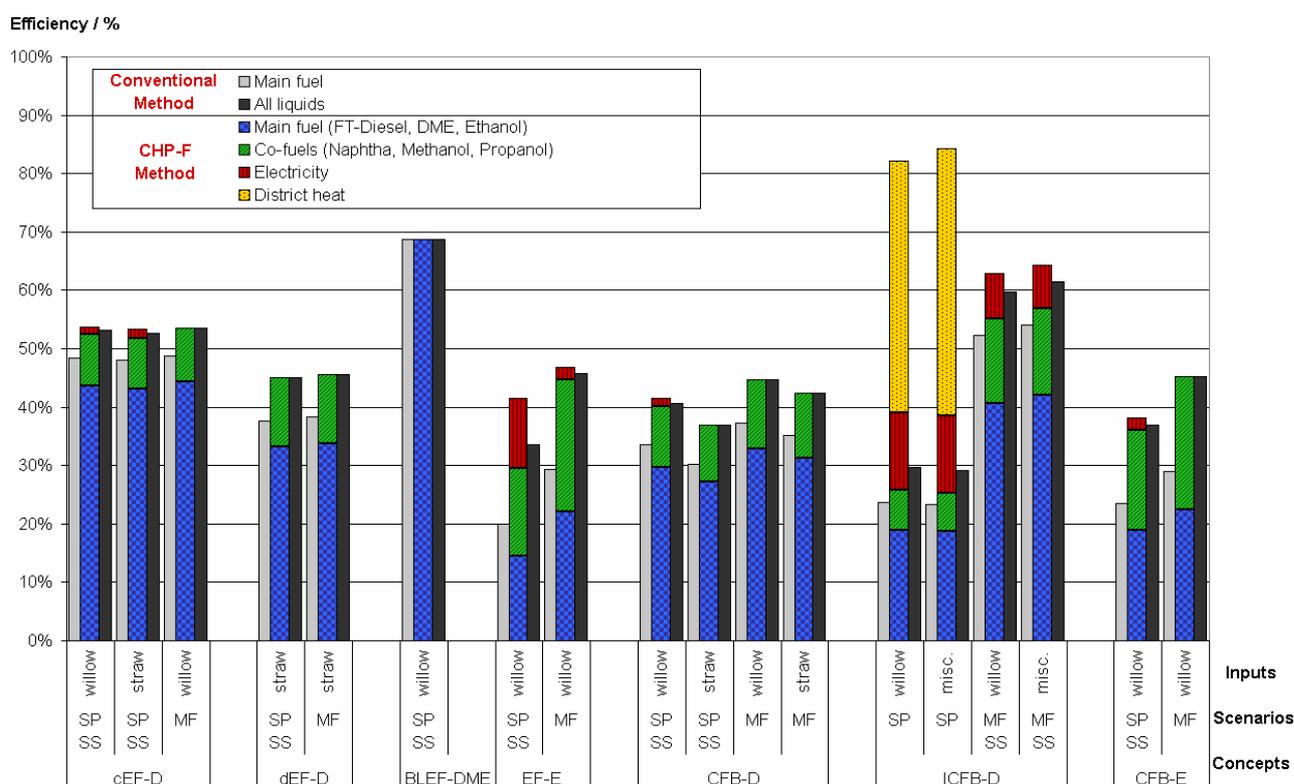
- applying this efficiency calculation a higher average value of 46 % is achieved by the concepts; this applies for all concepts producing by-products
- also co-fuels like naphtha, methanol and propanol are considered as output; thus, the strongest increase in efficiency appear in the Ethanol concepts (compared to the 'main fuel' efficiency), since their share of liquid by-product is the highest one of the concepts considered
- the other concepts increase in efficiency is quite moderate and of similar intensity compared to the 'main fuel' calculations, resulting from lower by-product amount
- for the BLEF-DME concept it is the same since no by-products are considered; in general; it obtains the best efficiency, the ICFB-D (SP) concept the lowest because of focus on tri-generation

1c: CHP-F method – all energy outputs. The focus of this overall efficiency is on tri-generation of fuel, electricity and district heat.

- applying this efficiency calculation a further increase in the average value (53%) can be drawn, which results from the efficiency definition (consideration of electricity and district heat (only for ICFB-D SP) as output
- the 50 MW ICFB-D concept shows the highest efficiency (80 – 85 %) due to tri-generation of heat, power and fuel (the highest share is heat, followed by fuels and power)
- all ICFB-D concepts show the highest output of electricity; 10 of 18 concepts feed electricity to the grid
- the least efficient concepts are around 40 % (CFB-D, EF-E and CFB-E)

2: CHP-F main fuel. The focus of this part of an overall efficiency is on direct applicable motor fuels without further upgrading and without credits for by-products like other fuels, electricity or heat.

- the Ethanol concepts show very poor efficiency in terms of the main fuel ethanol; however, the overall efficiencies of the MF scenarios are in the mid range along with the dEF-D concept
- the highest share of main fuel is obtained by the BLEF-DME concept (69%), resulting from integration into a pulp mill, where the biomass input is replacing the energy from original black liquor
- this concept is followed lined up by high efficiencies of the cEF-D (43 – 44 %) and the 500 MW ICFB-D concepts (41 – 43 %), mainly due to high process integration



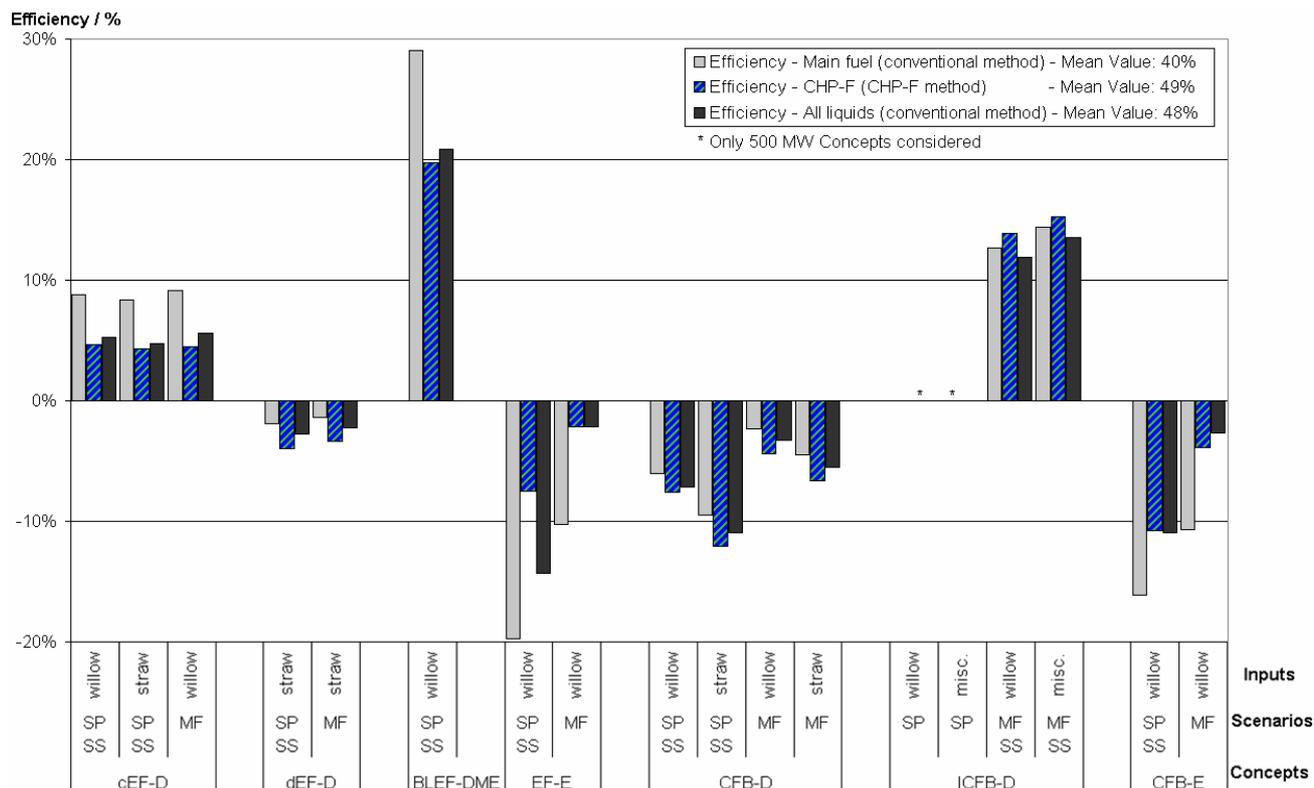


Figure 5-1: Overall Efficiency – Conversion Plant (upper part) and Deviation from Average Overall Efficiencies (lower part)

* Only large 500 MW concepts are considered to enable a qualitative comparison

Summary Overall Efficiency. A summary on the above results is given in headwords:

- the variations of the different calculation methods are either on the positive or the negative side. Thus, the calculation method is not influencing the overall results and these results are free from evaluation.
- the concept specific differences mainly result from the development focus (focus on different main or by-products):
 - the BLEF-DME concept is the most efficient considered and independent of the method of efficiency calculation applied
 - the most efficient concepts for diesel production are the cEF-D and the ICFB-D (MF) concepts
 - considering main fuel production, the 50 MW ICFB-D (SP) concept is among the weakest concepts; in terms of energy utilization (tri-generation), this concept has the most efficient use of biomass of the concepts considered
 - the Ethanol concepts are only little efficient in terms of ‘main fuel’ production but – considering by-products – they keep up with the average
 - the concepts dEF-D and CFB-D show average and lower than average overall efficiencies

- some maximum biofuel concept show the same or less efficiency than the self sufficient concepts (cEF-D and dEF-D). The fuel output is higher (almost double) but also the input (mainly electricity for hydrogen production)
- high efficiencies can be achieved by high process integration:
 - Integration of thermal processes and recycled syngas (cEF-D)
 - Integration of the overall process in a conventional pulp mill (BLEF-DME)
 - Integration of thermal processes, recycled syngas and large power production (gas & steam turbines) (ICFB-D)
- Applying electrolysis for maximum fuel scenario leads to same or lower efficiency; higher efficiency of this scenario can be achieved via better process integration and/or optimisation of system components

Overall Efficiency – Primary Energy Based. In the analysis above, the efficiency ‘conversion plant’ is based on the system boundary ‘plant gate’. To assess the conversion efficiency based on energy resources, another definition is required (compare chapter 9.3.2). Therefore, the following graphs consider the first conversion of primary energy into secondary energy as starting point for calculations and show these overall efficiencies (see calculation results in Table 9-11 and charts in Figure 5-2 (upper part)):

- The coloured staple are the sum of single efficiencies, calculated on the CHP-F method (see definition in chapter 9.3.2.2), whereby the colours are representing the parts listed in the legend of the figure; the sum is the overall efficiency according to the CHP-F method (see Equation 9-29)
- In contrast to this method, the conventional method is applied for the overall efficiency ‘main fuel’ (grey column left to the staple) (see Equation 9-27, chapter 9.3.2.2) and for the overall efficiency ‘all liquids’ (black column right to the staple) (see Figure 5-1, chapter 9.3.2.2)

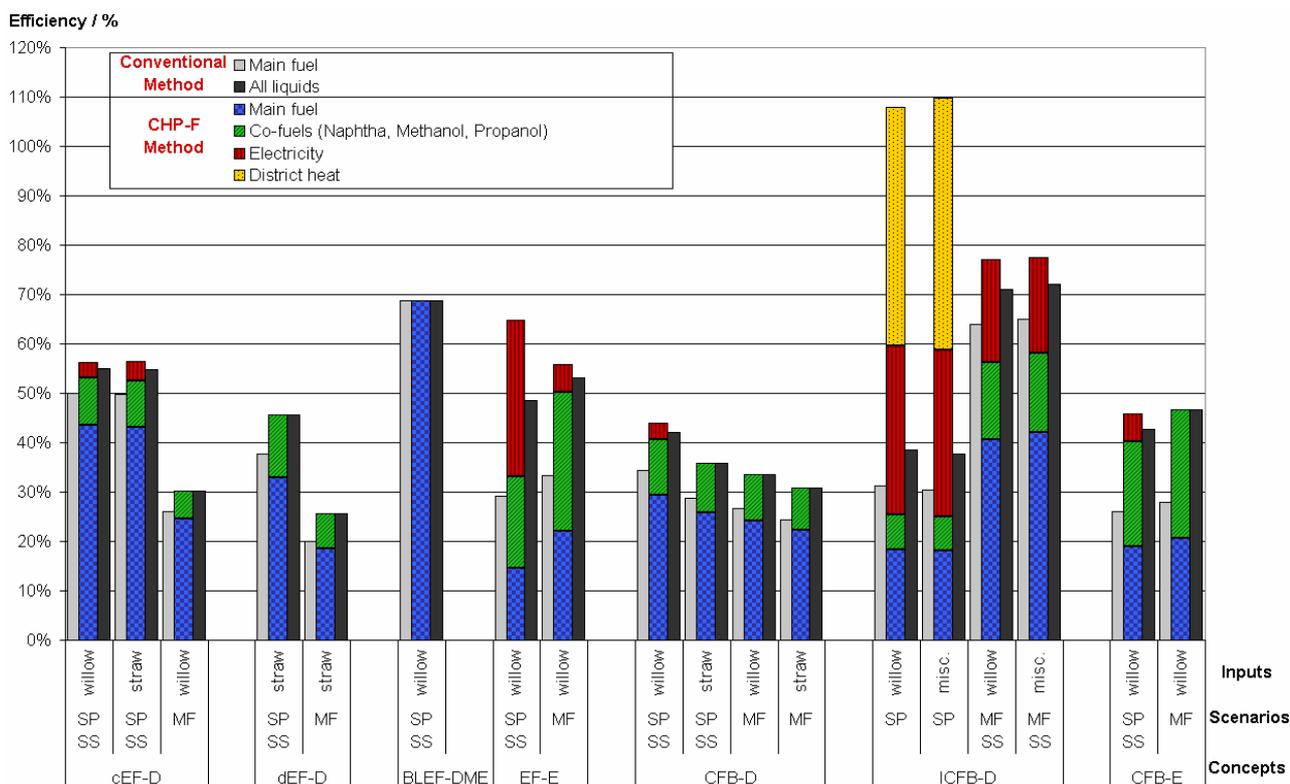
Additionally the primary energy based efficiency results are subtracted from the conventional calculations (conversion plant) to visualise the difference (see lower part in Figure 5-2).

General Results on Primary Energy Based Overall Efficiency Calculation. The following results can be drawn out of the considered system boundary and efficiency definition:

- the BLEF-DME and ICFB concepts are the most efficient
- the maximum biofuel concepts of cEF-D and dEF-D are the least efficient; this drastical reduction is due to the large input of electricity, which needs to be generated from primary energy sources with a certain efficiency

- the efficiencies of the 50 MW ICFB-D concepts are above 100 %; this is not a wrong calculation but showing the synergy effect of process integration and tri-generation; this process uses more synergy effects – better utilization of fossil fuels – than generating each energy form (fuel, electricity, district heat) separately and is thus more profitable than single generation of different energy forms

These results are connected to the PE-equivalent calculation, whereby heat and power get a high credit. Primary Energy is usually converted with a small efficiency to electricity with huge heat losses. Within the ICFB-D concept, the tri-generation is realised and thus the utilization degree of Primary Energy is higher. This synergetic effect turns out in an efficiency close to 100%.



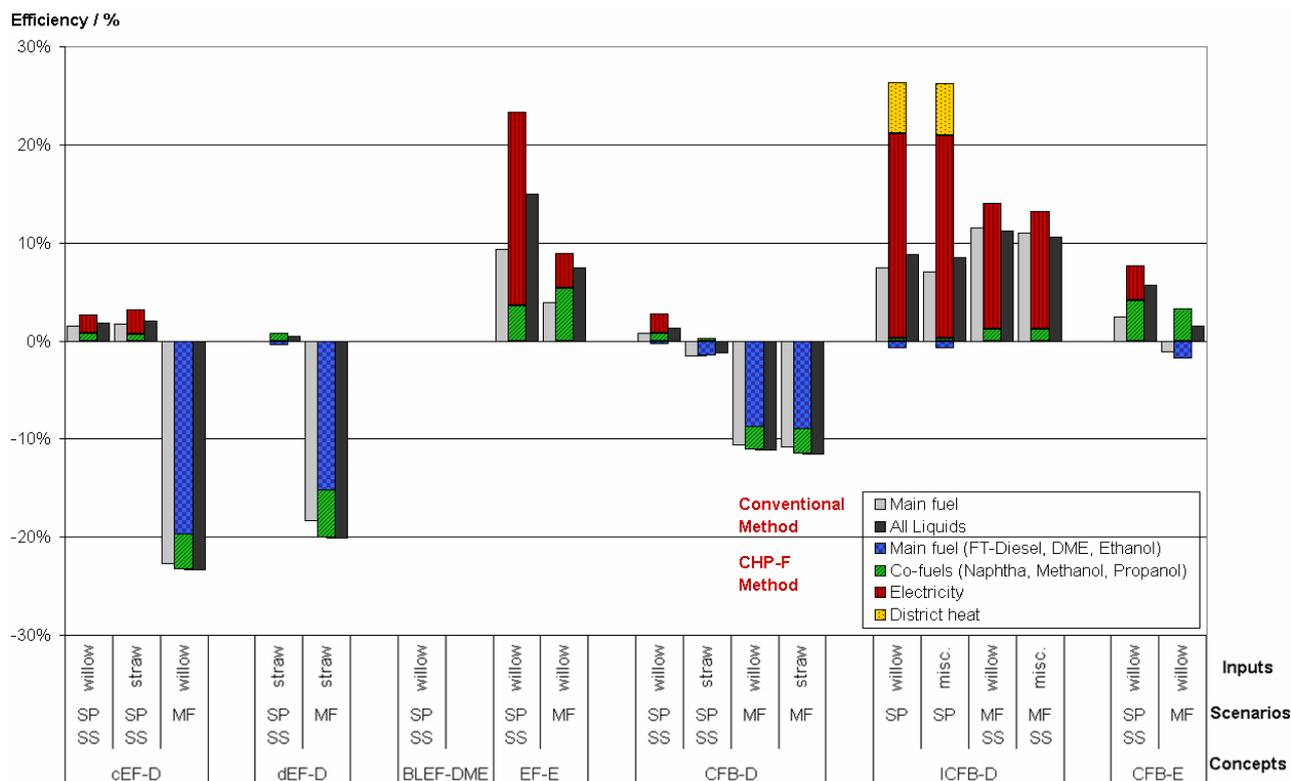


Figure 5-2: Overall Efficiency – Primary Energy Based (upper part) and Overall Efficiency – Difference Between the ‘Primary Energy Based’ Calculations and the ‘Conversion Plant’ Calculations (lower part)

Difference Among the Definitions (‘PE based’ vs. ‘conversion plant’ Calculations): Comparing the different overall efficiency definitions, the following conclusions can be made:

- the maximum biofuel scenarios of the concepts cEF-D and dEF-D show the largest efficiency drop down to 25 % and 20 % respectively according to the conventional method. This is due to an increase effort for fuel production: a large electrical power input (500 MW range) is required for an additional electrolysis plant, producing hydrogen and oxygen
- the largest increase in efficiency (CHP-F method) are due to a co-generation of electrical power, which is usually generated at an efficiency of 35 % to 45 % in commercial power plants; thus co-generation of electricity in a BtL-plant is saving fossil and renewable energy resources and recommendable

Overall Efficiency – Conversion Rates. Besides efficiency, a common interest is how much BtL can be produced from a given biomass input (potential). So two conversion rates of the concepts are shown in Figure 5-3, namely:

- conversion rate biomass to main fuel (FT-Diesel, DME or Ethanol)
- conversion rate biomass to all liquids (main fuel plus naphtha, methanol and propanol)

Biomass to Main Fuel. This conversion rate reflects how much direct applicable fuel can be produced from a given biomass input.

- applying this conversion rate calculation an average value of 39 % is achieved by the concepts; there the MF scenarios show higher conversion rates than the SP scenarios (average 47 % vs. average 32 %)
- the highest conversion rates are achieved by the maximum biofuel scenarios of the concepts cEF-D (90 %), dEF-D (67 %) and in the starting point scenario of the BLEF-DME concept (69 %); this is a result of using additional hydrogen for gas conditioning and synthesis in the cEF-D and dEF-D concept and process integration in the BLEF-DME concept
- the lowest conversion rates are obtained by the ethanol concepts and the ICFB-D (SP) concept, which is designed for tri-generation of fuel, power and district heat

Biomass to All Liquids. This conversion rate reflects how much fuel (with or without a need for further upgrading) can be produced from a given biomass input.

- Applying this conversion rate an higher average value of 53% is accomplished by the concepts; some conversion rates are exceeding a 100%, showing the meaning of these conversion rates, which are only focused on two parameters (main input and main output in this case)
- the highest conversion rates are achieved by the maximum biofuel scenarios of the concepts cEF-D (108 %) and dEF-D (91 %); this is a result of using additional hydrogen for gas conditioning and synthesis
- the 50 MW ICFB-D concepts show the lowest conversions rates due to a optimisation of the concept on tri-generation
- the most significant difference between these two conversion rate is within the ethanol concepts where the conversion rate doubles for 'all liquids'; this is a result of large by-product output of methanol, propanol, butanol and pentanol

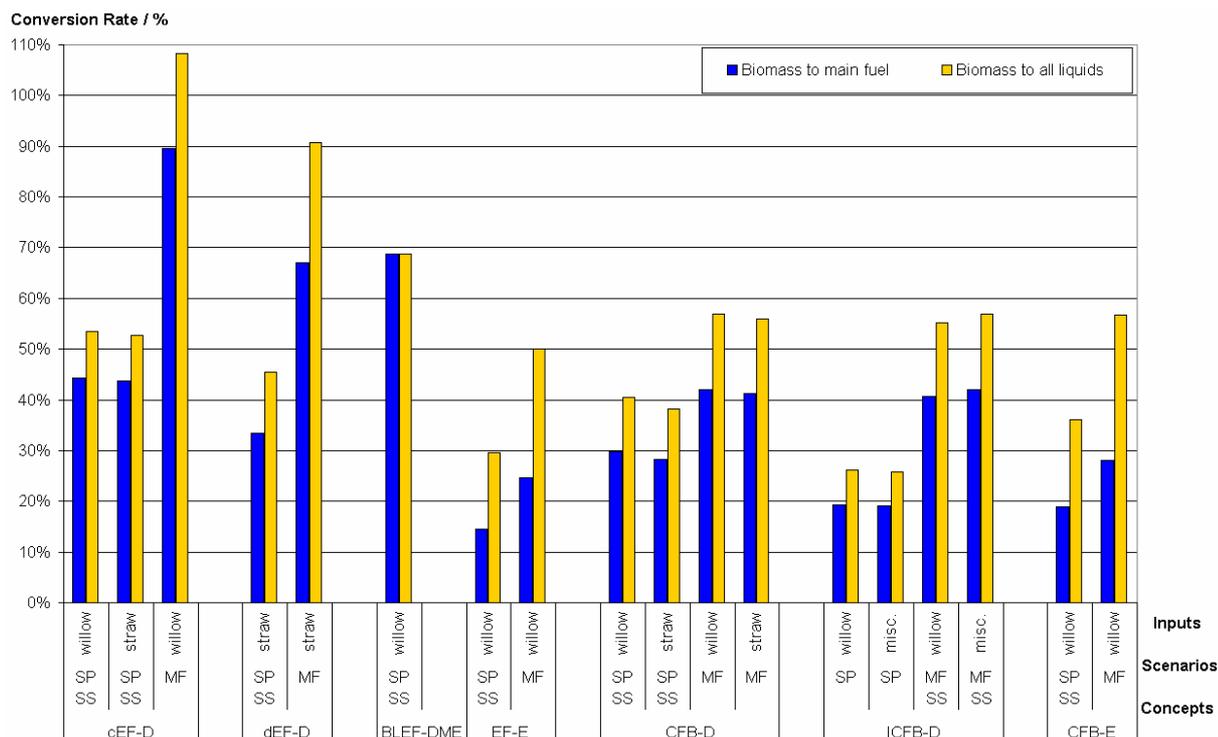


Figure 5-3: Overall Efficiency – Conversion Rates

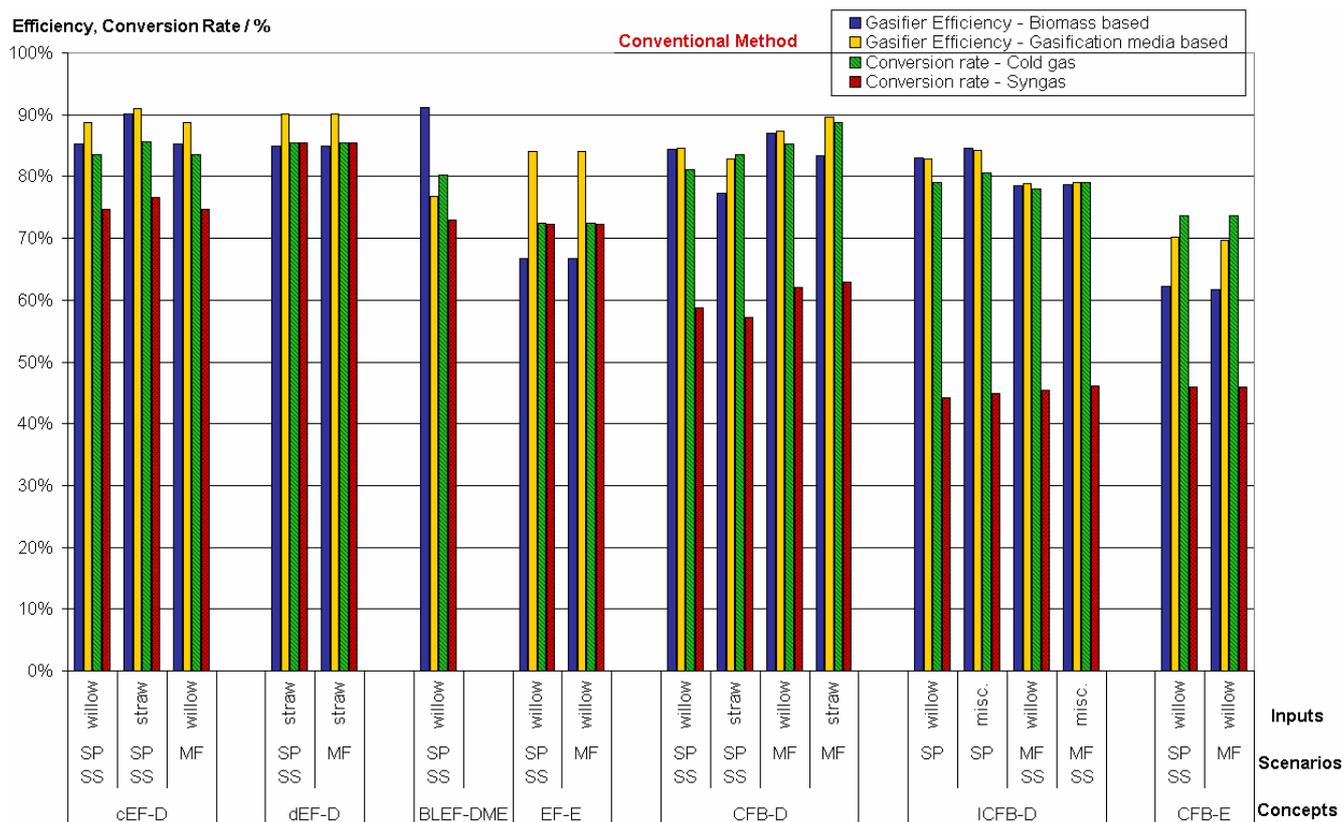


Figure 5-4: Gasification Efficiencies & Conversion Rates

5.1.2 Gasification

Gasification Efficiencies & Conversion Rates. The overall efficiency results from the sum of the single process step. One of the most crucial and important step is the gasification. It was examined separately and the calculation results of the gasification efficiencies of the different concepts and scenarios are presented in the annex in Table 9-12 and displayed below in Figure 5-4. The definition of these efficiencies and conversion rates are to be found in chapter 9.3.5.2.

Gasifier Efficiency – Biomass Based. This biomass based efficiency reflects how much raw gas can be produced from a given biomass input considering also all energy in- and outputs like natural gas, backgas, liquid scrubber residues (biodiesel) and the energy necessary for biomass pretreatment (heat and electricity).

- an average value of 80 % is the result of applying this efficiency calculation
- entrained flow concepts show a slightly higher gasifier efficiency in average than circulating fluidized bed concepts (EF: 82 % vs. CFB: 78 %)
- the highest efficiencies are achieved by the cEF-D concepts with straw input (90 %) and the BLEF-DME concept (91 %)
- the cEF-D concepts with input willow are less efficient than the cEF-D concept with input straw due to less effort on biomass pretreatment (in particular drying)
- vice versa the CFB-D concepts with input willow are more efficient than the CFB-D concepts with input straw because of a higher effort in pretreatment (straw pelletising)
- the high efficiency in the BLEF-DME concept results from a variable biomass input (here, the biomass is used to replace the steam and power generation of black liquor, which is gasified)
- the ethanol concepts show the poorest efficiencies (average 63 %) due to a low energy content of the raw gas (EF-E and CFB-E) and high electricity demand for gasification and preparation (EF-E)

Gasifier Efficiency – Gasification Media Based. This gasification media based efficiency is calculated in the same way as the previous efficiency with the difference of considering the gasification media as main input instead of the biomass feedstock. Furthermore, the energy necessary for preparation is not included in this indicator.

- applying this efficiency calculation, an average value of 83 % is the outcome
- entrained flow concepts also show a higher gasifier efficiency in average than circulating fluidized bed concepts (EF: 87 % vs. CFB: 81 %); this is due to the higher energy density of the gasification media in EF concepts (which needs a more sophisticated pretreatment than in CFB concepts)

- the higher efficiencies are obtained with straw compared to willow as biomass input (SP cEF-D, MF dEF-D and MF CFB-D concepts) mostly probably due to a higher carbon conversion rate
- the cEF-D and dEF-D concepts show the highest efficiency (mainly due to a similar reactor principle and thus a high caloric raw gas) but also and CFB-D (MF) is in the same range – the reason for this is not yet clear
- the CFB-E and BLEF-DME concepts obtain the least efficient gasification processes due to low energy content of the gasification media
- within the E-EF concept the differences between biomass based and gasification media based calculations are immense which is indicating big losses in torrefaction; until now no data is available to explain this more in detail

Conversion Rate – Cold Gas. This conversion rate reflects the amount of gasification media which can be converted into raw gas (incl. tar).

- the average value of this indicator is 81 %
- since methane is included in the product, there is no notable difference between EF and CFB concepts (81 % vs. 80 %)
- the average values for SP scenarios is the same as for MF scenarios (81%), i.e. no improvement of gasification reactors has been expected by the concept developers

Conversion Rate – Syngas. This conversion rate is also based on the gasification media, but the focus is the hydrogen and CO content of the raw gas.

- an average value of 63 % is accomplished applying this conversion rate calculation
- there is a large difference between EF and CFB concepts (77 % vs. 51 %) mainly due to a tar and almost methane clean raw gas in the EF concepts (carbon conversion at very high temperatures close to equilibrium conditions)
- there is no notable difference between SP and MF scenarios (63 % vs. 62 %), i.e. no improvement of gasification reactors has been expected by the concept developers
- there is no difference between the syngas and the cold gas conversion rate in the dEF-D and the EF-E concept; this shows the ideal calculation within these concepts

General. Summarising the calculations on the gasification unit, the following general results can be drawn:

- considering the criteria of efficiency the entrained flow concepts are favourable for production of a high quality raw gas
- straw as biomass input results in higher conversion rates and gasification efficiency than willow if the same technology is applied (example: cEF-D)

5.1.3 Gas Cleaning and Gas Conditioning

In this chapter, the gas cleaning and gas conditioning unit is examined. It must be noted, that some data were missing from the concept providers of BLEF-DME and ICFB-D.

Gas Cleaning and Gas Conditioning Efficiency & Conversion Rate. The gas cleaning and gas conditioning efficiency along with the syngas conversion rate will be shown in this chapter and in Figure 5-5.

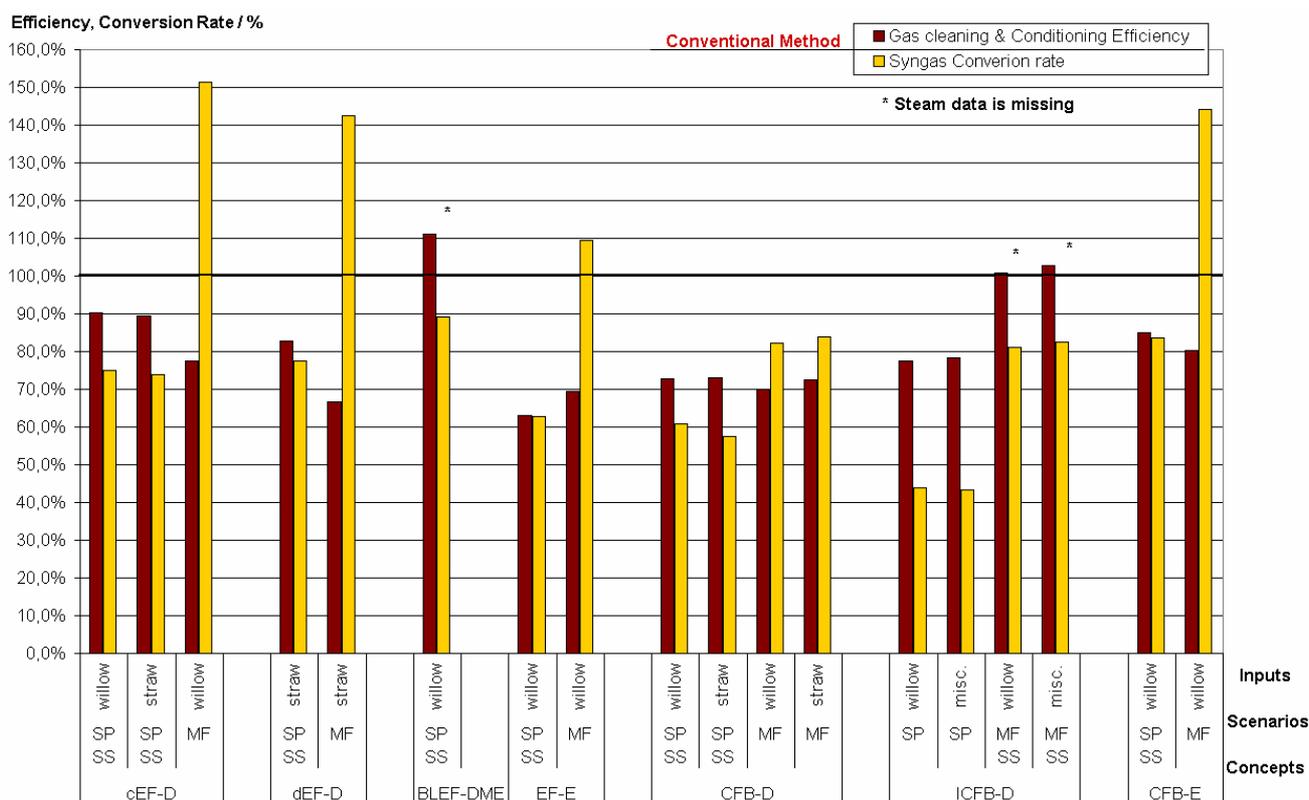


Figure 5-5: Gas Cleaning and Gas Conditioning Efficiency & Conversion Rates

Gas Cleaning and Gas Conditioning Efficiency. This indicator reflects the gas cleaning and gas conditioning efficiency which includes heat, electricity and all gases entering and leaving the gas cleaning and gas conditioning unit block.

- the average value of this efficiency calculation is 81 %
- there is no difference between EF and CFB concepts (both 81%)
- there is only a little difference between the SP and MF scenarios (80% vs. 82%)
- the BLEF-DME and ICFB-D (MF) concepts exceed a 100%; this is due to missing steam data
- the highest efficiency (~90%) under calculation of transparent data is obtained by the cEF-D concepts (SP);

- the MF scenarios of the cEF-D and dEF-D concepts are less efficient because of large electricity demand for hydrogen generation (produced via electrolysis); this effect is not appearing in the MF scenario of the CFB-D concept because in this scenario the quantity of additional hydrogen input is much smaller than in the other concepts adding hydrogen via electrolysis
- the EF-E concept (SP) has the lowest efficiency as a result of a low syngas power
- usually a rectisol washing system consumes a lot of electricity which is negative for the gas cleaning and gas conditioning efficiency; in the regarded concepts, this affect did not appear

Syngas Conversion Rate. The syngas conversion rate is based on the biomass input and thus includes all units in the BtL plant up to synthesis (pretreatment, gasification, gas cleaning and gas conditioning).

- the syngas conversion rate is on average 86%
- if the concepts are compared according to the application of a tar reformer, the result is a clear increase in conversion rate and efficiency, if such a reformer is applied (compared concepts: ICFB-D (50 MW) vs. ICFB-D (500 MW) and also EF-E vs. CFB-E)
- the MF scenarios have almost a double conversion rate compared with the SP scenarios (110% vs. 67%), which is a result of adding hydrogen to syngas (cEF-D, dEF-D and CFB-D); this showing that the definition of the syngas conversion rate is actually not a representative figure for the conversion of biomass to syngas, which is a weak point of this indicator
- the high rate in the MF scenarios of the ethanol concepts results from ideal calculation
- there is no significant difference notable among different types of biomass inputs
- the poorest conversion rate lays within the ICFB-D (SP) concept because of the focus on other energy form than synthetic fuel

5.2 Evaluation with Industrial Perspective

Beside efficiency of the concepts designed, an evaluation is set up to assess the technical potential and maturity of the different BtL concepts developed within RENEW, taking an **industrial perspective**. The point of this analysis is rather to assess the development status behind the data used (what are the **battery limits** of the concepts, how **detailed** the concept data has modelled, how close/far is the concept in terms of **industrial applicability/practicability**).

Therby two aspects have been analysed: (i) Flexibility of the concept and its (ii) development status.

Flexibility

Besides efficiency, the following flexibility related criteria are also of importance from an industrial viewpoint to compare the different concepts:

- Choice of feedstock: which biomass types and properties can be commercially used (and lower future cost)?
- Choice of end product: which syngas production and clean up concepts can be combined with which synfuel production process ?
- energy integration: what are the opportunities and limiting factors to improve the efficient use of energy by optimised process integration ?

These questions have been analysed based on different indicators (cf. D5.4.2.4.) and are discussed in detail. But based on the knowledge available at present the following conclusion can be drawn:

- Identification of the “most flexible concept” and therewith the potential best industrial performance can not be drawn yet. For each of the three mentioned criteria (feedstock, end product, energy integration) the specific conditions of the BtL industrial plant (i.e type and volume of feedstock, local industrial synergies ...) will have a crucial influence on technical choices and the overall performance will result from optimisation between conflicting goals (like for example maximum biofuel production versus maximum bioenergy production and CO₂ saving). Therewith none of the concepts can be excluded or favoured in general.
- In principle, the feedstock flexibility of the BtL concepts is high because gasification is able to deal with a broad range of type and quality of feedstocks in so far they contain carbon and hydrogen. This is valid for EF but also CFB-gasification. But only a couple of feedstock has already been tested in pilot plants. Commercial application should be technical possible, but need demonstration and verification on an industrial level. For practical reasons (different storage, conditioning and transport systems for different types of biomass), commercial BtL-plants will probably be adapted to 5 - 6 biomass types at maximum.
- Regarding the end product flexibility (or choice of synfuel process) the scale of the envisaged BtL-plant will have a major influence because of economic considerations. For the BtL production in large scale the syngas conditioning can adapt the syngas quality to the synthesis process demands (FT, DME, Alcohols) in principle. As result of these assessment works there is no obvious “show stopper” of product flexibility from a strictly technical viewpoint. This will more or less depend on location specific conditions and economics (economy of scale). But for small (and medium) scale it is obvious from techno-economic viewpoint that the product flexibility is limited. For example the upgrading of FT syncrude into commercial grade fuels and/or blend components can only be implemented in a refinery environment for techno-economic reasons. Thus, for small scale application processes a “lower effort synthesis” (SNG or Methanol) could be one technical option in short- or medium term.

- Since the energetic integration has a high influence on the overall efficiency (see above) and therewith on the BtL-cost it is a main criteria for future plant developments. But in many cases it could be a limitation in finding suitable locations/offsets. For example the high process integration of pulp-mill Annex plants (cf. BLEF-DME concept) leads to high efficiencies but can only be installed directly at such location. The same is true for concepts producing large contents of district heat (as ICFB-D). Therewith this aspect is not limited by the available BtL-technologies but rather by finding suitable locations.

Development Status

Besides efficiency and flexibility, the technical assessment of the different RENEW concepts has been extended to a preliminary qualitative evaluation of the development status of the technologies involved, based on an industrial perspective. A selection of industrially relevant criteria have been analysed regarding the overall concept, the gasification, the gas cleaning and gas conditioning as well. The criteria investigated have been selected because they allow addressing some of the most critical industrial challenges in the implementation of new and complex technologies. The intention is not to request and/or perform in depth studies corresponding to each of them in the framework of the RENEW project but rather to identify those concepts that have started to tackle them and can thus be considered as more industrially advanced. These criteria are essentially based on qualitative assessment and should not be considered as a quantitative measurement of relative maturity of the different concepts:

- Scale up issues: number of steps/needed from actual status up to commercial scale and justification (reactor design, scale up factors, experiences from other plants, calculation method etc.)
- Process design issues: availability of advanced process data (detailed mass and energy balance, utility flows...) reflecting in depth investigation of different process conditions (start of run, mid run and end of run) needed to for the engineering design of the industrial plant.
- Critical items identification, sourcing and management: for example, identification and preliminary selection of reliable catalyst and/or other critical component providers.
- CAPEX/OPEX data: availability, methodology for calculation and level of detail/accuracy of these data gives an indication of the level of industrial development.
- Availability of plot plan, process water flow, HSE studies (HAZOP, HAZID ..): similar to the cost issues the concept development will be influenced by site issues. Thus, the availability/status of site related engineering work gives an indicator on level of development.
- Process modelling status and quality: overall chain process modelling as well as specific process units modelling of mass, thermodynamic, kinetics and/or fluid dynamics data also reveal the level of development for such complex process chains .

Concept scenario	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D	CFB-E
	SP + MF					SP / MF	SP + MF
scale up steps	1,5	(1)	1,5	no gasifier	2	1/2	no gasifier
mass balances (start/end run)	β: existing ε: progress	not available	included	not available			
cat. provider contracted	1	-	3	-	-	(1)	-
CAPEX/OPEX	available	not available	available	simulation level	not available	avail. / n.a.	simulation level
plot plan	available	not available	available	not available	not available	not available	not available
water flow plan	β: existing Σ: progress	not available	available for gasifier	not available	not available	not available	not available
HSE studies	β: existing Σ: progress	not available	not available	not available	not available	partly / n.a.	not available
modelling quality	test data + mass balances	mass balances	(test data +) mass balances	mass balances	mass balances	(test data+) mass balances	mass balances

Figure 5-6: Comparison of Renew-concepts from viewpoint of selected industrial criteria (Scale up factors: number of steps/needed from actual status up to commercial scale; mass balances: knowledge regarding the changes of process conditions under start up/end run; cat. Provider: umber of commercial providers contracted for synthesis catalyst provision in future plants; CAPEX/OPEX: knowledge of capital- and operation-related costs for the main equipment with preliminary sizing data; plot and water flow plan, HSE issues: developments status of project specific plant design assessed by availability of a plot plan and water flow plan and HAZID and/or HAZOP studies; modelling quality: knowledge of quality of data sources of SP5; n.a.-not available)

Based on these industrial indicators it can be concluded that there are significant differences between the Renew concepts in terms of maturity. This results mainly from the different time-frames of process developments of the technology providers (3 up to more than 10 years experiences) and the development focus (from research institutes up to industrial enterprises with different departments for engineering, construction etc.). Regardless these large differences it also has to be pointed out, that none of the concepts can be called “proven technology” that can be bought off-the-shelf. Some of the concepts show a promising maturity justifying the development of a first industrial demonstration project in 50 MW-range together with (industrial) monitoring. Others need further development and demonstration in pilot scale (<10 MW-range) also including monitoring.

5.3 Further Evaluation Criteria with Scientific Perspective

Besides efficiency analysis and assessment from industrial viewpoint, there are further indicators important and essential for a technical realisation of BtL concepts. These indicators – which are of interest from scientific viewpoint but not yet assessable from industrial viewpoint – are summarised in the following regarding (i) maturity and (ii) flexibility aspects. This is done for the overall concept, the gasification and the gas cleaning and gas conditioning respectively. Both aspects as well as the efficiency analysis are the basis for the target oriented multicriterial aggregation in chapter 6.

5.3.1 Maturity

Besides efficiency, there are further indicators important and essential for a technical realisation of BtL concepts. These indicators are summarised regarding maturity aspects and presented in the following chapter. This is done for the overall concept, the gasification and the gas cleaning and gas conditioning respectively. Later, the selection and character of indicators will be checked and adopted by industrial experts. They are defined and justified (why does it make sense to have a look on this indicator, etc.) in the annex in chapter 9.6.

Overall Concept. The definition and justification of the following indicators can be found in the annex in chapter 9.6.1. The results are summarised in Table 5-1.

The indicator 'development stage – single components' describes how many of the system components are already in industry application. The BLEF-DME concept shows the best results due to the application of mature system components. The ethanol concepts are very theoretical and have therefore a low score.

The indicator 'development stage – R&D facilities' describes the development stage of existing technology at the test facilities regarding a running overall process. The highest scores are obtained by the concepts which are based on existing demo plants (cEF-D and ICFB-D (50 MW)). Again the ethanol concepts show low scores since the concept is based on principal options.

The parameter 'upscale steps' indicates how many steps are necessary for the gas production based on the local available technology. Here all concepts are more or less in the same range.

The parameter 'investment cost data' reflects whether the information on investment cost is available for single components or not, i.e. how close are the concepts to practical realisation. For the concepts cEF-D, BLEF-DME and ICFB-D this data is available, for the ethanol concepts not. The dEF-D concept's information is available for the overall plant but not for the single components.

The indicator 'technical design' specifies how the concepts was developed and on what it is based on (simulation, literature, existing lab- or demo plants). The BLEF-DME concept shows the maximum result since the simulation is implemented practical data from all system components. The indicator 'investment costs of the concepts' reflects whether a concept is limited by economical feasibility. Here, the economy-of-scale is clearly notable.

The evaluation of these indicators is done in chapter 6.1.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D Wood / straw	ICFB-D 50/500 MW	CFB-E
development stage 'single components' [%]	84	86	92	71	78 / 73	81 / 85	63
development stage 'R&D facilities' [%]	72 ^C	45	42	25	50	70 / 38	25
upscale steps [-]	1,5	1	1,5	1 ^A	2	1/2	2 ^B
Investment cost data	+++	+	+++	-	++	+++ / ++	-
technical design [%]	81	59	100	75	81	90 / 88	75
Investment costs of the concept [T€/MW]	ca. 720	ca. 740	ca. 500	ca. 740 ^A	ca. 920	ca. 1400 / ca. 920 ^B	ca. 920 ^B

Table 5-1: Indicators on Maturity for the Overall Plant

^A assumed to be the same as dEF-E; ^B assumed to be the same as ICFB-D (500 MW); ^C since β -plant is not yet operated the result is calculated from average of α and β -plant; % = % of best possible score

Gasification. The definition and motivation of the indicators can be found in the annex in chapter 9.6.2. The results are summarised in Table 5-2.

The same definition as in the previous chapter can be applied for the first four indicators. No gasification unit is fully developed. The development stages of the gasification units are similar, except of the theoretical ethanol concepts.

The development stages of the gasification R&D facilities are fully developed for the concepts cEF-D (beta-plant), dEF-D and ICFB-D 50 MW and not existing for the ethanol concepts.

The information on investment cost data is available for most of the concepts. The technical design of almost all concepts is mature as well as the fact that most of the gasifiers are able to scale up to 500 MW in one single line. The maximum pressure reflects the limit for advantageous pressurized gasification (less effort on compression and gas cleaning). The EF concepts are the best suited for this purpose. The feeding system is standard 'off-the-shelf' technology and thus all concepts show here good results.

The evaluation of these indicators is done in chapter **6.2**.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Development stage 'single components' [%] (see 9.6.1.1)	++	++	+	++ ^C	+/-	++/+	-
Development stage 'R&D-facilities' [%] (see 9.6.1.2)	++/+++	+++	++	-	+	+++/-	-
Investment cost data available (see 9.6.1.4)	Yes	No	Yes	No	Yes	Yes	No
Technical design [%] (see 9.6.1.5)	+++	+++	+++	++	+++	+++	++
500 MW single-line [-]	1	1	1	1	1	5/1	5
Maximum pressure	30 bar	80 bar	80 bar	80 bar	n.a.	n.a.	n.a.
functionality feeding system	+++	+++	+++	+++ ^A	++(+)	++(+)	++(+) ^B

Table 5-2: Indicators on Maturity for the Gasification Unit

n.a. = not available, ^A assumed to be the same as dEF-D; ^B assumed to be the same as ICFB-D (500 MW); ^C assumed to apply the same reactor as dEF-D

Gas Cleaning and Gas Conditioning. The definition and motivation of the indicators can be found in the annex in chapter 9.6.3. The results are summarised in Table 5-3.

The same description as in chapter 0 can be applied for the first four indicators. Based on the listed indicators, the following results can be drawn:

Gas Cleaning. Almost all concepts show a high maturity of the planned gas cleaning units. The barriers for the CFB-D and the ICFB-D 500 MW concepts are the lab scale tar crackers and biodiesel washers. The R&D facilities are poor of most of the concepts.

Only the cEF-D and the ICFB-D 50 MW concept can base on good facilities. Investment cost data is available for four concepts and the technical design (simulation) is good for almost all concepts except for dEF-D since the gas cleaning part was neglected in this concept.

Gas Conditioning. The foreseen gas conditioning units of all concepts are mature. The R&D facilities for gas conditioning are only principal options except in the cEF-D concept. Investment cost data is only available for half of the concepts and the technical design is good for almost all concepts except for dEF-D where the outcome of this unit is only a rough estimation.

In general the gas cleaning and gas conditioning units are approved in commercial syngas plants and the investment costs reflect again the economy-of-scale regarding the small ICFB-D 50 MW concept and another fact: the EF concepts are more sophisticated in gasification but the produced raw gas contents less impurities, resulting in a lower gas cleaning and gas conditioning effort.

The evaluation of these indicators is done in chapter **6.3**.

Concept		cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Development stage 'single components' [%] (see 9.6.1.1)	Clean.	++	+++	+++	++	- ... + ^B	+/ ^B +++	- ^B
	Cond.	+++	+++	+++	+++	+++	n.e./+++	+++
Development stage 'R&D-facilities' [%] (see 9.6.1.2)	Clean.	++/+++	-	-	-	+	+++/-	-
	Cond.	++/-	-	-	-	+	n.e./-	-
Investment cost data available (see 9.6.1.4)	Clean	Yes	No	Yes	No	Yes	Yes	No
	Cond.	Yes	No	Yes	No	No	Yes/No	No
Technical design [%] (see 9.6.1.5)	Clean.	++	-	+++	++	++(+)	+++	++
	Cond.	++	+	+++	++	++	n.e./++	++
Investment cost (T€/MW biomass input)	C&C	149	188	179	179 ^C	245	716/ 245 ^A	245 ^A
Experiences/Ratio of Commercial Systems	+++	+++	+++	++	++	++	++	+++

Table 5-3: Indicators on Maturity for the Gas Cleaning and Gas Conditioning Unit

n.e. – not existing, ^A assumed to be the same as ICFB-D (500 MW); ^B tar cracker only in lab scale, biodiesel-washer only in t/h-scale; ^C assumed to be same as BLEF-DME; % = % of best possible score

5.4 Feedstock and Product Quality

Besides efficiency, there are further indicators important and essential for a technical realisation of BtL concepts. In the previous chapter the focus was on maturity. Another important indicator is 'feedstock and product quality'. These indicators are presented and evaluated in the following chapter. The selection and character of indicators will be checked and adopted by industrial experts. Also these indicators are defined and well-founded (why does it make sense to have a look on this indicator, etc.) in the annex in chapter and 9.7.

Overall Concept. The definition and motivation of the indicators can be found in the annex in chapter 9.7.1. The results are summarised in Table 5-4.

The indicator 'feedstock flexibility' reflects the percentage of the European biomass potential usable the foreseen plant. All concepts show more or less high feedstock flexibility except BLEF-DME where only black liquor can be gasified.

The parameter 'infrastructure feedstock provision' indicates if provision concepts are available for the applied feedstock or not. The small (ICFB-D 50 MW) and decentral (dEF-D) concepts can be based on a mature provision chain while the infrastructure for large central concepts is there but not yet adopted to the requirements of this feedstock flows. In general, it will be difficult to supply sustainably harvested feedstock of this magnitude to single 500 MW BtL plants. The biomass input is on average about 140 tons per hour.

The parameter 'infrastructure for feedstock provision' indicates whether a concept (infrastructure) for product distribution is available or not, related to motor applicable fuels. The main product of many concepts is diesel, which is blendable. The distribution infrastructure for other fuels (DME and ethanol) has to be adopted.

The indicator 'product quality' shows whether commercial technology is available and necessary for product upgrading on motor fuel quality. For almost all products, no further upgrading is necessary (or already foreseen in the concept) except the CFB-D and ICFB-D concepts which require such an upgrading (see also chapter 9.2).

The amount of ash residues at a biomass input of about 140 t/h is around the magnitude of 5 t/h, making an ash recycle concept very important. The handling of ash residues differs among the countries and depends strongly on legislation. The ash of the BLEF-DME concept can be used best since the biomass is not gasified but burned and used for steam and power generation. Thus only grate ash is left as residue which is much easier to handle than fly or filter ash. The other evaluation results may be taken from the legend of Table 5-4.

The evaluation of these indicators is done in chapter 6.1.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D Wood / straw	ICFB-D 50/500 MW	CFB-E
Feedstock flexibility [%]	75	56	5	75	75	75	75
infrastructure feedstock provision [-]	+	++	+	+	+	++/+	+
infrastructure product distribution[-]	++	++	+	+...++	++	++	+...++
product quality [-]	+++	+++	+++	+++	+	+	+++
ash reuse concepts	+ ^B	+ ^B	++ ^A	+ ^B	- ... + ^C	+	+

Table 5-4: Indicators on Feedstock and Product Quality for the Overall Plant

^A only grate ash from combustion process, slag would require further upgrading for forestry/agric. usage (e.g. milling); fly ash shows higher content of heavy metals in general, ^B Max. fulfillment 5 pts, Min. fulfillment 1 pt., ^C higher carbon content assumed would require further thermal treatment before disposal or use; % = % of best possible score

Gasification. The definition and justification of the indicators can be found in the annex in chapter 9.7.2. The results are summarised in Table 5-5.

The indicator 'effort on preparation of gasification media' describes the need of basic operations for feedstock pretreatment. The BLEF-DME concept along with the CFB-D and CFB-E concepts shows the least effort while a thermochemical feedstock pretreatment is a sophisticated task in the other concepts (low-temperature gasification, flash pyrolysis and torrefaction).

The parameter 'limitation for ash content' shows the requirements of the applied gasification on the feedstock. It is varying very much and has to be further discussed with the gasifier developers.

The evaluation of these indicators is done in chapter 6.2.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
effort on preparation of gasification media	+	+	+++ ^A	+	+++ / ++	+++	+++
limitation for ash content [%]	Max. 15	1 -30	Min. 15	1 -30 ^C	Max. 40 ^B	Max. 40	Max. 40 ^B

Table 5-5: Indicators on Feedstock and Product Quality for the Gasification Unit

^A black liquor is considered as available residue; i.e. the effort within the pulp and paper mill is not considered; ^B assumed to be the same as ICFB-D (500 MW); ^C assumed to be the same as dEF-D; % = % of best possible score

Gas Cleaning and Gas Conditioning. The definition and justification of this indicator can be found in chapter 9.7.3. The result is shown in Table 5-6.

The indicator ‘syngas quality’ describes whether the produced syngas fits the requirements of the applied synthesis. The concepts dEF-D and BLEF-DME apply a rectisol unit, which is well adapted and commercially proven technology. The other concepts use technologies which are adapted for tolerant synthesis but not yet commercially proven.

The evaluation of this indicator along with other indicators is done in chapter 6.3.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Syngas quality	++	+++	+++	+	+	++/+	+

Table 5-6: Indicator on Feedstock and Product Quality for the Gas Cleaning and Gas Conditioning Unit

6 Target-oriented Multicriteria-Aggregation and Evaluation

In this chapter, the results on technical assessment for each considered unit are shown, explained and evaluated. First the results of the secondary goals will be presented and then summarized to the primary goals by different weighing in each sub-chapter. In addition, a sensitivity check will be done like described chapter 4.3.2.

Thereby these aggregations are not based on the evaluation with industrial perspective (chapter 5.2) since the an aggregation on these criteria would only lead to significant differences under local specific concept development and more detailed plant engineering. Thus, the following summary is an scientific aggregation of the efficiency criteria as well as the entirety of scientific aspects shown in chapter 5.3.1 and 5.4.

6.1 Overall Plant

The overall plant is assessed using the defined and weighted criteria described in the annex in chapter 9.8 (Table 9-35, Table 9-38 and Table 9-43).

6.1.1 Secondary Goals

Based on the assessment of the indicators in chapter 4 and the specification of the TA method in chapter 4.3 the criteria are multiplied with their according weighting factors and summarized in three secondary goals:

- *'high efficiency'* (focus on 'primary energy equivalent and conversion plant efficiency')
- *'high maturity'* (focus on 'development stage')
- *'high feedstock and product quality'* (focus on 'feedstock flexibility and infrastructure for product distribution')

The weighing factors are listed in chapter 9.8 (Table 9-35, Table 9-38 and Table 9-43). Resulting from Figure 6-1 the following conclusions can be drawn:

Efficiency. The evaluation of this secondary goal - which was focusing both conventional calculations (conversion plant) and primary energy based calculations - is concluding in the following:

- the score of the BLEF-DME concept is by far the best concept considered due to a high process integration

- the second highest points are achieved by the ICFB-D (MF) concept, although this is not reliable due to information lacks on steam data of process internals (see chapter 5.1)
- high scores are accomplished by the cEF-D (SP) and the ICFB-D (SP) concepts; reason: high process integration
- the MF scenarios of the cEF-D and the dEF-D concepts are less positive than their SP scenarios. This is mainly a result of large electricity consumption for hydrogen production.
- the other concepts show little results in overall efficiency due to various reasons (see chapter 5.1.1)

generally, the differences in efficiency are similar to the results in chapter 5.1.1. In this criterion 'overall efficiency' all different definitions have been led together and so the influence of the efficiency definition was minimized. The main results are still the same, provided that fuel production is the target and proving that the main statements on overall efficiency are correct.

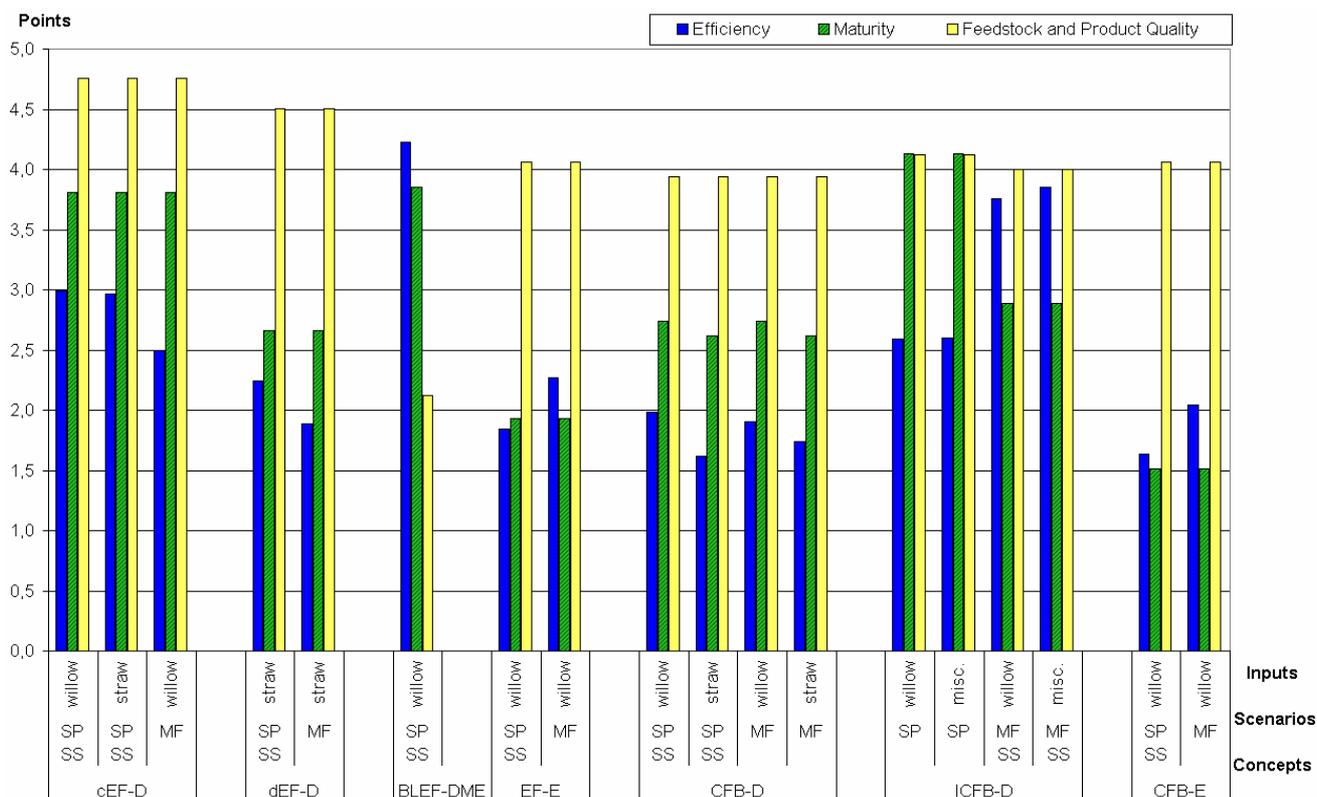


Figure 6-1: Overall Plant – Secondary Goals ‘Efficiency, Maturity, Feedstock and Product Quality’

Maturity. The focus of this secondary goal was on the development stage of the concept and resulted in the following:

- the concepts cEF-D, BLEF-DME and ICFB-D (SP) are having the highest overall maturity because of a high development stage of the foreseen single components, good R&D facilities and a high quality technical design based on simulation with implemented pilot and demo plant data

- the concepts EF-E and CFB-E show little maturity due to a low development stage in all areas and no information on investment cost (and thus very distant from practical realization)
- other concepts are in the range of average maturity of the overall plant
- concluding the concept based on real existing demonstration plants (cEF-D, BLEF-DME and ICFB-D) are the most promising for commercial application

Feedstock and Product Quality. This goal was focused on the feedstock flexibility of the concepts and the infrastructure for product distribution; the following can be concluded:

- for most of the concepts the scores are in the same, quite high range
 - the best score was obtained by the cEF-D concepts due to a broad feedstock flexibility, an existing infrastructure for the main fuel and an upgrading of the raw product to main fuel (Diesel) at plant site (high fuel quality)
 - the dEF-D concept also scored very high as a result of a very good infrastructure for feedstock provision (decentral concept) and as well a good infrastructure for product distribution and high fuel quality
 - as well the ethanol concepts have good results due to a good applicability of ethanol on the market at present
- the BLEF-DME concept shows a low result because of little feedstock flexibility (only black liquor can be gasified) and the product distribution infrastructure is not yet existing for DME

Sensitivity Check. The sensitivity check was done by setting the security factors of all criteria to 1. The result of this is that the basic statements and conclusions are the same like with the initial security factors. This applies as well for the relations among the concepts.

6.1.2 Primary Goals

Based on the previous assessment, the secondary goals are summarized and weighted regarding two focuses:

- 'high technical performance' (focus on 'efficiency')
- 'good industrial applicability' (focus on 'maturity' and 'feedstock and product quality')

The weighing factors are listed in chapter 9.8 (Table 9-33 and Table 9-34). The data quality in the analysis of the primary goals is considered to be equal to exclude this parameter from the results and make sure that they are independent. The sensitivity analysis of these results will be done in chapter 6.1.3.

High Technical Performance. This primary goal was formed by weighing and summarizing the secondary goals. The focus was on ‘efficiency’.

Resulting from Figure 6-2 the following conclusions can be drawn:

- in terms of the technical performance the cEF-D, the BLEF-DME and the ICFB-D (MF) concepts yield the highest results, mainly due to a high overall efficiency (BLEF-DME, ICFB-D (MF)) and a good and well designed concept with high efficiency, high maturity and high product quality (cEF-D)
- the ICFB-D (SP) concepts is of similar performance, resulting from the highest maturity among the concepts and good feedstock and product quality
- the MF scenarios of cEF-D and dEF-D have a lower technical performance by reason of lower efficiency (large electricity demand for hydrogen production)
- the EF-E, CFB-E and the CFB-D concepts attain the lowest results, based on low efficiencies and low maturity of the overall concepts

Good Industrial Applicability (Close to Practical Realisation). In this primary goal the focus was less on (theoretical) efficiencies but more on ,maturity’ and market-ability.

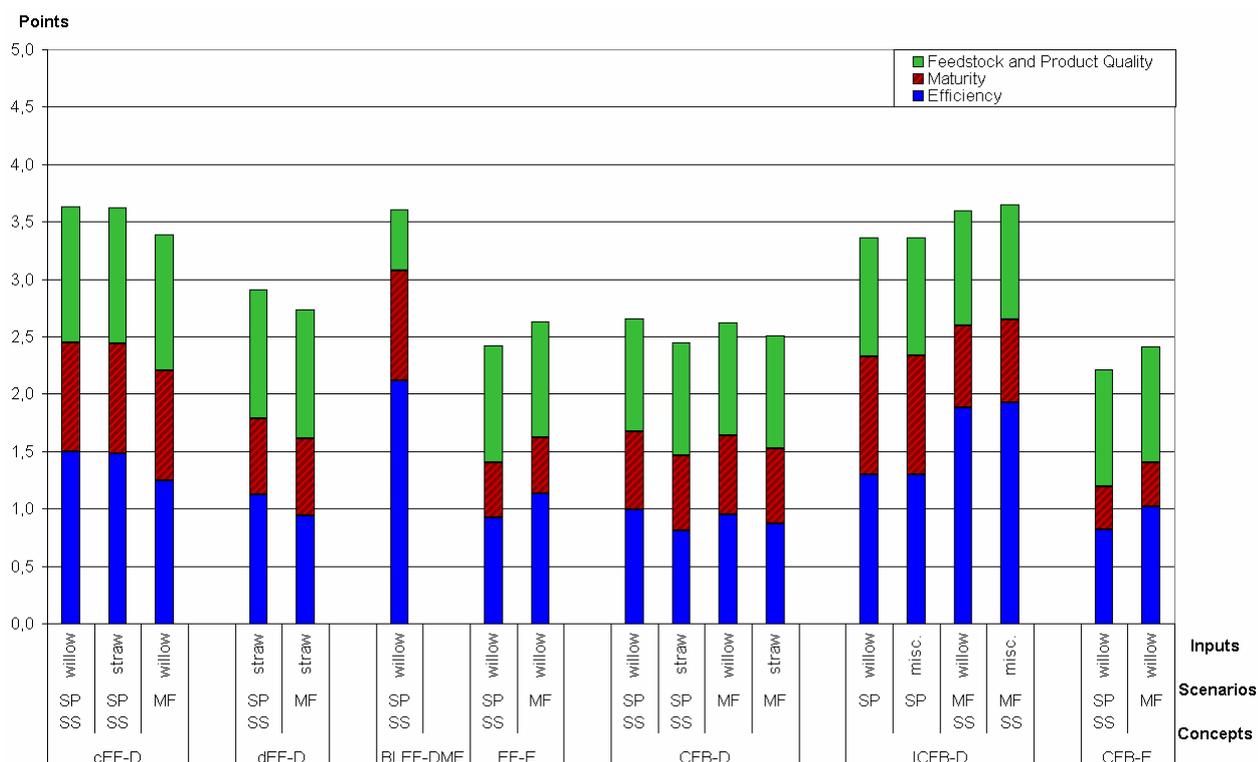


Figure 6-2: Overall Plant – Primary Goal ‘High Technical Performance’

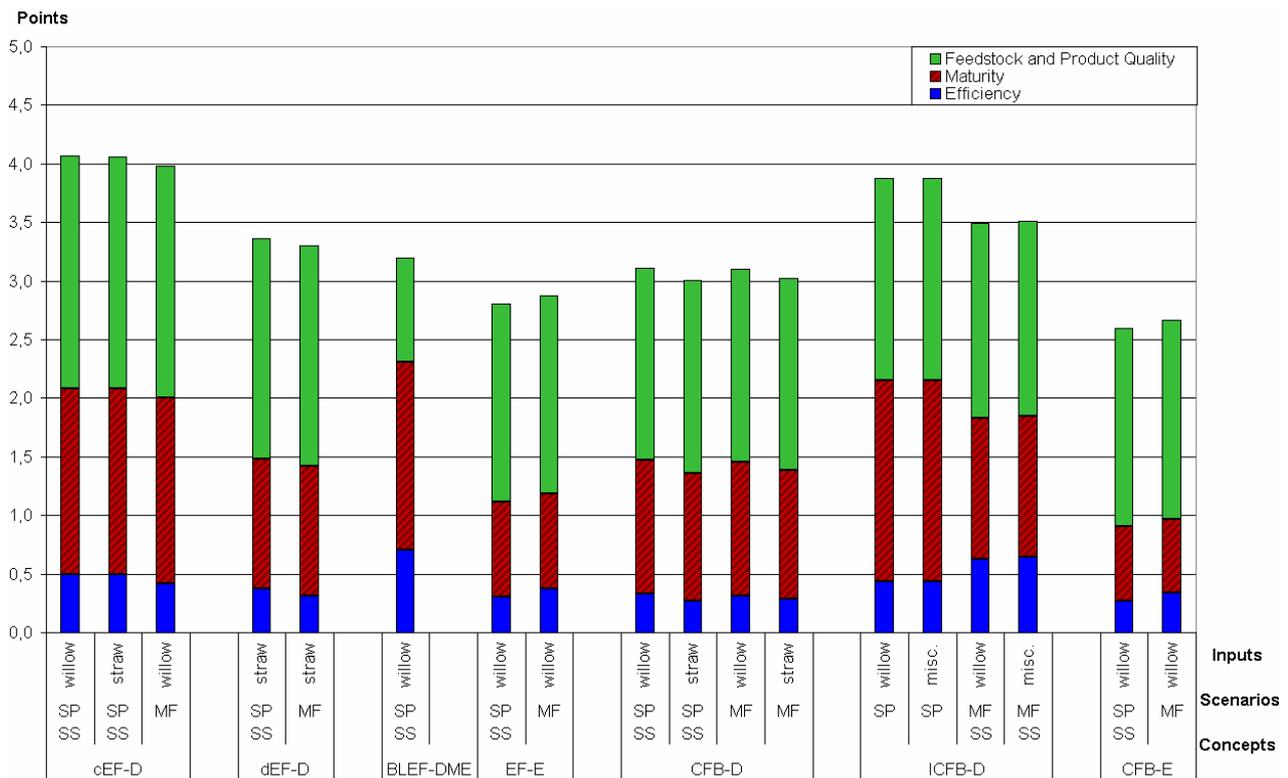


Figure 6-3: Overall Plant – Primary Goal ‘Industrial Applicability’

Resulting from Figure 6-3 the following conclusions can be drawn:

- the highest score is accomplished by the cEF-D and the ICFB-D (SP) scenarios because of the highest maturity among the concepts (existing pilot and demonstration plants); thus these concepts are the closest to practical realization
- the EF-E and CFB-E concepts obtain the lowest score due to poor efficiencies and little maturity, resulting from the more or less theoretical background of these concepts; despite the currently good possibilities of a market implementation of synthetic ethanol
- the score of BLEF-DME concept is only middle-class not because of being close to practical realization (the longest research experience in this field, demonstration plants, etc.) but due to less market possibilities (only in combination with a pulp mill) and the problematic introduction of DME (new infrastructure and motor technology)
- the other concepts are in the middle field and thus on the way to industrial applicability

6.1.3 Sensitivity of Primary Goals

In this chapter, the methods described in chapter 0 are applied for sensitivity analysis.

Variation of Secondary Goals Weighing Factors. A different weighting of secondary goals is leading to a variation of primary goals which are compared with the initial values.

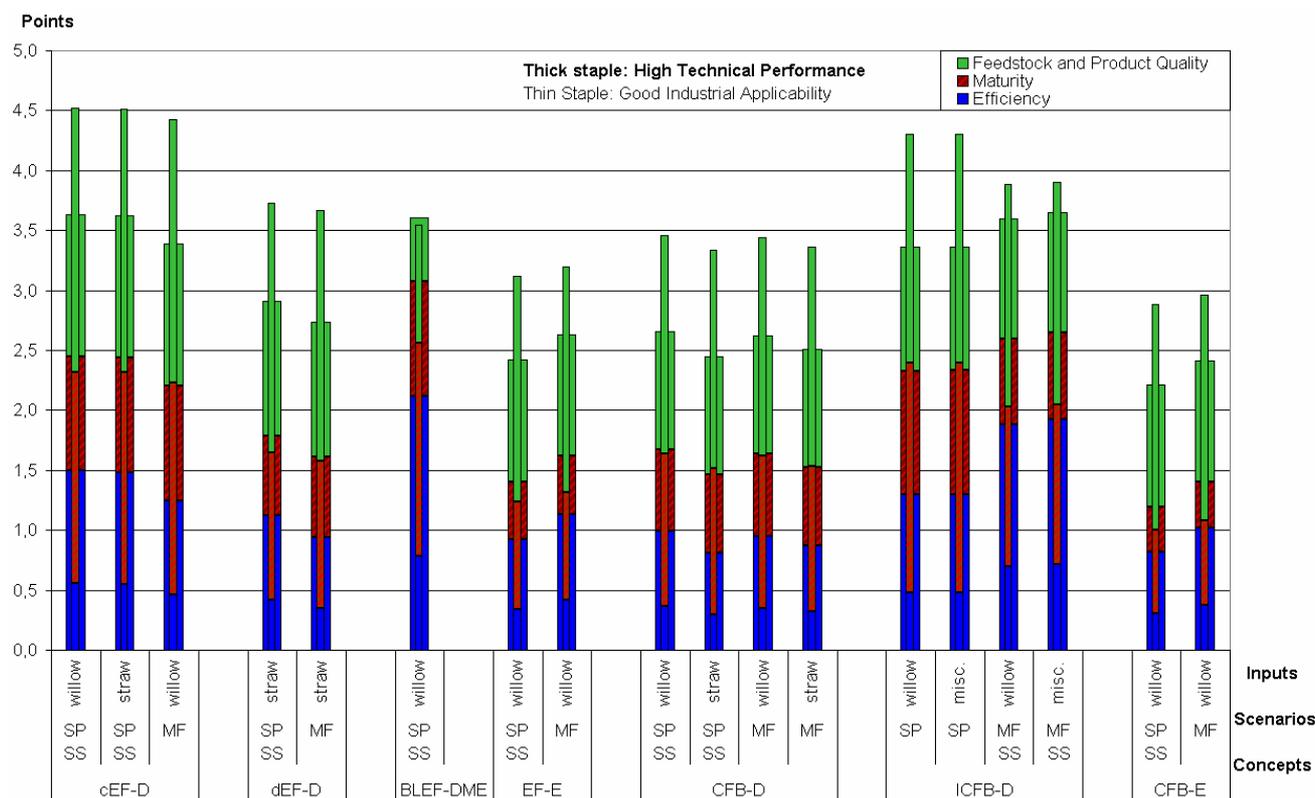


Figure 6-4: Overall Plant – Sensitivity of Primary Goals – Weighing Factors

Resulting from Figure 6-4 the following conclusions can be drawn:

- most concepts show higher points when the focus is more on the secondary goals ‘maturity’ and ‘feedstock and product quality’
- BLEF-DME is the only exception, where the biggest efficiency in PG1 and the little feedstock flexibility are balancing the results of weighing factor variations
- the variation between the MF and SP scenarios are smaller in PG2; i.e. these concepts could be theoretically implemented; yet this would not be useful from an energetic point of view. The variations are mainly due to different weighting of the subgoals

Variation of Data Security Factors.

Now the data security factors are varied to see what happens if some criteria are emphasized or damped. The following variations are applied:

- PG1: the security factor of efficiency is raised to 1 (others are left constant at 0,66)
- PG2: the security factors of maturity & feedstock and product quality is raised to 1 (efficiency left constant at 0,66)

Variation of Data Security Factors in PG1 and PG2.

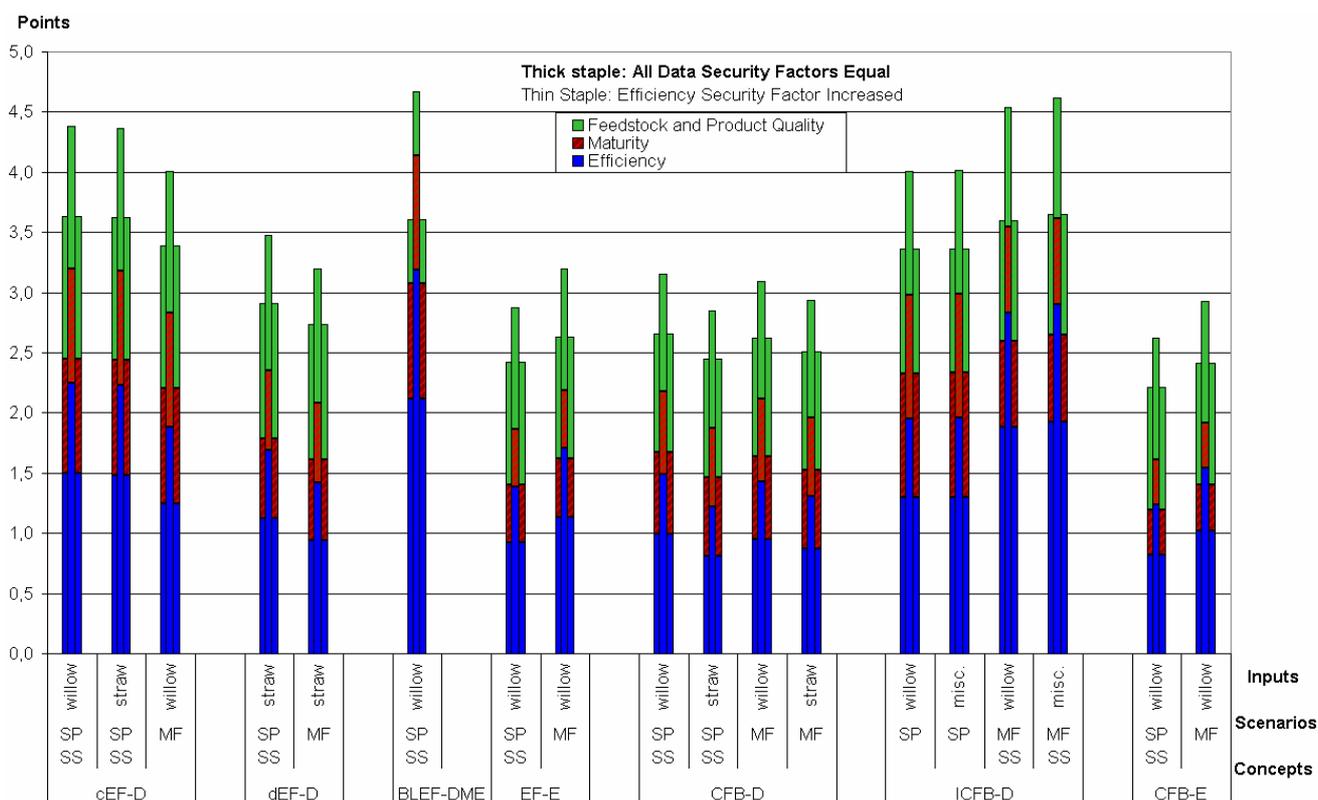


Figure 6-5: Overall Plant – Sensitivity of Primary Goals – Data Security Factors PG1

The sensitivity of PG1 and PG2 was checked (see Figure 6-5 for PG1). The results vary a bit in one direction (both for PG1 and PG2). Yet in general the results and basic relations among the concepts are the same; thus the method chosen is independent and giving an objective view on the concepts.

6.2 Gasification

The gasification unit is assessed using the defined and weighted criteria described in the annex in chapter 9.8 (Table 9-36, Table 9-39 and Table 9-43).

6.2.1 Secondary Goals

Based on the assessment of the indicators in chapter 4 and the specification of the TA method in chapter 4.3 the criteria are multiplied with their according weighting factors and summarized in three secondary goals:

- 'high efficiency' (focus on 'primary energy equivalent and conversion plant efficiency')
- 'high maturity' (focus on 'development stage')
- 'high feedstock and product quality' (focus on 'feedstock flexibility and infrastructure for product distribution')

The weighing factors are listed in chapter 9.8 (Table 9-36, Table 9-39 and Table 9-43).

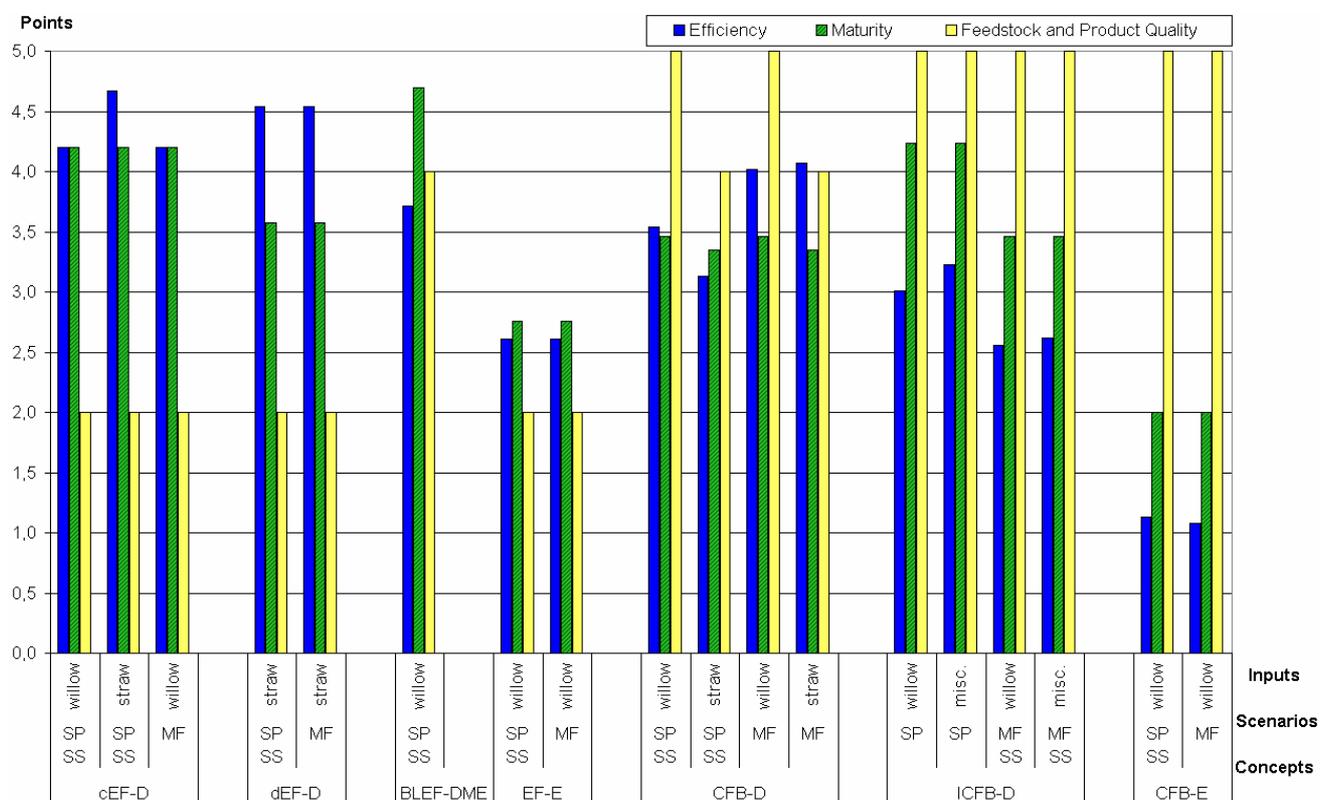


Figure 6-6: Gasification – Secondary Goals 'Efficiency, Maturity, Feedstock and Product Quality'

Resulting from Figure 6-6 the following conclusions can be drawn:

Efficiency. The focus in this evaluation was the biomass based gasification efficiency, i.e. how much raw gas power could be extracted from the feedstock.

- the gasification efficiency of the cEF-D concept along with the dEF-D concept are the best among the concepts considered
- the difference between the willow and straw scenarios within the cEF-D concept originates from leaving out the biomass drying for straw
- the very good result of the dEF-D concept is based on theoretical calculations

- the CFB-D concepts have in general less points than the EF concepts (with EF-E as exception); this is due to the methane content in the raw gas
- the CFB-D (SP) straw scenario gains less points because of a higher preparation effort (pelletising)

Maturity. The focus of this secondary goal was on the development stage of the gasification unit. Out of this consideration, the following can be concluded:

- the concepts cEF-D, BLEF-DME and ICFB-D (SP) are having the highest overall maturity because of a high development stage of single components and R&D facilities and high quality technical design; the BLEF-DME concept shows the best results among these three concepts due to a high possible maximum pressure for the gasifier and the high redundancy of the 500 MW concept (there will be 4 x 167 MW reactors installed ($4 \times 33\% = 133\%$ of full load)), other concepts have not shown an equal 'backup strategy'
- the concepts EF-E and CFB-E show little maturity due to a low development stage in all areas; the EF-E concept is better than the CFB-E concept due to higher possible pressures for gasification
- other concepts show average maturity of the gasification unit

Feedstock and Product Quality. This secondary goal is based only on two indicators ('effort on preparation of gasification media' and 'limitation for ash content') which are of equal importance / focus. Their data quality is only 'quite good' (value: 0,66) (see indicator evaluation in chapter 0).

- the scores of the CFB concepts are much higher than of the EF concepts due to less effort on gasification media preparation (here, the biomass is mostly used directly; no thermochemical pretreatment necessary like in the EF-scenarios)
- another influence on these high CFB results was the limitations of ash content for the EF scenarios
- the only exception among the EF scenario is BLEF-DME, since black liquor is used as gasification media which is a 'residue' of a pulp mill

Sensitivity Check. The sensitivity check was done by setting the security factors of all criteria to 1. This resulted in the following:

- the maturity within the BLEF-DME concept rose a bit while the maturity of the cEF-D concepts decreased; this is due to a higher weighing of criteria which are also part of the overall maturity, where the BLEF-DME shows better results
- the other basic statements and conclusions are the same like with the initial security factors, the relation among the concepts was maintained

6.2.2 Primary Goals

Here the secondary goals in gasification are summarized and weighted regarding two focuses:

- ‘high technical performance’ (focus on ‘efficiency’)
- ‘good industrial applicability’ (focus on ‘maturity’ and ‘feedstock and product quality’)

The weighing factors are listed in chapter 9.8 (Table 9-33 and Table 9-34). The data quality in the analysis of the primary goals is considered to be equal to exclude this parameter and give independent results. The data quality parameters will be modified in the sensitivity analysis of these results in chapter 6.2.3.

High Technical Performance. This primary goal was formed by weighing and summarizing the secondary goals. The focus was on ‘efficiency’.

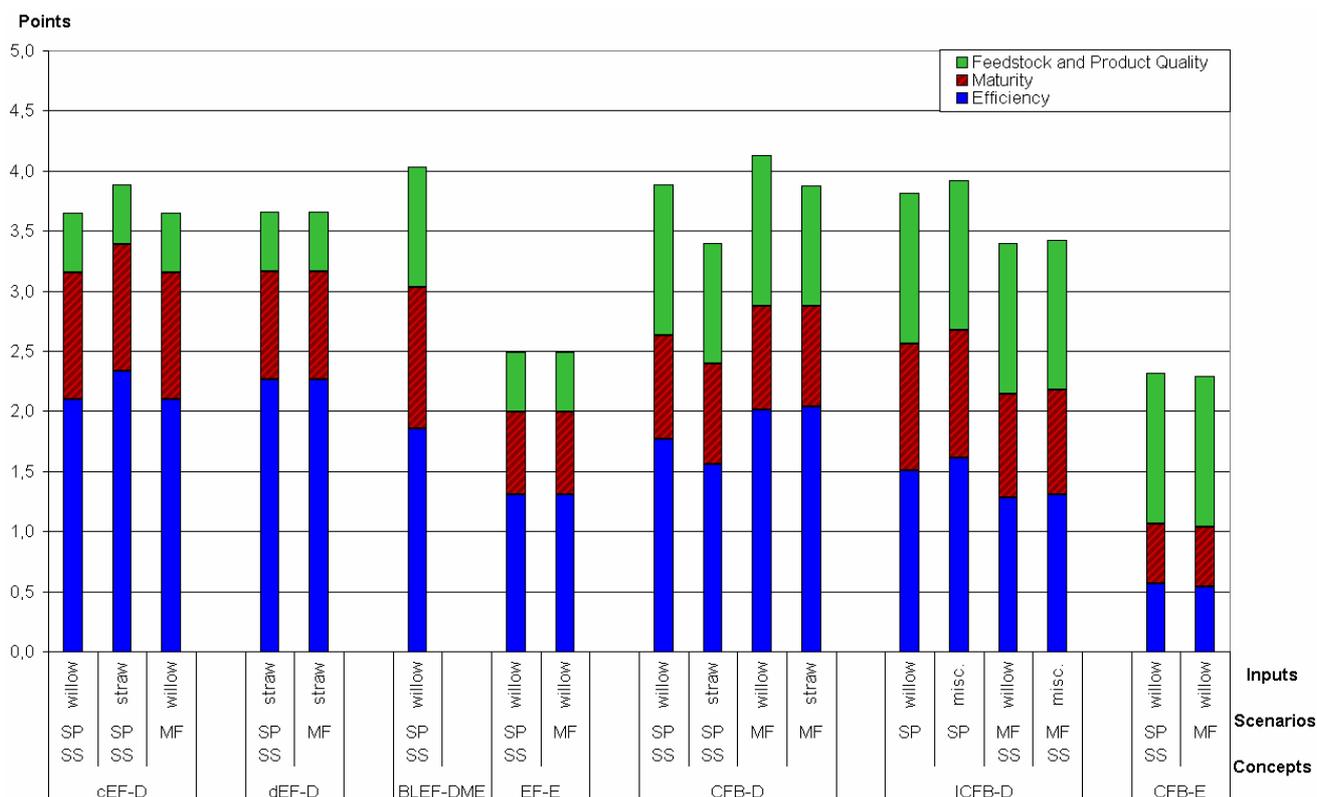


Figure 6-7: Gasification – Primary Goal ‘High Technical Performance’

Resulting from Figure 6-7 the following conclusions can be drawn: The EF scenarios are ‘stronger’ in efficiency, but ‘weaker’ in feedstock and product quality due to the reasons named in the previous chapter ‘secondary goals’ of gasification resulting in a similar performance (except in the theoretical ethanol concepts).

Further there is no clear trend comparing SP scenarios with MF scenarios. Generally, the performance of most of the gasification concepts is quite high and at one (similar) level; the only exception are the ethanol concepts, where poor efficiency and little maturity influence the result negatively.

Good Industrial Applicability (Close to Practical Realisation). In this primary goal the focus was less on (theoretical) efficiencies but more on the concept's 'maturity' and market-ability.

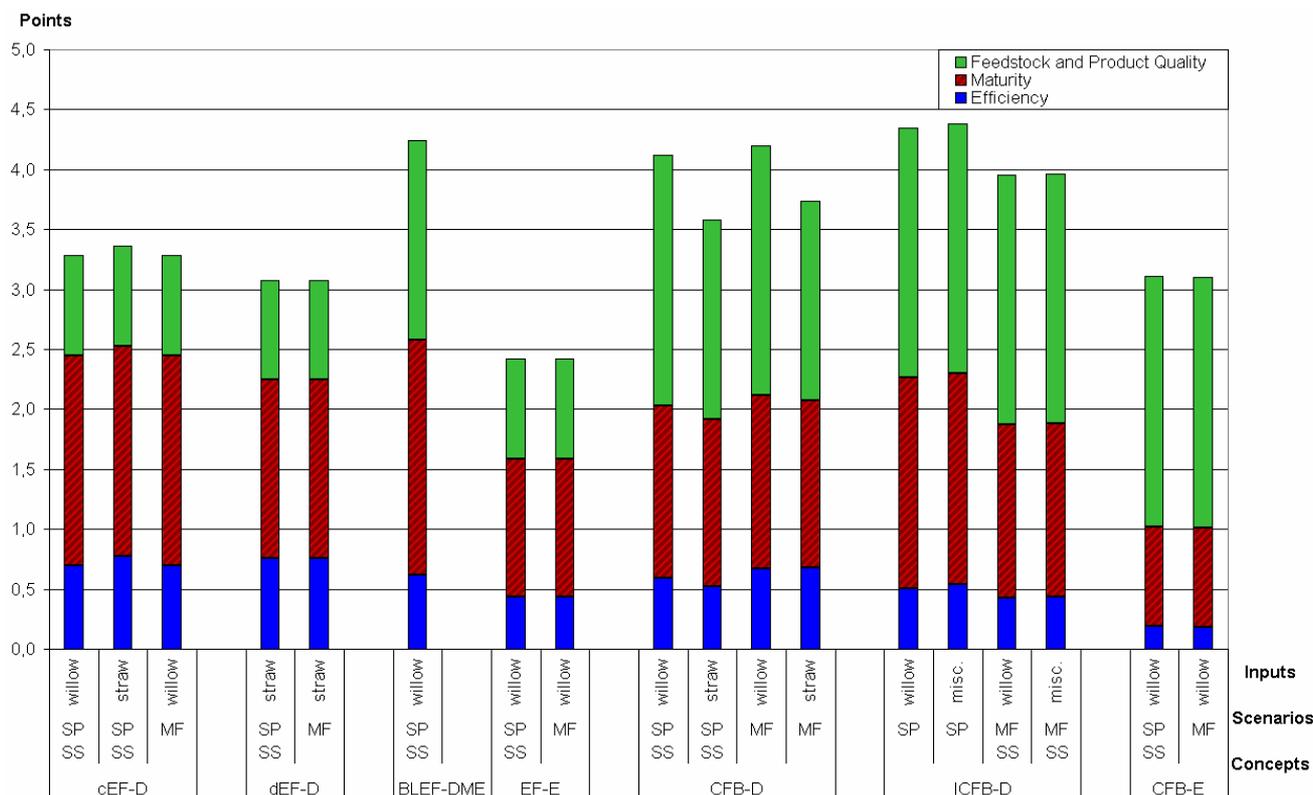


Figure 6-8: Gasification – Primary Goal 'Industrial Applicability'

Regarding the results (Figure 6-8), the following can be concluded: The industrial applicability is differing much from the technical performance. The CFB gasification concepts and the liquid residue based BLEF-DME gasification concept are clearly stronger than the others. There is a need for further R&D for these other EF concepts with regard to the feedstock pretreatment and the gasification conditions (feedstock grain size and pressure).

6.2.3 Sensitivity of Primary Goals

In this chapter, the methods described in chapter 0 are applied for sensitivity analysis.

Variation of Secondary Goals Weighing Factors. A different weighting of secondary goals is leading to a variation of primary goals which are compared with the initial values.

Resulting from Figure 6-9 the following conclusions can be drawn: The basic results do not change by variation of the weighing factors. The EF scenarios can keep up with the CFB gasification concepts in terms of 'high technical performance'; regarding good industrial applicability, the CFB concepts are favourable (mainly due to less effort on gasification media preparation; only exception: BLEF-DME).

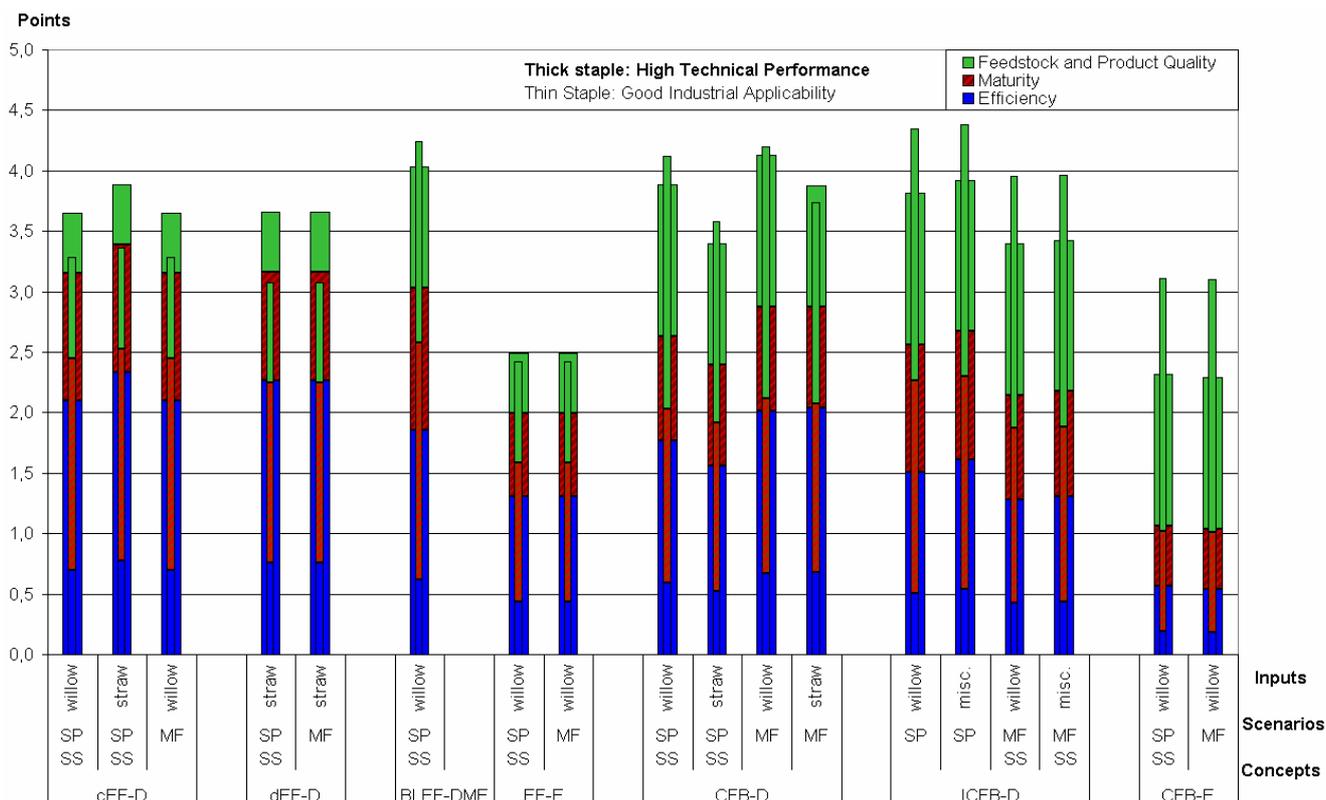


Figure 6-9: Gasification – Sensitivity of Primary Goals – Weighing Factors

Variation of Data Security Factors.

Now the data security factors are varied to notice what happens if some criteria are emphasized or damped. The following variations are applied:

- PG1: the security factor of efficiency is raised to 1 (others are left constant at 0,66)
- PG2: the security factors of maturity & feedstock and product quality is raised to 1 (efficiency left constant at 0,66)

Variation of Data Security Factors in PG1 and PG2. The results and relations among the concepts are the same (see Figure 6-10 for PG1). Some concepts show a stronger increase in the result (cEF-D and dEF-D) which indicates a dependency of data quality and final results for the gasification unit. In this context the efficiency data can be assumed as secure (under the conditions described in chapter 4.4.1) and thus the final result is a high and comparable equal score of the named scenarios. The variation of data security factors in PG2 did also not bring out new results (the scores were differing only +/- 3% of the original ones).

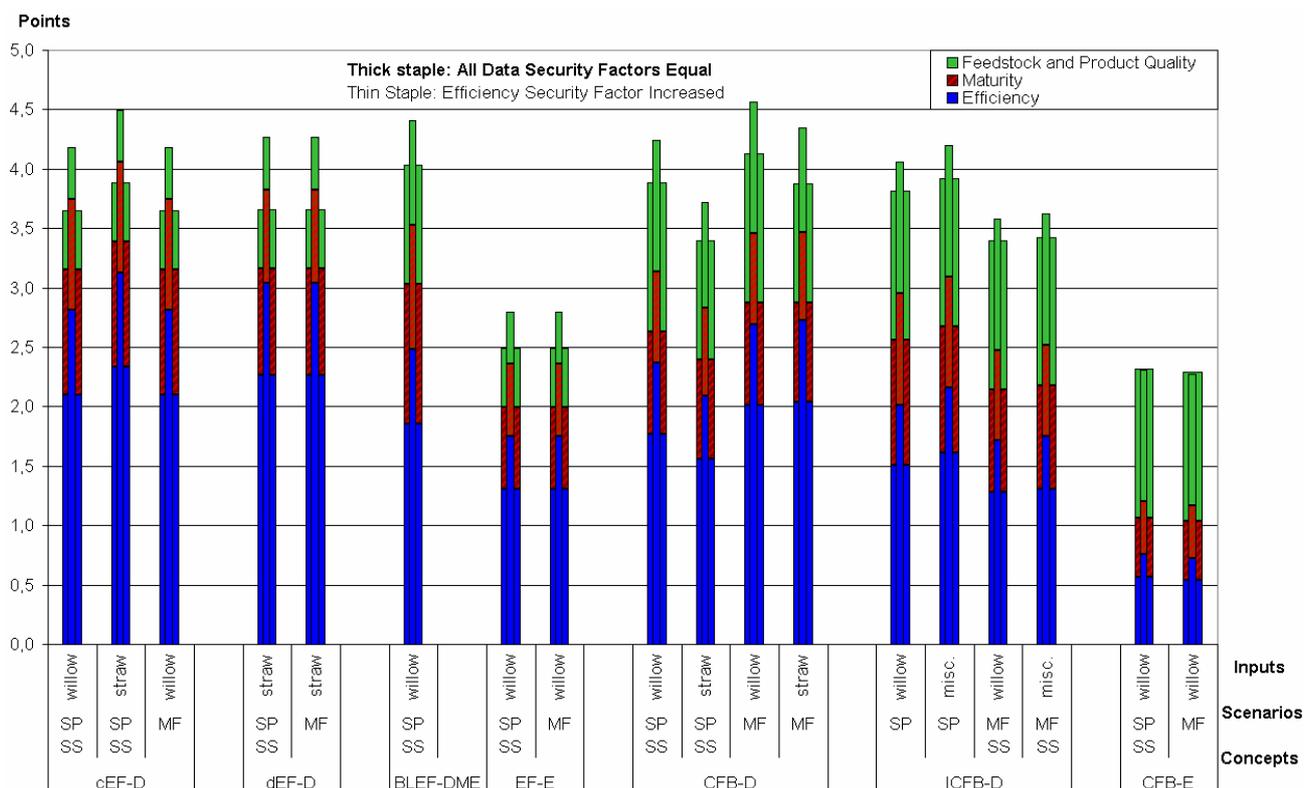


Figure 6-10: Gasification – Sensitivity of Primary Goals – Data Security Factors PG1

6.3 Gas Cleaning and Gas Conditioning

The gas cleaning and gas conditioning unit is assessed using the defined and weighted criteria described in the annex in chapter 9.8 (Table 9-37 and Table 9-41).

6.3.1 Secondary Goals

Based on the assessment of the indicators in chapter 4 and the specification of the TA method in chapter 4.3 the criteria are multiplied with their according weighting factors and summarized in three secondary goals:

- 'high efficiency' (focus on 'primary energy equivalent and conversion plant efficiency')
- 'high maturity' (focus on 'development stage')
- 'high feedstock and product quality' (focus on 'feedstock flexibility and infrastructure for product distribution')

The weighing factors are listed in chapter 9.8 (Table 9-37 and Table 9-41).

Resulting from Figure 6-11 the following conclusions can be drawn:

Efficiency. The focus of this secondary goal was the 'gas cleaning and gas conditioning efficiency' and resulted in the following:

- the highest score is obtained by the concepts BLEF-DME and ICFB-D; whereby the security on this value is rather low (no information on steam data)
- high scores are accomplished by the cEF-D concepts as a result of high efficiency and conversion rates (based on high process integration, e.g. recycled gas)
- the CFB-E concepts score higher than the EF-E scenario since they use a tar reformer (the EF-E concepts do not have tar in the raw gas)
- although the MF scenarios of cEF-D, dEF-D and CFB-E are very high, they have little influence on these results because of a stronger weighing on efficiency
- the difference within the CFB-E scenarios results from a higher conversion rate in the MF scenario
- the CFB-D and ICFB-D (SP) concepts along with the EF-E concepts show little performance

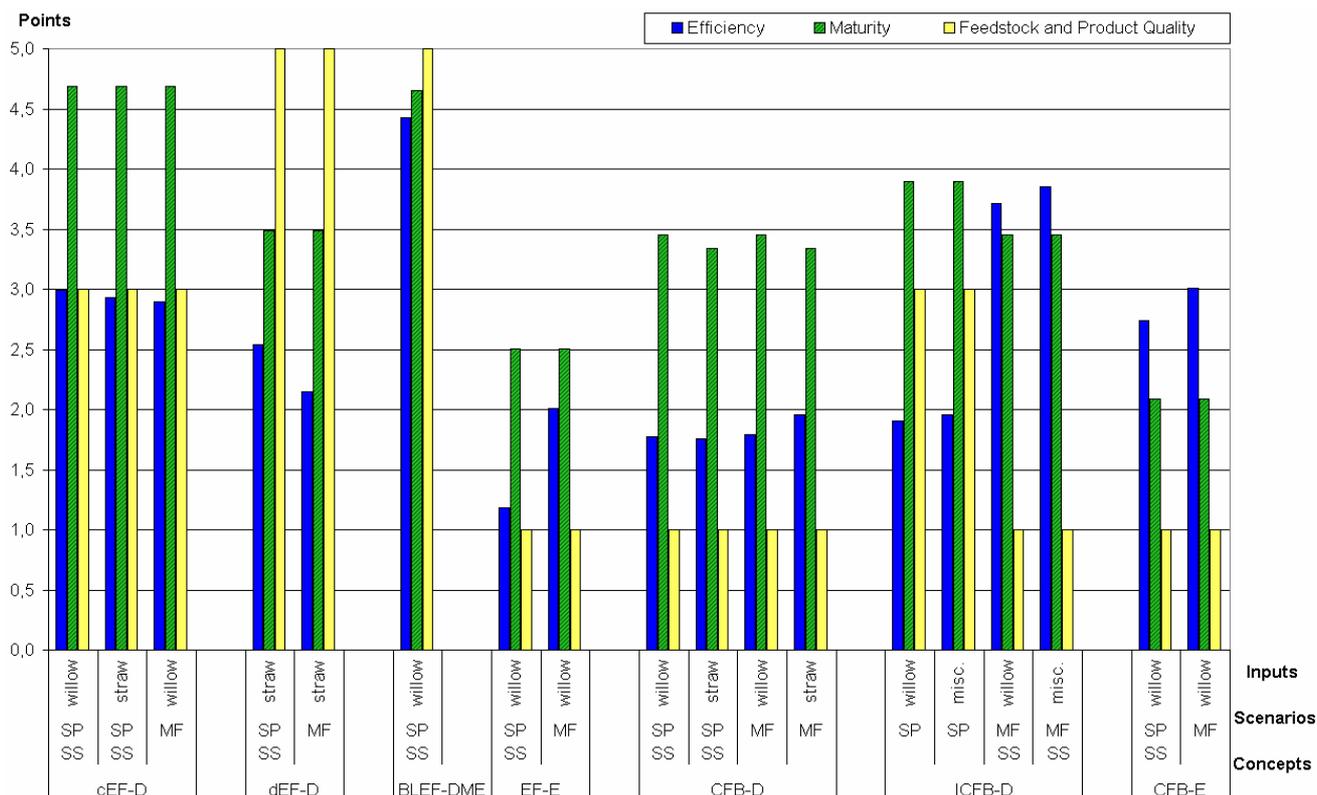


Figure 6-11: Gas Cleaning and Gas Conditioning – Secondary Goals ‘Efficiency, Maturity, Feedstock and Product Quality’

Maturity. The focus of this secondary goal was on the effort (cost) on gas cleaning and gas conditioning along with its development stage. Out of this consideration, the following can be concluded:

- the concepts cEF-D and BLEF-DME are the most mature in this aspect due to little effort on gas cleaning and gas conditioning and again a high development stage of single components and R&D facilities as well as high quality technical design
- the concepts EF-E and CFB-E show also here little maturity due to a low development stage in all areas and no information on investment cost
- the maturity of the other concepts is in a similar range, whereby ICFB-D (SP) performs best among them due to existing R&D facilities (although the effort (= cost) is the largest for the gas cleaning and gas conditioning unit, since it is a small concept)

Feedstock and Product Quality. This secondary goal is based only on one single indicators (‘syngas quality for fuel-synthesis) which has only a ‘quite good’ data quality (value: 0,66). Therefore the following conclusions are quite uncertain (see indicator evaluation in chapter 0).

- the dEF-D and BLEF-DME concepts have the highest score due to a well adapted and proven (commercial systems) syngas quality

- the cEF-D and ICFB-D concepts have a high score as well because of a well adapted and proven (demonstration plant) syngas quality for FT-synthesis
- the other concepts have the lowest score since they adapted the syngas for a tolerant synthesis catalyst (little risk is left concerning catalyst life time)

Sensitivity Check. The sensitivity check was done by setting the security factors of all criteria to 1. Only the maturity values changed, but all in the same direction and intensity (all values went up by 0.3 – 0.5 points). The result itself is that the basic statements and conclusions are the same like with the initial security factors. The relations among the concepts were the same.

6.3.2 Primary Goals

The secondary goals in gas cleaning and gas conditioning are summarized and weighted regarding two focuses:

- 'high technical performance' (focus on 'efficiency')
- 'good industrial applicability' (focus on 'maturity' and 'feedstock and product quality')

The weighing factors are listed in chapter 9.8 (Table 9-33 and Table 9-34). The data quality in the analysis of the primary goals is considered to be equal to exclude this parameter from the results and make sure that they are independent. The data quality parameters will be modified in the sensitivity analysis of these results in chapter 6.3.3.

High Technical Performance. This primary goal was formed by weighing and summarizing the secondary goals. The focus was on 'efficiency'.

Resulting from Figure 6-12 the following conclusions can be drawn:

- the BLEF-DME concept shows the highest technical performance and reaches the highest score by far through high efficiency, mature technology and an applicable syngas product quality
- quite high scores (high technical performance) are accomplished as well by the cEF-D, dEF-D and ICFB-D concepts due to good overall gas cleaning and gas conditioning results
- the least performance is shown by the other concepts as a result of low efficiency and little adopted syngas quality

Good Industrial Applicability (Close to Practical Realisation). In this primary goal the focus was less on (theoretical) efficiencies but more on the concept's 'maturity' and market-ability.

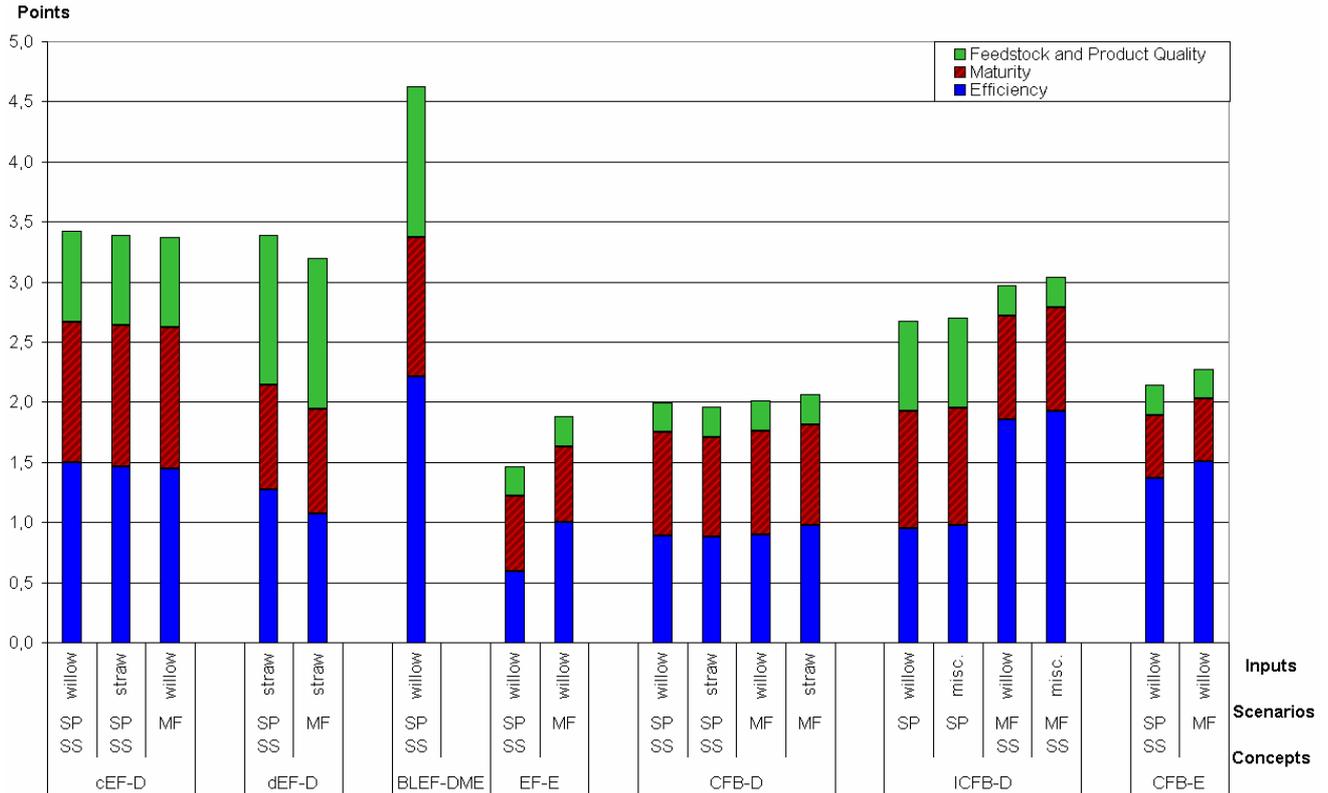


Figure 6-12: Gas Cleaning and Gas Conditioning – Primary Goal ‘High Technical Performance’

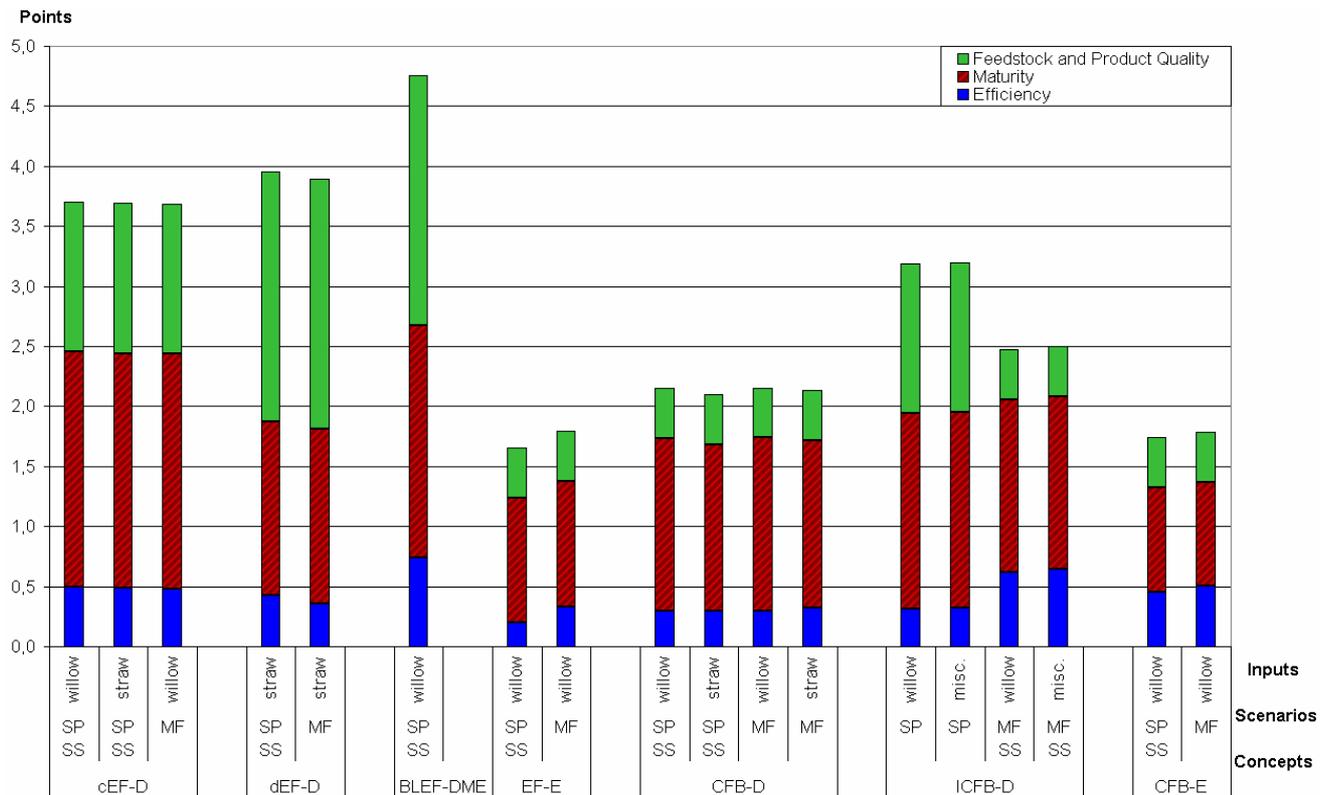


Figure 6-13: Gas Cleaning and Gas Conditioning – Primary Goal ‘Industrial Applicability’

Resulting from Figure 6-13 the following conclusions can be drawn:

- the gas cleaning and gas conditioning concept closest to practical realization is the BLEF-DME concept
- the cEF-D and dEF-D concepts are as well very close to industrial application
- the ICFB-D concept shows also good results due to a high maturity and adopted syngas quality
- the other concepts are not meeting this goal fully mainly because of low efficiency and low syngas adaptation to synthesis requirements

6.3.3 Sensitivity of Primary Goals

In this chapter, the methods described in chapter 0 are applied for sensitivity analysis.

Variation of Secondary Goals Weighing Factors. A different weighting of secondary goals is leading to a variation of primary goals which are compared with the initial values.

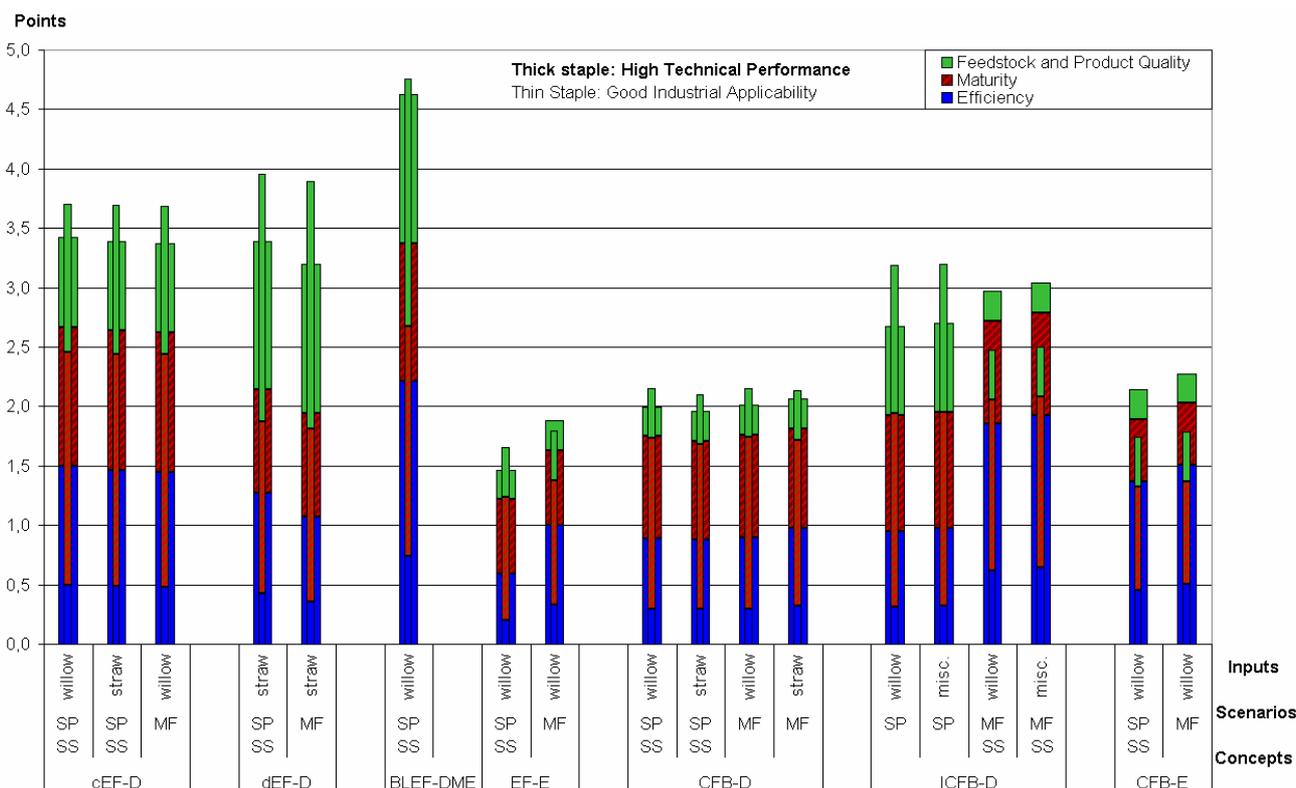


Figure 6-14: Gas Cleaning and Gas Conditioning – Sensitivity of Primary Goals – Weighing Factors

Resulting from Figure 6-14 the following conclusions can be drawn: The results in relation among the concepts are generally the same. All concepts show better results if the focus is on PG2. There are two exceptions: the ICFB-D (MF) and the CFB-E concepts show better results in PG1 when the focus is on 'efficiency'.

Variation of Data Security Factors. Now the data security factors are varied to see what happens if some criteria are emphasized or damped. The following variations are applied:

- PG1: the security factor of efficiency is raised to 1 (others are left constant at 0,66)
- PG2: the security factors of maturity & feedstock and product quality is raised to 1 (efficiency left constant at 0,66)

Variation of Data Security Factors in PG1 and PG2.

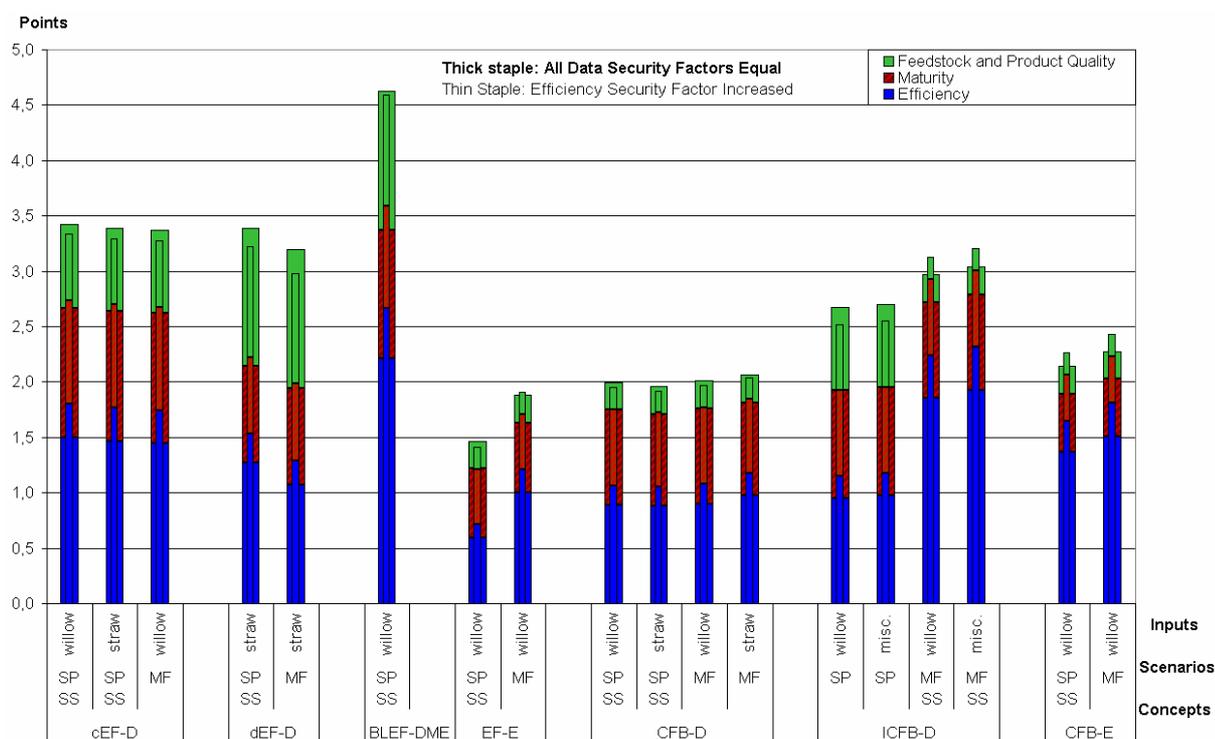


Figure 6-15: Gas Cleaning and Gas Conditioning – Sensitivity of Primary Goals – Data Security Factors PG1

The sensitivity of PG1 and PG2 was checked (see Figure 6-15 for PG1). The results vary mostly only marginal in one direction (lower results, both for PG1 and PG2). The exceptions are the ICFB-D (MF) and the CFB-E concepts, which profit more of a focus on efficiency, since the other two parameters are comparably not so good. Nevertheless in general the results and basic relations among the concepts are the same.

6.4 Conclusions on Multicriteria-Aggregation

Based on the results on technical assessment in this chapter, the following conclusions can be made:

- the superior concept evaluated in terms of high technical performance is the BLEF-DME concept also showing good industrial applicability (close to practical realization), however the market applications and niches are limited by the combination with a pulp mill and the 'still-to-built' distribution infrastructure and power trains (motors) for DME
- very good concepts with are the cEF-D (SP) and ICFB-D (SP) concepts (high process integration, high technical performance, good starting points through large experience in pilot and demonstration plant construction and operation)
- very high potentials are also within the large ICFB-D (MF) concept (good process technology) and the dEF-D concept (decentral approach in combination with approved gasification technology and applicable motor fuel)
- up to now the ethanol concepts are not yet technically mature and far away from practical realisation; further they show low technical performance (little efficiency) mainly due to the manifold by-products (co-fuels)
- the CFB gasification shows in general a higher maturity than the EF gasification and is therefore better suited for near future industry application; there is a further need for R&D activities in the promising and generally advantageous EF gasification
- the maximum fuel concepts are not reasonable in combination with hydrogen via electrolysis but more meaningful by a further process integration (recycling and reforming of unconverted syngas) and component improvement (synthesis reactors – raw fuel yields); this is an important focus for further R&D activities in the field of BtL production
- tri-generation or poly-generation of fuel, heat and power is energetically very useful and reasonable; combined fuel and power production pays of always; combined fuel, heat and power generation only if the heat can be used properly (district heat, industrial processes, etc.)
- concerning maturity; the concept based on real existing demonstration plants (cEF-D, BLEF-DME and ICFB-D) are the most promising for commercial application
- to achieve a more profound evaluation of gas cleaning and gas conditioning, more parameters are needed
- to get a deeper and better analysis of 'maturity' and 'feedstock and product quality' further input on indicators is required from industrial experts and mineral oil industry partners

7 Summary and Conclusion

In the final part of this paper, some conclusions will be drawn and an outlook given on BtL technologies. The goal of this work was to analyse and evaluate different BtL concepts for synthetic biofuel production from a technical viewpoint. This was done to identify which technology is advantageous in which application and to assess the need for further development.

7.1 Summary

The goal of this work was to analyse and evaluate different concepts for synthetic biofuel production from a technical viewpoint. This was done to perform a consistent comparison of BtL-concepts being currently developed and to show both pro's/con's and prospects/risks of the BtL-systems from different viewpoints. Because of the differences in development stages and application purposes of these concepts a "multicriteria assessment" method was developed, based on a combination of quantitative and qualitative data.

This assessment shows that 3 concepts have already achieved a more advanced technical status (cEF-D, BLEF-DME and ICFB-D). But it also could be shown that none of them has reached an industrial production .

- cEF-D: EF-gasification of biomass has been demonstrated. The installation of the first overall process on BtL-production will finalised in 2008. Engineering of future medium to large scale processes is ongoing.
- BLEF-DME: syngas production from black liquor has been demonstrated. The efficiency gain of the concept depends on integration with existing industrial facility (pulp mill). Demonstration of whole concept planed to start up 2010..
- ICFB-D: fuel gas/syngas production has been demonstrated. Addition of labscale syngas cleaning and FT-synthesis production has been shown under stable conditions.

Therewith implementation of the ongoing pilot and demonstration projects should bring valuable insight into the effective performance that could be expected as well as delivering critical design data for detailed engineering of BTL-plants on the large scale.

Beside these general conclusions the following aspects have to be taken into account based on the previous analysis results.

Integration – the keyword in BtL technologies. Integration is the key to an efficiency BtL plant operation. The higher the process integration, the higher the overall and particular efficiencies. High efficiencies can be achieved best by process integration. Less fuel power is wasted, loops help to maximise the energy in the flowing media. The efficiencies in chapter 5.1 are the highest for the concepts which have a high process integration.

The BLEF-DME concept is integrated into a pulp mill, using residue black liquor for motor fuel production. The cEF-D concepts show also very high overall efficiencies by many loops of gases and a highly integrated water steam distribution. The ICFB-D (SP) concepts combine fuel with district heat and power production. The ICFB-D (MF) concepts base on a highly integrated gasification concept, which makes use of flue gas and recycles unconverted syngas to steam reforming. Concluding, the high efficiencies of this concept result from a high process integration.

To reflect on the additional potential of BTL integration into a refinery or the co-processing of coal and biomass to achieve higher economy of scale needs further investigations.

Saving fossil fuels and reducing CO₂ emission best by maximized feedstock utilization.

If the global goal is to reduce CO₂ emissions and save fossil fuels, the best way is to use biomass as efficient as possible. The efficiencies of the regarded BtL processes are around 40% - 45% for motor fuel production. If material and energetic competitions rise, the BtL processes will not be the first choice from an energetic viewpoint. A remedy is a tri- or poly-generation of heat, power and motor fuel. The small ICFB-D (SP) concept is following this approach and shows the highest overall efficiency according to the CHP-F calculation (combined heat, power and fuel) method. BtL processes will have to be highly efficient out of two reasons: feedstock competition will increase and CO₂ emissions will have to be reduced more efficiently. If there is no proper application for heat (district heat, process heat), still the co-generation of power and motor fuel is energetically reasonable.

However, power can also be produced by other regenerative ways (wind, solar), but the mobility sector strongly depends on biomass as regenerative carbon source.

On the way to maturity by operating pilot and demonstration plants. BtL technologies will only have a large breakthrough if they are approved, state-of-the-art and economic. The way to industrial application has to be done via pilot and demonstration plants. The designed concepts cEF-D, BLEF-DME and ICFB are already on that way by being based on experience from pilot and demonstration plants. The overall concepts dEF-D, EF-E and CFB-E are still very theoretical and merely based on practical experience. For stepping up to a commercial scale, the mineral oil industry is demanding for proven technology. The way to a more mature technology will be in small step-ups. It will be hard and difficult for concept developers to go on large-scale commercial BtL production without the support of the mineral oil industry which has the knowledge on large-scale synthesis and product upgrading (thereby large scale application has to be profitable for private investors). Pilot and demonstration projects can also fail because of lacking licences for synthesis and other units. It took some time for UET, the technology provider for the cEF-D concepts, to be accepted and supported by large companies. It will be similar with energetically meaningful concepts which show fantastic results in research but do not have the support in the industry. Therefore, further support from industry and politics is necessary to go ahead with reasonable new developments in synthetic biofuel production.

Using additional hydrogen from electrolysis is energetically not efficient. The main target of introducing biofuels is to replace fossil fuels and reduce CO₂ emissions. The production of motor fuel can be maximized by adding hydrogen to the synthesis of biomass based syngas. Hydrogen is produced by electrolysis, powered by electricity. This electricity needs to be generated at some point and transferred to the BtL plant. The efficiency of power production is on average 40%, based around 90% (2005: Germany) on fossil fuels.

Thus, adding hydrogen in large quantities with a respective high electricity demand drops the overall efficiency (primary energy based) in the case of cEF-D and dEF-D by around 50% (down to an efficiency of around 25%) and in the case of CFB-D by 20%. Therefore it is energetically not efficient and recommendable to use additional hydrogen for increasing motor fuel production. Thus, a decision on additional hydrogen can only be driven by economic aspects. But therefore only the application of natural gas based hydrogen production could be an alternative to be considered⁴.

Ash recycling concepts are necessary for an environmentally sustainable plant operation. Large amounts of biomass will be withdrawn from agricultural and forestry land for future 500 MW BtL plants. Since these concepts can process the entire plant, they will not be residues left on the field. Minerals which usually stay on the fields in residues (needles, bark, etc.) are not recirculated to the soil. They stay in the grate ash and fly ash of the process. At a biomass feedstock input of approximately 140 t / h, there are about 3 – 6 t ash accumulated every hour. This ash can be used as fertilizer, if its impurities does not exceed national limits. In the current assessment, no concept provider included an ash recycling concept. This issue still needs to be discussed with agricultural experts, ministries and industry and adopt legislations accordingly. Only by recycling the residue ash the BtL plant operation and motor fuel production from biomass will be sustainable. Ash recycling will be necessary to close the nutrient cycle.

7.2 Conclusions

The goal of this work was to analyse and evaluate different concepts for synthetic biofuel production from a technical viewpoint. This was done to perform a consistent comparison of BtL-concepts being currently developed and to show both pro's/con's and prospects/risks of the BtL-systems from different viewpoints. Because of the differences in development stages and application purposes of these concepts a "multicriteria assessment" method was developed, based on a combination of quantitative and qualitative data.

This assessment shows that 3 concepts have already achieved a more advanced technical status (cEF-D, BLEF-DME and ICFB-D). But it also could be shown that none of them has reached an industrial production.

⁴ Regardless the lower primary energy efficiency a use of hydrogen – which could be produced regenerative (e. g. via electrolysis via wind) – could be attractive in future due to a high CO₂-reduction potential of the overall concept. Thus, these options have been analysed within Renew.

- cEF-D: EF-gasification of biomass has been demonstrated. The installation of the first overall process on BtL-production will be finalised in 2008. Engineering of future medium to large scale processes is ongoing.
- BLEF-DME: syngas production from black liquor has been demonstrated. The efficiency gain of the concept depends on integration with existing industrial facility (pulp mill). Demonstration of whole concept planned to start up 2010.
- ICFB-D: fuel gas/syngas production has been demonstrated. Addition of lab-scale syngas cleaning and FT-synthesis production has been shown under stable conditions.

Therewith implementation of the ongoing pilot and demonstration projects should bring valuable insight into the effective performance that could be expected as well as delivering critical design data for detailed engineering of BTL-plants on the large scale.

7.3 Outlook

Three conceptual development routes can be distinguished:

- small / medium size concepts which suit with low temperature CFB gasification to combined with synthesis not displaying strong scale requirements (methanol, DME) and leveraging heat integration with existing facilities (district network, pulp mill ...)
- larger size concepts based on high temperature entrained flow gasification and possibly integrated in a refinery, to produce final transportation fuels as FT-Diesel but if need be DME
- central gasification /decentral pyrolysis concepts aiming Gigawatt-size BtL-production

For each of the development directions different technical challenges/restraints exist:

- Large scale: feedstock pretreatment (pyrolysis, carbonization, ...)
- Small scale: syngas treatment, synfuel process selection and economy

Optimisation of the technico-economic performance is one of the common key challenge, but in many cases experiences from other XtL can be used, despite the comparably lower scale of BtL-technologies considered.

It also can be concluded that depending on the system component and its integration into an overall BTL-production chain different bandwidths of technical performance exists. Thereby the efficiency as one main criteria depends on process integration within/outside BTL-plant (energy and mass flows) and can be optimised via different design philosophies. However, above all the key issues of maturity and reliability have to be demonstrated since with the existing status of technology a BtL-production on industrial level is not yet achievable. Therewith the future R&D requires to “Demonstrate (efficiency, reliability, operability) the overall chain under industrial conditions (including waste water management, HSE, ...)”.

To achieve these targets most of the technical concepts analysed and further developed in Renew could be useful in some context and are influenced (but not limited in principal) by project/location specific frame conditions. For each processes unit (like e.g. gasifier) industrial applications exists, but in a different environment (feedstock, size, end product). In order to leverage maximum learning and progress from these demonstration activities, a detailed scientific support, modelling and monitoring in the field of feedstock preparation & handling (for different feeds), gasifier operation, syngas cleaning and overall process integration is needed.

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9 Annex

9.1 VDI 3780 (Excerpt)

– 4 – VDI 3780

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1 Begriffsbestimmungen

Technische Gebilde und Verfahren stehen in mannigfachen Systemzusammenhängen mit anderen technischen Gegebenheiten, mit der natürlichen Umwelt, mit einzelnen Menschen, sozialen Gruppen und der Gesellschaft insgesamt. Die Technik darf daher nicht als Selbstzweck, sondern muss immer als Mittel zur Erreichung bestimmter Ziele betrachtet werden.

- (1) Ein *Ziel* ist ein als möglich vorgestellter Sachverhalt, dessen Verwirklichung erstrebt wird; es wird durch eine Entscheidung gesetzt.

Sachverhalte sind z.B. Zustände, Gegenstände, Handlungen, Prozesse, Beziehungen. Die Erhaltung eines bereits bestehenden und die Vermeidung eines unerwünschten Sachverhaltes sind Sonderfälle der vorstehenden Definitionen.

Ein Ziel wird in einem Zielsatz formuliert. Ein Zielsatz enthält zwei Bestandteile: (a) die beschreibende Kennzeichnung des Sachverhaltes, (b) die Auszeichnung dieses Sachverhaltes als erstrebt, erwünscht, gefordert, befürwortet. Wenn der Zielcharakter eines gemeinten Sachverhaltes aus dem Zusammenhang eindeutig ersichtlich ist, genügt häufig schon die Kennzeichnung des Sachverhaltes.

Beispiel:¹⁾ Das Ziel Z1 „Der Ottomotor eines Personenkraftwagens soll eine hohe Leistung aufbringen“ kann in verkürzter Form heißen: „Hohe Motorleistung“

- (2) Ein Ziel ist häufig Bestandteil eines *Zielsystems*, das mehrere Ziele und Beziehungen zwischen den Zielen umfasst.
- (3) Ist ein bestimmtes Ziel in einem allgemeineren *Oberziel* enthalten oder enthält es selbst speziellere *Unterziele*, so liegt eine begriffliche Hierarchiebeziehung vor.

Durch die Angabe von Unterzielen kann konkretisiert werden, was mit einem Ziel genau gemeint ist.

Beispiel: Zwei weitere Ziele mögen lauten:
Z2 „Der Motor soll von hoher Qualität sein.“
Z3 „Der Motor soll bei der Drehzahl 50 pro Sekunde ein Drehmoment von 150 Nm aufweisen.“
Gegenüber Z1 ist Z2 ein Oberziel, Z3 ein Unterziel.

- (4) Zwischen zwei Zielen liegt eine *Indifferenzbeziehung* vor, wenn jedes der beiden Ziele angestrebt werden kann, ohne dass die Erreichung des anderen dadurch beeinträchtigt wird.

¹⁾ Dieses und die folgenden Beispiele erheben nicht den Anspruch einer systematischen Technikbewertung. Sie sollen lediglich die jeweiligen Definitionen und Unterscheidungen veranschaulichen und beschreiben typische (aber nicht unbedingt für jeden Einzelfall gültige) Zusammenhänge.

1 Definitions

Technological objects and processes are connected in a multiplicity of systemic ways to other technological givens, the natural environment, individual persons, social groups, and society as a whole. Thus technology must not be viewed as an end in itself but instead always as a means to achieve particular goals.

- (1) A *goal* is a state of affairs imagined to be possible and whose realisation is pursued; a goal is set by means of a decision.

States of affairs include e.g. conditions, objects, actions, processes, and relationships. The preservation of an already existing state of affairs and the avoidance of one that is undesired are special cases of the preceding definition.

A goal is formulated in a goal statement. A goal statement contains two components: (a) the descriptive identification of the state of affairs, and (b) the designation of this state of affairs as sought, desirable, demanded, or approved. If the goal character of a particular state of affairs is unambiguously clear from the context, it is often sufficient to just identify the state of affairs.

Example:¹⁾ The goal G1 "An automobile's Otto engine should be highly powerful" can be shortened to: "Powerful engine"

- (2) A goal is frequently one component of a *goal system* that comprises multiple goals and relationships among these goals.
- (3) If a particular goal is contained within a more general *overarching goal* or if it contains more specific *subgoals*, a conceptual *hierarchical relationship* exists.

What precisely is meant by a goal can be specified by denoting subgoals.

Example: Two further goals might be:
G2 "The engine should be of high quality."
G3 "The engine should attain 150 Nm of torque at 3000 rpm."
With respect to G1, G2 is an overarching goal and G3 a subgoal.

- (4) A *relationship of indifference* exists between two goals if each of them can be pursued without affecting the achievement of the other.

¹⁾ This example and those that follow make no claim to be systematic technology assessment. They are simply intended to illustrate each definition and distinction, and they describe typical interrelations (which are however not necessarily valid for each individual case).

- Beispiel:** Das Ziel Z4 „Der im Fahrzeug eingebaute Motor soll leicht zugänglich sein“ ist gegenüber Z1 indifferent und umgekehrt.
- (5) Zwischen zwei Zielen liegt eine *Konkurrenzbeziehung* vor, wenn die Erreichung des einen Ziels durch die Verfolgung des anderen Zieles beeinträchtigt wird.
- Beispiel:** In Konkurrenz mit Z1 steht das Ziel Z5 „Die Versicherungsprämien für den Personenkraftwagen sollen niedrig liegen“, sofern die Versicherungsprämien mit zunehmender Motorleistung steigen.
- (6) Ein *Mittel* dient dazu, ein Ziel zu erreichen. Man spricht dann von einer *Instrumentalbeziehung*. Jedes Mittel kann selbst wiederum als Ziel betrachtet werden.
- Häufig gilt auch die Umkehrung, dass ein Ziel als Mittel zur Verwirklichung eines anderen Zieles anzusehen ist. Die Kenntnis und die Gestaltung von Mitteln können rückwirkend auch ein Ziel verändern.
- Beispiel:** Wählt man, um Z1 zu erreichen, ein hohes Verdichtungsverhältnis, so ist diese Maßnahme, da sie den thermischen Wirkungsgrad erhöht, ein Mittel. Für die einschlägige konstruktive Gestaltung des Ottomotors wird dieses Lösungsprinzip seinerseits zum Ziel:
- Z6 „Es soll ein hohes Verdichtungsverhältnis vorgesehen werden.“
- Umgekehrt erweist sich Z1 seinerseits als Mittel bezüglich des Zieles
- Z7 „Der Personenkraftwagen soll bei gegebener Geschwindigkeit eine große Bergsteigefähigkeit besitzen.“
- (7) Die Anwendung eines Mittels hat neben der Verwirklichung des angestrebten Zieles weitere, gegebenenfalls auch unerwünschte *Folgen*.
- Indem man solche Folgen identifiziert, entdeckt man in der Regel weitere Ziele, die in den Folgen entweder verwirklicht oder verfehlt sind; dadurch erweitert sich das Zielsystem.
- Beispiel:** Ein hohes Verdichtungsverhältnis ist nicht nur ein Mittel für hohe Motorleistung, sondern hat auch die Folgen: a) der relative Kraftstoffverbrauch wird niedriger; (b) die Materialbeanspruchung steigt; c) der Ottomotor wird klopfempfindlich.
- (8) Eine *Präferenz* bedeutet, dass ein Ziel oder Mittel einem anderen Ziel bzw. Mittel vorgezogen wird.
- (9) *Kriterien* sind Auswahlgesichtspunkte für die Bestimmung von Präferenzen bei der Entscheidung über Ziele und Mittel; soweit möglich, werden Kriterien mit Hilfe von *Maßstäben* quantifiziert.
- (10) Kriterium für die *Auswahl von Mitteln* ist insbesondere die Tauglichkeit zur Verwirklichung der Ziele; ein Mittel darf jedoch nicht nur hinsicht-
- Example:** The goal G4 "The engine installed in the vehicle should be easily accessible" is indifferent with respect to G1 and vice versa.
- (5) A *competitive relationship* exists between two goals if the achievement of one goal is impaired by pursuing the other goal.
- Example:** The goal G5 "Insurance premiums for the automobile should be low" competes with G1 insofar as insurance premiums rise with increasing engine power.
- (6) A *means* serves to achieve a goal. One then speaks of an *instrumental relationship*. In turn, each means can itself be regarded as a goal.
- Frequently the converse is also true – a goal may be seen as a means to attain another goal. The knowledge of means and the way in which they are realised can also change a goal retrospectively.
- Example:** If one chooses a high compression ratio in order to achieve G1, this measure is a means, since it increases thermal efficiency. This principle of construction, for its part, becomes a goal in the appropriate design of the Otto engine:
- G6 "A high compression ratio should be provided for."
- Conversely, G1 is itself a means toward the goal
- G7 "The automobile should be able to climb hills easily at a given speed."
- (7) The application of a means has – in addition to the realisation of the desired goal – additional *impacts*, some of which may be undesirable.
- By identifying such impacts, one usually discovers additional goals that are either achieved or not with each impact. The goal system enlarges in this way.
- Example:** A high compression ratio is not only a means for achieving a powerful engine; it also has other impacts: (a) relative fuel consumption decreases; (b) stress on the materials increases; (c) the Otto engine is more liable to knock.
- (8) A *preference* means that one goal or means is favoured over another goal or means.
- (9) *Criteria* are selection standpoints for determining preferences in deciding on goals and means. Insofar as possible, criteria are quantified with the help of *standards*.
- (10) A criterion in the *selection of means* is, most particularly, suitability for realising the goals. However, a means may not be chosen solely

lich seines Mittelcharakters in Bezug auf die erklärten Ziele, sondern muss auch hinsichtlich aller seiner anderen Folgen beurteilt werden.

Beispiel: Bei der Festlegung eines bestimmten Verdichtungsverhältnisses entscheidet man nicht nur nach dem Kriterium, wie weitgehend das Ziel Z1 erreicht wird, sondern überprüft auch, in welchem Maße mit den anderen Folgen, z. B. (a), (b) und (c) aus Ziffer (7), weitere Ziele verwirklicht oder nicht verwirklicht werden.

So dient Folge (a) dem Ziel

Z8 „Der Kraftstoffverbrauch soll niedrig sein“.

Folge (b) dagegen widerspricht, soweit nicht besondere konstruktive Vorkehrungen getroffen werden, dem Ziel

Z9 „Der Motor soll eine lange Lebensdauer haben“,

wobei Z9 ebenso wie Z1 im Oberziel Z2 enthalten ist. Gleiches gilt auch für das weitere Ziel

Z10 „Der Motor soll umweltfreundlich arbeiten.“

Diesem Ziel widerspricht Folge (c), sofern man den Ottomotor, um das Klopfen zu vermeiden, mit bleihaltigem Kraftstoff betreiben muss.

- (11) Kriterien für die Gewichtung und *Auswahl von Zielen* sowie für die Beurteilung von Mitteln können unter Bezug auf Werte gewonnen werden.

Beispiel: Eine Präferenz des Zieles Z1 mag sich auf den Wert „Bewegungsfreiheit“ beziehen. Gibt man den Zielen Z8 oder Z9 den Vorzug, steht der Wert „Sparsamkeit“ im Vordergrund. Präferiert man Z10, wozu auch Z8 ein Mittel sein kann, so greift man auf den Wert „Umweltqualität“ zurück.

- (12) *Werte* kommen in Wertungen zum Ausdruck und sind bestimmend dafür, dass etwas anerkannt, geschätzt, verehrt oder erstrebt wird; sie dienen somit zur Orientierung, Beurteilung oder Begründung bei der Auszeichnung von Handlungs- und Sachverhaltsarten, die es anzustreben, zu befürworten oder vorzuziehen gilt.

Allgemein wird mit Werten ein Anspruch auf Geltung und Zustimmung verbunden.

Werte sind Ergebnisse individueller und sozialer Entwicklungsprozesse, die sich in der Auseinandersetzung mit natürlichen, gesellschaftlichen und kulturellen Bedingungen vollziehen; daher unterliegen Wertsysteme dem historischen Wandel und können in verschiedenen Kulturen und gesellschaftlichen Gruppen voneinander abweichen.

Der Inhalt eines Wertes kann aus Bedürfnissen hervorgehen; er konkretisiert sich insbesondere in Zielen, Kriterien und Normen.

- (13) Ein Wert ist häufig Bestandteil eines *Wertsystems*, das mehrere Werte und Beziehungen zwischen den Werten umfasst.

Für die Beziehungen gelten die Definitionen (3) bis (6) entsprechend.

with respect to its character as a means for attaining the declared goal; it must also be evaluated with respect to all of its other impacts.

Example: In determining a particular compression ratio, one makes a decision not only according to the criterion of the extent to which the goal G1 will be achieved. Instead, one also examines the degree to which other goals will be realised or not, due to other impacts – e. g., (a), (b), and (c) under number (7).

Thus, impact (a) serves to achieve the goal

G8 "Fuel consumption should be low."

However, unless special design precautions are taken, impact (b) contradicts the goal

G9 "The engine should have a long operating life",

whereby G9 and G1 are both comprised within the overarching goal G2. The same holds true for an additional goal

G10 "The engine should function in an ecologically friendly manner."

This goal contradicts impact (c), insofar as one will have to operate the Otto engine with leaded gasoline in order to prevent knocking.

- (11) Criteria for the weighting and *selection of goals* and for the evaluation of means can be obtained only if values are taken into account.

Example: A preference for the goal G1 may refer to the value "freedom of movement." If one gives priority to G8 or G9, the value "economy" is foregrounded. If one prefers G10 (to which G8 can also be a means), one refers to the value "environmental quality".

- (12) *Values* are expressed in evaluations; they are characteristic of something being recognised, prized, admired, or sought after. They thus help in orientation, assessment, or justification when it comes to distinguishing the types of action and states of affairs that are to be pursued, approved, or preferred.

In general, a claim of validity and consent is associated with values.

Values result from individual and social development processes that take place in confrontation with natural, social, and cultural conditions. Thus, value systems are subjected to historical change and can vary among different cultures and social groups.

The content of a value can derive from needs; it takes shape particularly in goals, criteria, and norms.

- (13) A value is frequently a component of a *value system* that comprises multiple values and relationships among these values.

For these relationships, definitions (3) through (6) apply, respectively.

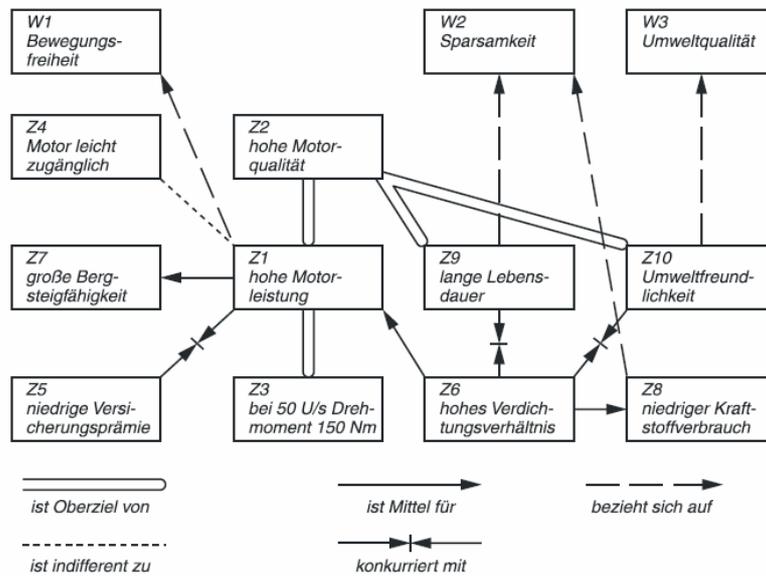


Bild 1. Beziehungen zwischen Zielen und Werten (dargestellt am Beispiel typischer Zusammenhänge bei einem PKW-Ottomotor)

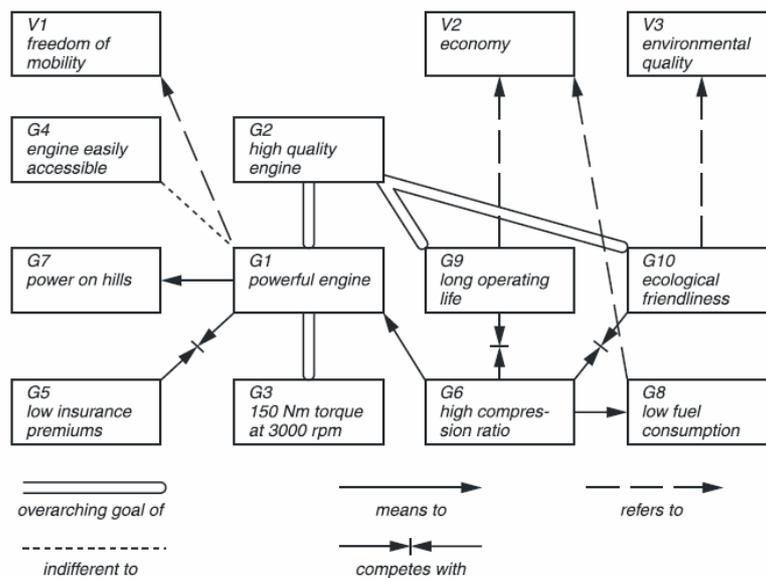


Fig. 1. Relationships among goals and values (illustrated with typical connections in the example of a car's Otto engine)

(14) *Bedürfnisse* sind der Ausdruck für das, was zur Lebenserhaltung und Lebensentfaltung eines Menschen notwendig ist.

Im Gegensatz zur Beliebigkeit des Wunsches hebt das Bedürfnis auf die Notwendigkeit der Befriedigung ab. Was allerdings als unerlässlich gilt, hängt vom jeweiligen Entwicklungsstand von Kultur und Gesellschaft ab; in der Industriegesellschaft konkretisieren sich die Bedürfnisse anders als in einem Naturvolk.

(14) *Needs* expresses that which is necessary to preserve and develop human life.

In contrast to the arbitrariness of desires, a need emphasises the necessity of its being satisfied. However, what counts as indispensable depends on the level of development of a particular culture and society; needs form differently in an industrialised society than in a less developed one.

Oft wird ein nicht befriedigtes Bedürfnis subjektiv als Gefühl eines Mangels erlebt; es gibt aber auch Bedürfnisse, die mit keinem Mangel-erlebnis verbunden sind, weil sie entweder regelmäßig und dauerhaft befriedigt werden oder aus anderen Gründen dem Individuum nicht zu Bewusstsein kommen. Bedürfnisse können sich in Einzel- oder Gruppeninteressen äußern.

- (15) *Interessen* sind spezifische Zielorientierungen, die aus den Werten und Bedürfnissen einzelner Individuen, Gruppen oder Organisationen hervorgehen und von diesen in Wirtschaft, Gesellschaft und Politik mehr oder minder öffentlich vertreten und mit verfügbarer Macht verfolgt werden.

Interessen sind in jeder Gesellschaft eine selbstverständliche Erscheinung; ein harmonischer Gesellschaftszustand, in dem es keine miteinander konkurrierenden Interessen gäbe, ist eine unrealistische Fiktion. Interessengegensätze können zu Konflikten führen, die in geregelter Form ausgetragen und günstigenfalls durch Kompromisse beigelegt werden. Soweit Interessen das Gemeinwohl zu beeinträchtigen drohen, werden sie durch rechtliche und politische Regelungen begrenzt.

- (16) *Normen* sind auf soziale Verbindlichkeit und Vereinheitlichung angelegte Verhaltensregeln, die unter Bezug auf Werte in einer gesellschaftlichen Gruppe oder in der Gesamtgesellschaft Verhaltenserwartungen und Handlungsanweisungen bestimmen; Verstöße gegen Normen ziehen Sanktionen nach sich, die von der Missbilligung bis zur Bestrafung reichen können.

Oft sind Normen schriftlich oder gar gesetzlich festgelegt. Auch technische Normen fallen unter diesen allgemeinen Normbegriff, indem sie auf die Vereinheitlichung technischer Lösungen hinwirken.

2 Die Bedeutung von Wertsystemen für die Technik

Die Existenz und die Beschaffenheit der technischen Mittel gehen auf menschliche Zielsetzungen, Entscheidungen und Handlungen zurück, in denen Werte zum Ausdruck kommen.

Beispiele: Die Errichtung von KohlegröÙkraftwerken und der Aufbau großflächiger elektrischer Energieversorgungsnetze anstelle kleinerer Einheiten war vor allem ein Ergebnis von Wirtschaftlichkeitsüberlegungen. – Durch die Ausrüstung von Kraftwerken mit Entschwefelungs- und Entstickungsanlagen trägt man gestiegenen Umweltschutzforderungen Rechnung.

An unfulfilled need will often be experienced subjectively as a feeling of scarcity; but there are also needs that are not associated with any experience of scarcity, either because they are satisfied on a regular and long-lasting basis, or because they do not enter the consciousness of the individual for some other reason. Needs can be expressed as individual or group interests.

- (15) *Interests* are specific goal orientations that follow from the values and needs of individual persons, groups, or organisations. They are more or less publicly represented by these entities in the economy, society and politics and pursued with the power at these entities' disposal.

Interests are a normal phenomenon in every society; a harmonious state of social affairs, in which there would be no conflicting interests, is an unrealistic piece of fiction. Clashes of interests can lead to conflicts that are carried out in a well-ordered form and in the best case can be put to rest with a compromise. Insofar as interests threaten to harm the common good, they are limited by legal and political regulations.

- (16) *Norms* are rules of behaviour meant to promote social obligation and standardisation, which – with reference to values – determine behavioural expectations and guidelines for action in a social group or in the entire society. Violations of norms result in sanctions that can range from disapproval to punishment.

Often, norms are laid down in writing or even in law. Technical norms also fall under this general notion of norms in that they work toward standardisation of technological solutions.

2 The significance of value systems for technology

The existence and qualities of technological means originate from human objectives, decisions, and actions in which values are expressed.

Examples: The construction of huge coal power stations and the creation of electric distribution systems over a large area instead of smaller units was primarily a result of economic considerations. – By equipping power plants with desulphurisation and DeNox systems, heightened demands for environmental protection are taken into account.

9.2 Upgrading

9.2.1 Introduction

As established at the 5.4-Workshop in Berlin, the concepts of CUTEC, FZK and TUV show incomplete process chains regarding the upgrading of the FT-raw product. So the products of the various RENEW-concepts are different, but since the results have to be combined with the results of the other assessments (WPs), an upgrading of the products is needed.

The plant operators decided that the gaps will be closed by the TA-working group via rough simulation. The partners of SP2 concerned are aware of the fact, that this procedure will influence their concept in a negative way due to external energy and hydrogen demands without any energetic integration.

9.2.2 Approach

Different process schemes are possible for FT wax upgrading in a BTL chain (or rather based on a GTL chain or refinery). The choice of process scheme will result from an optimization based on constraints, in our case related the amount of end products (max. liquid fuels) that are targeted.

To improve yield and quality of the middle distillate cut, the FT product requires hydrocracking. This is a process which is a combination of hydrogenation and cracking. The heavy distillate fractions are cracked (broken into smaller molecules) in the presence of hydrogen at high pressure and temperature to produce gasoline or middle distillates with good flow characteristics. The quality of the products and their distribution are deeply affected by the operating conditions [1].

During hydrocracking an unmanageable multiplicity of components exists and not less reactions occur. A modelling approach needs to capture the complex chemistry of the process. But there is limited process model for the hydrocracking process with sufficient accuracy available. There is only low information about any dependencies of operating parameters and no information about energy demands which can be used for modelling. Process design of refineries is often based on experience values [2].

For the sake of upgrading FT products, Shell has developed the Heavy Paraffinic Conversion (HPC) process that is somewhat of a combined hydrocracker and isomerisation unit, over dual function catalyst (0.3 wt % Pt catalyst on an aluminium-silica support) [3] which is stable for at least three years [4].

The long, waxy components in the raw synthesis product are hydrocracked selectively to the desired middle distillates products. Simultaneously, isomerisation occurs to some extent to improve the cold flow properties of the product [5],[6]. This is necessary because bad cold flow properties hamper the use of the middle distillate cut as transportation fuel.

Shell's HPC process is used in the Bintulu plant and is characterised as mild hydrocracking [3]. Until successful start up of Oryx GTL plant in Qatar (expected in late Q1 2007), this is the only industrially operating FT upgrading process for the production of diesel from low temperature FT waxes [7]. Since the Choren-upgrading will be done by Shell, it makes sense to adapt the other concepts to this HPC-proceeding to have a good basis of comparison. Further on it is relative easy to adapt this upgrading procedure to the incomplete process chains of Cutec, FZK and TUV.

9.2.3 Application to the Incomplete Process Chains of CUTEC, FZK and TUV

The considered scenarios for upgrading are the Starting Point Scenario and Scenario 1 (max. fuel production) with woody or rather herbaceous plants for the Cutec- and TUV-concept and straw for the FZK-concept.

The choice of process is the HPC process developed by Shell and is used as a part of their Shell Middle Distillate Synthesis (SMDS). The upgrading of the liquid FT raw product (C₅+ fraction) will contain a HPC-unit (350 °C, 30 bar) and afterwards a distillation as shown in Figure 9-1.

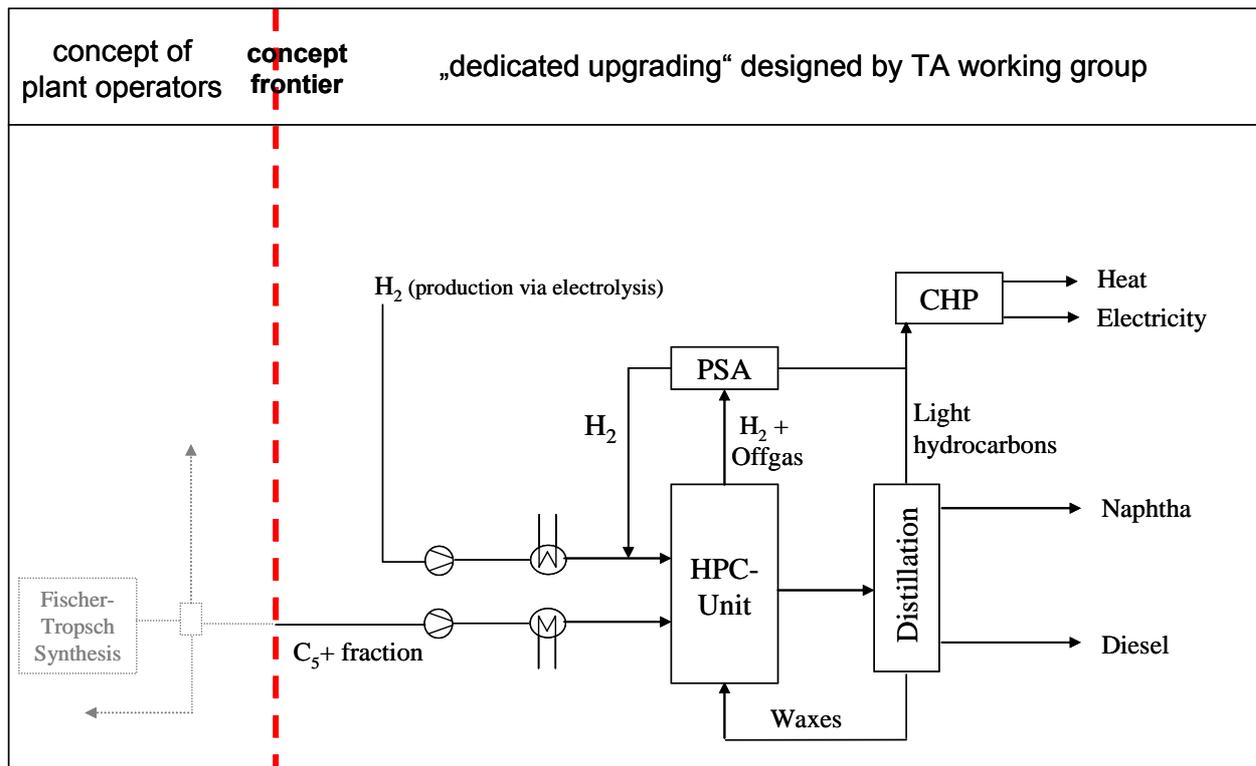


Figure 9-1: Simplified Flow Sheet of the Upgrading Process

With Fischer-Tropsch product a further upgrading including a HPC unit or rather hydrocracking unit is needed before a fractionation column separates naphtha and diesel as end-products [3]. This was confirmed by CERTH [8] and IFP [9], because in this case we are operating with a relative small amount of raw product which must be upgraded and it would not be economic to have an additional distillation column.

9.2.4 Detailed Explanation

The FT process leads to the formation of products essentially made up of n-paraffins whose distribution covers a wide range of molecular weights which can be described by the Anderson-Schulz-Flory model. It has to be considered, that after the FT synthesis the FT liquids are sent to a three phase separator, where water and the C₅₊ fraction are condensed. Roughly, the C₁-C₄ fraction is sent to flue gas. The C₅₊ fraction is separated from the water and sent to the HPC. This represents the concept frontiers of the Cutec- and TUV-concept, so the end product of the Cutec- and TUV concept is the separated C₅₊ fraction.

As for the FZK-concept no specifications for the work-up (condensation of C₅₊) are given, it is mentioned that stream conditions of the C₅₊ stream ("synfuel" fraction) are the same as for the Cutec-C₅₊ stream. This is valid as the FT conditions (200 °C, 25 bar, $\alpha = 0.9$, Co-catalyst) for both concepts are the same.

Since the gasoline fraction of the TUV-concept includes C₄-hydrocarbons, this fraction (thus butane) must be subtracted from the amount of the liquid FT products, so that we get a C₅+ fraction just like it is in the concepts of Cutec and FZK. The separation of butane is integrated in the three phase separator, which is not explicit shown in Figure 9-1. Calculation of the mass fraction of products consisting of four carbon atoms is done via ASF-equation:

$$W_n = n(1-\alpha)^2\alpha^{n-1} \quad \text{Equation 9-1}$$

where W_n is the mass fraction of a product consisting of n carbon atoms and the chain growth probability factor (α) [3]. With $\alpha = 0.9$ and $n = 4$ the sought-after mass fraction is 2.9 %. So the amount of the C₅+ fraction of the TUV-concept is reduced about 2.9 % from 12.07 t/h to 11.72 t/h. The amount of the C₄ fraction from TUV is calculated to be used for electricity production at the BTL plant. Light hydrocarbons that will be generated in all machined concepts during upgrading will also be used for electricity production, but at refinery. Calculation results are shown in the overall Table 9-4. It has to be considered that for the TUV concept the electricity and heat out of the light hydrocarbons includes also the additional electricity and heat out of the C₄ fraction. Stream conditions of the C₅+ fraction coming out of the “concept boundary” can be found in Table 9-3.

It is known that besides n -paraffins FT waxes contain small percentages of by products, mainly olefins and alcohols, but in our case we assume that the feedstock is made of exclusively of n -paraffins. The reason for this is the fact that both, olefins and alcohols, show a much higher reactivity than n -paraffins and are turned into the respective n -paraffins.

Since the higher hydrocarbons have much higher reactivity in the HPC than the lower, it may be assumed that only waxes (C₂₁+) are cracked [10]. The product of the HPC is constituted of n -paraffins and isomers. The isomerisation reactions are thermally almost neutral, whereas the hydrocracking reaction is exothermic [11], for example:



Taking the C₅+ fraction from the FT synthesis of the three incomplete concepts (CUTEC, FZK, TUV) entering the HPC and with Figure 9-2 from Shell’s SMDS process, it is possible to estimate the product composition after hydrocracking.

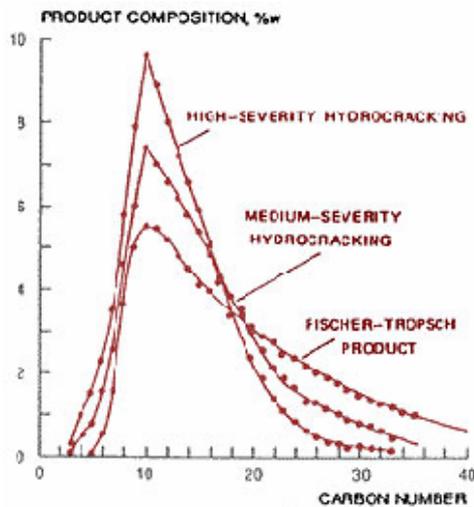


Figure 9-2: Distribution of a Fischer-Tropsch Product Before and After Selective Hydrocracking [3]

The Fischer-Tropsch product distribution shown in Figure 9-2 is more or less an ASF-distribution with an alpha of 0.9. This alpha value is also supposed or rather close to our considered scenarios. For our purpose of mild hydrocracking the medium-severity hydrocracking curve is chosen [8].

Because of a high number of species involved, we assumed that a high number of species are lumped together corresponding the cuts of interest for the refinery (C_1-C_4 = light hydrocarbons, C_5-C_8 = naphtha, C_9-C_{20} = diesel, C_{20+} = wax).

The conversion of wax in the HPC unit is not 100 %. So the unconverted wax coming out from the HPC must be separated from the diesel and naphtha and is recycled to the HPC. To separate the diesel, naphtha and waxes from each other, the mixture from the HPC is sent to a distillation column.

In a mode designed to maximize middle distillates, a split of approx. 70/30 diesel/naphtha forms the product [10]. But the naphtha is only a kind of raw naphtha, which requires further upgrading. There are also some light hydrocarbons ($< C_5$) in low quantities produced, if process is managed properly 5 % w/w [7]. A range of 2-7 % was also estimated by Choren. These light hydrocarbons are separated and used for electricity. So the product distribution is set to 70 % diesel, 25 % naphtha and 5 % light hydrocarbons for electricity generation, as shown in Table 9-1.

		Liquid FT product (C_5+ fraction)	after medium-selective hydrocracking	After distillation*
		% w/w	% w/w	% w/w
Light hydrocarbons	C_1-C_4		4	5
Naphtha	C_5-C_8	20	20	25
Diesel	C_9-C_{20}	40	58	70
Wax	C_{21+}	40	18	recycled

Table 9-1: Product Fractions Before and After Mild-Severity Hydrocracking

* under consideration that waxes are recycled and do not form a product after distillation

9.2.5 Calculation of H₂-Demand for Mild Hydrocracking

The hydrogen consumption is 176 g/GJ FT liquid [12],[13], when assuming that 1 GJ FT liquid has a LHV of 44,2 MJ/kg. This hydrogen amount is also mentioned for mild hydrocracking operations by Moulijn [14]. The outcome of these calculations is shown in Table 9-2.

Given that no information is supplied by BTL concept developers on the olefin content of the FT wax (exception Cutec: 30 % of FT products are olefins, but it is not shown where this data come from), the hydrogen consumption due to olefin saturation is taken with 10 % into account. There is little available data in the literature to propose any such "typical" figure. Indeed, low temperature FT production and upgrading is hardly typical, industrial experience is very limited and publications on it even more [7]. Hydrogen lost by dissolution is set to 8-12 % of "chemical" consumption [7].

		Cutec	FZK	TUV
C ₅ +fraction	kg/h	16910	17800	11720
H ₂ -demand for cracking paraffins	kg/h	132	139	91
H ₂ -demand for olefin saturation	kg/h	13	14	9
H ₂ -demand due to dissolution	kg/h	13	14	9
Sum H ₂ -demand	kg/h	158	167	109

Table 9-2: H₂ Demand

Calculating the H₂/wax ratio (wax = 40 % of C₅+ fraction) we get a value of approx. 0.023 wt/wt. In literature there are also data that set the H₂/wax ratio to 0.06-0.15 wt/wt. That would mean that our assumptions from other literature that are specified above leads to an underestimation of hydrogen consumption. When producing hydrogen via electrolysis, 53.3 kWh/kg hydrogen is needed [15].

9.2.6 Calculation of Energy Demand for Upgrading

Energy demand for the upgrading process is determined via Chemcad (simulation tool) and can be divided into a hydrocracking and a distillation part. For simplification it is for the simulation assumed that the C₅+ fraction contains only alkenes.

The energy required for the hydrocracking part is made of the energy which is needed for heating up hydrogen and the C₅+ fraction to 350 °C (temperature of hydrocracking) and the energy which is needed to compress hydrogen and the C₅+ fraction to 30 bars (pressure of hydrocracking) [7]. The conditions of the input streams are presented in Table 9-3.

		Cutec	FZK	TUV
T	°C	60	60	60
p	bar	23.26	23.26	19.65

Table 9-3: Conditions of the C₅+ Fraction

If the C₅+ fraction is not worked up directly at the BTL plant, temperature and pressure will decrease during transport and relocation. Thereby, energy demand for heating up at the upgrading place will increase up to 10 %. This is considered for the TUV SP scenario, where transport of the FT raw product is needed due to the ten 50 MW plants which are located at different places.

Since there is a H₂-overhang in the HPC-unit, which is recycled, only fresh hydrogen needs to be compressed and heated up. Also the hydrogen demand for olefin saturation and dissolution is included. Energy, which is needed to adjust the H₂-recyclestream to HPC-conditions, is neglected, because we assume that the hydrogen make up has limited impact on compressor energy consumption). Results of these calculations are represented in **Fehler! Verweisquelle konnte nicht gefunden werden..**

A complete calculation of a multi-component distillation includes a tower with trays, condensers and a heat exchanger in the bottom. Due to the fact that number of trays, reflux ratio etc. are unknown, calculations contains uncertainties. It must be noted, that no energy integration (heat recovery from hot streams) was made.

Beside diesel and (raw) naphtha, electricity and heat (out of the light hydrocarbons) is produced. A combined heat and power plant (CHP) produced out of 1 MJ light hydrocarbons 0.32 MJ electricity and 0.55 MJ heat. The electricity and heat produced out of the light hydrocarbons is credited to the overall electricity or rather heat demand. Energy content of 1 kg light hydrocarbons is set to 46 MJ/kg. Results of these calculations are displayed in **Fehler! Verweisquelle konnte nicht gefunden werden.** and **Fehler! Verweisquelle konnte nicht gefunden werden..**

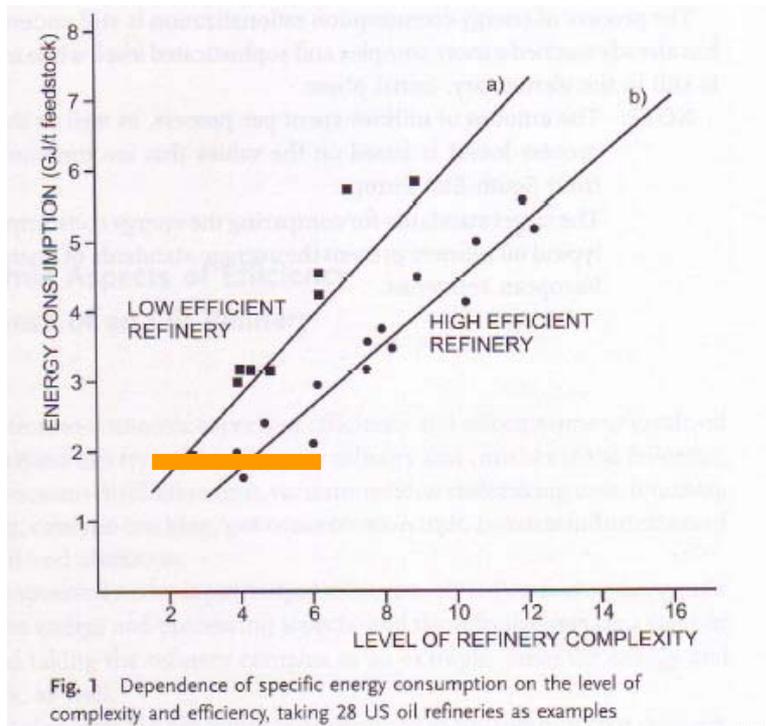


Figure 9-3: Plausibility Check for Energy Consumption of Upgrading Process [16]

The orange line represents the calculated energy consumption data of the considered concepts and scenarios. We can see that the calculated values are in the range of a reasonable area.

			C ₅ + fraction	C ₄ fraction of the "liquid FT rawproduct"	H2 demand (hydrocracker consumption only + 10 % olefin saturation + dissolution)	Energy H2 production (hydrocracker consumption only + 10 % olefin saturation + dissolution)	Energy hydrocracking	energy distillation	energy sum	energy demand (heat)	energy demand (electricity)	light hydrocarbons	Naphtha product	Diesel product	Energy content light hydrocarbons + C ₄	heat out of light hydrocarbons	Electricity out of light hydrocarbons	energy demand (heat) minus heat out of light hydrocarbons	energy demand (electricity) minus electricity out of light hydrocarbons
			[t/h]	[t/h]	[kg/h]	[MW]	[MW]	[MW]	[MW]	[MW]	[MW]	[t/h]	[t/h]	[t/h]	[MW]	[MW]	[MW]	[MW]	[MW]
FZK	SP	straw	17,80		23,46	1,25	4,12	3,14	8,51	7,22	1,29	0,89	4,45	12,46	11,37	6,25	3,64	0,96	-2,35
	MF	straw	35,60		46,93	2,50	8,24	6,25	16,99	14,41	2,58	1,78	8,90	24,92	22,74	12,51	7,28	1,90	-4,69
Cutec	SP	willow	16,91		22,28	1,19	3,93	2,79	7,91	6,68	1,23	0,846	4,23	11,84	10,80	5,94	3,46	0,74	-2,23
	SP	straw	15,28		20,09	1,07	3,52	2,54	7,13	6,02	1,11	0,764	3,82	10,70	9,76	5,37	3,12	0,66	-2,02
	MF	willow	23,81		31,40	1,67	5,53	3,93	11,13	9,40	1,73	1,191	5,95	16,67	15,21	8,37	4,87	1,04	-3,14
	MF	straw	22,37		29,38	1,57	5,13	3,65	10,35	8,73	1,62	1,119	5,59	15,66	14,29	7,86	4,57	0,87	-2,96
TUV	SP	willow	11,72	0,35	15,36	0,82	2,95	1,94	5,71	4,86	0,85	0,586	2,93	8,20	11,96	6,58	3,83	-1,71	-2,98
	SP	miscanthus	11,12	0,33	14,69	0,78	2,84	1,87	5,50	4,69	0,81	0,556	2,78	7,78	11,32	6,23	3,62	-1,54	-2,81
	MF	willow	24,62	0,74	32,40	1,73	5,73	4,10	11,56	9,77	1,78	1,231	6,16	17,23	25,19	13,85	8,06	-4,08	-6,27
	MF	miscanthus	24,48	0,73	32,22	1,72	5,43	4,02	11,17	9,40	1,77	1,224	6,12	17,14	24,97	13,73	7,99	-4,34	-6,22

Table 9-4: Calculation of Energy Demand and Yields

			C ₅ + fraction	C ₄ fraction of the "liquid FT rawproduct"	H ₂ demand (hydrocracker consumption only + 10 % olefin saturation + dissolution)	Energy H ₂ production (hydrocracker consumption only + 10 % olefin saturation + dissolution)	Energy hydrocracking	energy distillation	energy sum	energy demand (heat)	energy demand (electricity)	light hydrocarbons	Naphtha product	Diesel product	Energy content light hydrocarbons + C ₄	heat out of light hydrocarbons	Electricity out of light hydrocarbons	energy demand (heat) minus heat out of light hydrocarbons	energy demand (electricity) minus electricity out of light hydrocarbons
			[t/h]	[t/h]	[kg/h]	[MW]	[MW]	[MW]	[MJ/kg FT-raw-product C5+]	[MJ/kg FT-raw-product C5+]	[MJ/kg FT-raw-product C5+]	[t/h]	[t/h]	[t/h]	[MW]	[MJ/kg FT-raw-product C5+]	[MJ/kg FT-raw-product C5+]	[MJ/kg FT-raw-product C5+]	[MJ/kg FT-raw-product C5+]
FZK	SP	straw	17,80		23,46	1,25	4,12	3,14	1,721	1,460	0,261	0,89	4,45	12,46	11,37	1,265	0,736	0,195	-0,475
	MF	straw	35,60		46,93	2,50	8,24	6,25	1,718	1,457	0,261	1,78	8,90	24,92	22,74	1,265	0,736	0,192	-0,475
Cutec	SP	willow	16,91		22,28	1,19	3,93	2,79	1,683	1,422	0,261	0,846	4,23	11,84	10,80	1,265	0,736	0,157	-0,475
	SP	straw	15,28		20,09	1,07	3,52	2,54	1,680	1,419	0,261	0,764	3,82	10,70	9,76	1,265	0,736	0,154	-0,475
	MF	willow	23,81		31,40	1,67	5,53	3,93	1,683	1,422	0,261	1,191	5,95	16,67	15,21	1,265	0,736	0,157	-0,475
	MF	straw	22,37		29,38	1,57	5,13	3,65	1,665	1,405	0,260	1,119	5,59	15,66	14,29	1,265	0,736	0,140	-0,476
TUV	SP	willow	11,72	0,35	15,36	0,82	2,95	1,94	1,755	1,494	0,261	0,586	2,93	8,20	11,96	2,021	1,176	-0,526	-0,915
	SP	miscanthus	11,12	0,33	14,69	0,78	2,84	1,87	1,780	1,517	0,263	0,556	2,78	7,78	11,32	2,016	1,173	-0,499	-0,910
	MF	willow	24,62	0,74	32,40	1,73	5,73	4,10	1,690	1,429	0,261	1,231	6,16	17,23	25,19	2,025	1,178	-0,596	-0,918
	MF	miscanthus	24,48	0,73	32,22	1,72	5,43	4,02	1,642	1,382	0,261	1,224	6,12	17,14	24,97	2,019	1,175	-0,638	-0,914

Table 9-5: Calculation of Energy Demand and Yields Relating to 1 kg FT Raw Product

To check the plausibility of the calculated energy demand data, Figure 9-3 is helpful. On the ordinate the energy consumption per GJ/t feedstock is outlined. On the x-axis the level of refinery complexity is indicated. Refinery complexity is bigger the more upgrading steps you have. Would for example our raw naphtha be upgraded to fuel naphtha, the level of refinery complexity would increase.

9.2.7 Bibliography of Chapter 9.2

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9.3 Efficiency In-Depth

9.3.1 General Definitions

To compare different process technologies, the definition of the efficiencies and conversion rates is a fundamental part of technical assessment. This applies not only for an overall system, but also for system components like e.g. gasification and gas cleaning & conditioning.

9.3.1.1 Efficiency

In general, the efficiency η of a system is defined as the quotient of the power output (benefit) and the power input (effort) [VDI 4661, 2003].

$$\eta = \frac{P_{out}(benefit)}{P_{in}(effort)}$$

Equation 9-3

The definition of benefit and effort depends on the application [Stiens, 2000]. From theory, if multiple input parameter ($i = 1 \dots n$) and multiple output parameter ($j = 1 \dots m$) exist, the efficiency η is defined as the ratio of the power outputs ($j = 1 \dots m$) and the power inputs ($i = 1 \dots n$).

$$\eta = \frac{P_{out_1} + P_{out_2} + \dots + P_{out_m}}{P_{in_1} + P_{in_2} + \dots + P_{in_n}}$$

Equation 9-4

Thereby a system boundary is defined (Figure 9-4), which indicates the border of the system consideration. Only those energy flows are considered, which are passing this border.

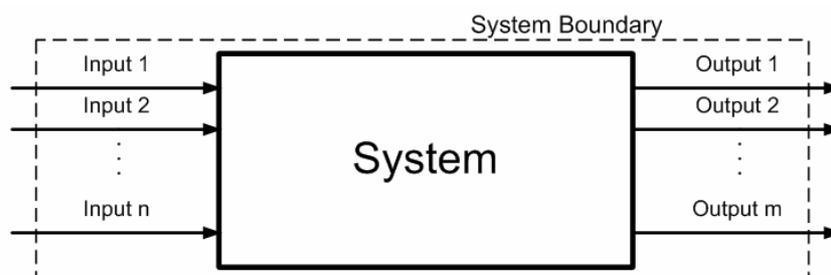


Figure 9-4: General Definition of System Boundary for Efficiency Calculations

Target Energy. The target energy is the benefit of the system. It is the form of energy aimed at in the energy-conversion process. The target energy flow is the target power. [VDI 4661, 2003]. In Equation 9-3, the target power is the power output, the benefit. Relation to Equation 9-4: If there are several power outputs, the question of identifying the target power is discussed in chapter 9.3.3 (Definition of Additional Power Integration).

Primary Energy. Primary Energy is energy available in natural resources or energy carriers. This energy did not pass any kind of conversion process.

Primary energy carriers are:

- fossil energy sources (coal, crude oil, natural gas)
- nuclear energy sources (natural uranium)
- renewable energy sources (solar energy and its consequences (wind energy, hydro energy, tidal energy, etc. and biomass)

Against this background the input (effort) and the output (benefit) (shown in the previous chapter 9.3.1) can be primary or a secondary energy based. This aspect needs to be distinguished and will be discussed in detail in the following.

9.3.1.2 Conversion Rate

A conversion rate is defined as the ratio of a specific power output to a specific power input. One input is defined as the 'main power input', degrading other inputs to 'auxiliary power'. One output is chosen as the 'target power output', degrading other outputs as 'by-products power' (Figure 9-5).

Example: Input 1 is chosen as 'main power input'

Output 2 is chosen as 'target power output'

The conversion rate y thus is defined as the ratio of main power output to target power input. Regarding conversion rates, the definition of a system boundary is not mandatory.

$$y = \frac{P_{out_TARGET}}{P_{in_MAIN}}$$

Equation 9-5



Figure 9-5: General Definition of System Boundary for Conversion Rate Calculations

Conversion rates are often used as mass- or volume-based criteria (i.e. kg/kg or l/kg). The chosen output is mostly the target power, the chosen input the main power. This criterion is giving an idea of how much power output of a certain quantity can be converted for a specific input quantity.

Example: main power input: 10 kg of biomass
 Target power output: 10 l of biofuel
 Thus, the conversion rate is $y = 1 \text{ l/kg}$.

9.3.2 Definition of System Boundaries

As described in chapter 9.3.1.1, the definition of efficiency goes along with a definition of a system boundary, to differ between the energy flows within a system and passing the system. Two different system boundaries are defined:

- system boundary: conversion plant (chapter 9.3.2.1)
- system boundary: primary energy (chapter 9.3.2.2)

9.3.2.1 Conversion Plant

Definition of System Boundary: The system boundary is the system itself. Therefore this approach is not primary energy related. The energy flows passing the system boundary (e.g. the plant gate itself) are a mixture of primary and secondary energies (Figure 9-6). The transport and conversion of the energy carriers up to the system is not considered. In technical descriptions and datasheets, this is the most common method.

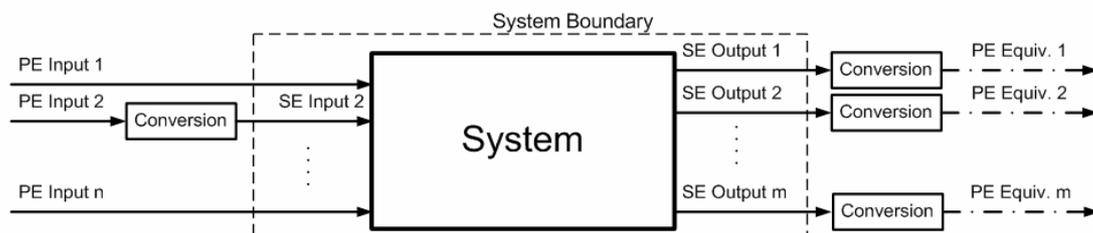


Figure 9-6: Definition of Conversion Plant System Boundary for Efficiency Calculations

Example for a primary energy input. PE Input 1: Biomass
 Biomass is a primary energy carrier which can enter the system directly. Its first conversion into secondary energy is within the system.

Example for a secondary energy input. SE Input 2: electrical power mix

One part of a power mix is from a coal-fired power plant. The production and transport of the energy carrier coal and its conversion and the transport of electricity are outside the system and thus not within the system's boundary.

9.3.2.2 Primary Energy Based

Definition of System Boundary: All in- and output calculations are based on the primary energy (PE) equivalent of the energy carriers (Figure 9-7).

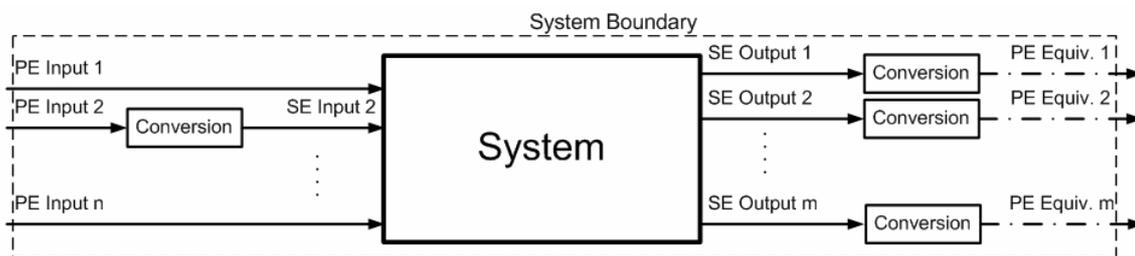


Figure 9-7: Definition of Primary Energy Based System Boundary for Efficiency Calculations

Inputs. The system boundary for the inputs (main power input and auxiliary power) is defined at the place of first energetic conversion of the primary energy carrier.

Example for auxiliary power: one part of the power mix is from a coal-fired power plant. The production and transport of the energy carrier coal is not within the border, but the conversion of coal and the transport of the electricity to the BtL-plant.

Outputs. The system boundary for the outputs (target power and by-product power) is defined as the conversion of the energy carriers to a primary energy equivalent.

Example for a by-product: the primary energy equivalent of surplus electricity of a certain power mix is subtracted from the primary energy equivalent overall input power

9.3.3 Definition of Additional Power Integration

As shown in chapter 9.3.1 and 9.3.2, there are different power in- and outputs into a system, which can be distinguished between main power and auxiliary power on the input side and target power and by-product power on the output side.

In efficiency definition, there are two possibilities of including additional power into the calculations. Both are described for auxiliary power in chapter 9.3.2.1 and for by-product power in 9.3.2.2 respectively.

9.3.3.1 Auxiliary Power



Figure 9-8: Definition of Auxiliary Power Integration

There are two possible variations to define the efficiency including auxiliary power (Figure 9-8):

a) Adding auxiliary power to the input

$$\eta = \frac{P_{\text{TARGET}}}{P_{\text{MAIN}} + P_{\text{AUXILIARY}}}$$

Equation 9-6

b) Subtracting auxiliary power from the output

$$\eta = \frac{P_{\text{TARGET}} - P_{\text{AUXILIARY}}}{P_{\text{MAIN}}}$$

Equation 9-7

Based on these two options the question is whether to consider auxiliary power as an additional effort or a reduction of benefit. Formally, the auxiliary power is part of the effort and therefore added to the main power input. Auxiliary power like electrical or mechanical energy in steam power plants is as well added to the effort and not reduced from the benefit [Strauß, 2006], [Bolhár-Nordenkamp, 2004]. Hence variation a) is selected for all efficiency calculations.

9.3.3.2 By-Product Power



Figure 9-9: Definition of By-Product Power Integration

Regarding the by-products, there are as well two possible variations to define the efficiency including by-product power (Figure 9-9):

a) Subtracting by-product power from the input ('Conventional method')

$$\eta = \frac{P_{\text{TARGET}}}{P_{\text{MAIN}} - P_{\text{BY_PRODUCTS}}}$$

Equation 9-8

b) Adding by-product power to the output ('CHP-F method')

$$\eta = \frac{P_{TARGET} + P_{BY_PRODUCTS}}{P_{MAIN}}$$

Equation 9-9

Conventional Method. By-products are co-products of a conversion system and not target energy. In almost all cases by-products are used internally in the process itself. If electricity is generated in a chemical process, it is subtracted from the electricity used for generating the target power; the chemical product in a certain period. The 'by-product' electricity is reducing the effort. In definitions for conventional power plants, main input power is fuel power (chemical/nuclear power of the fuel) and target energy is **net** electricity. If additional electricity is required in the process (compressor, feeding pump), it is subtracted from the gross electrical power output. The additional power can be also supplied by a gas turbine, combining both gas and steam turbines. Then, the additional power is the fuel power of the gas and added to the effort of the unit. Out of these VDI-definitions, it becomes clear, that surplus energy is only added or subtracted from the target energy, if it is of the same energy from [VDI 3986, 2000].

In BtL-processes, it is still discussable, whether to consider the by-product naphtha as desired target power or exclusively synthetic biofuel BtL (FT-diesel, DME and Ethanol). As a result, both efficiencies will be defined: energetic efficiency with target energy 'BtL' and 'raw product' (BtL + naphtha output) respectively.

Another aspect in this discussion is the definition of benefit and effort, which depends on the application. The system/process evaluated has to compete with other processes. Here, BtL-processes are in focus. Synthetic biofuels compete with other synthetic fuels like CtL and GtL and conventional fuels like Diesel as well. Thus, the target of the process is to produce synthetic fuel ready to distribute and consume. Target energy is synthetic biofuel (BtL). Surplus energy like electricity and heat are not multiplying the fuel, but reducing the effort of producing the fuel. Surplus energy, useable for internal processes, can be regarded as credit, which is a negative effort in this case and consequently subtracted from the effort. E.g. surplus thermal energy (steam) from an internal process 1, substituting part of the steam generation for another internal process 2, is subtracted from the effort of process 2 [Stiens, 2000].

Thus, in the following definitions for BtL-process technology, the target energy is BtL-fuel and variation a) is chosen preferably for all efficiency calculations.

CHP-F Method. Another way to look at by-products is regarding them as additional benefit, which can be used outside the plant ('over the fence'). This definition is similar to the efficiency definition of CHP plants, where heat and (electrical) power are considered equally as target power. The CHP-F method is based on the same principle; considering heat, (electrical) power and (synthetic bio) fuel as target power. Another term for CHP-F would be 'tri-generation'. Therefore by-products powers are added to the target power and equal to another. They are useful for other applications and have not to be generated by another conversion process. Considering by-products as such a benefit upgrades them to target power. This leads the definition to a combined power production (heat, power and fuel).

Variation b) is chosen for the CHP-F method to compare all efficiency calculations.

9.3.4 Definition of Constants

Boundary conditions are defined in the workgroup internal document ‘Deliverable 5.4.1’ [Boundary, 2006], which apply in the definitions of constants. Some constants have to be added from various sources. In this chapter, these constants are defined and shown in Table 9-6.

Magnitude	Unit	Value		Source
		2005	2020	
Lower Heating Values				
Biomass - willow-salix	MJ/kg	12,16		boundary conditions
Biomass - wheat-straw	MJ/kg	13,1		boundary conditions
Biomass - miscanthus	MJ/kg	13,64		boundary conditions
BtL - FT-diesel	MJ/kg	44		boundary conditions
BtL - DME	MJ/kg	28,84		boundary conditions
BtL - Ethanol	MJ/kg	26,8		[FNR, 2006]
Methanol	MJ/kg	19,5		boundary conditions
1-Propanol	MJ/kg	30,7		chemical tables - internal
1-Butanol	MJ/kg	33,5		chemical tables - internal
1-Pentanol	MJ/kg	36,1		[Ullmann, 2006]
CO	MJ/kg	10,1		chemical tables - internal
Hydrogen	MJ/kg	120,1		boundary conditions
CH ₄	MJ/kg	50,1		chemical tables - internal
H ₂ S	MJ/kg	15,2		chemical tables - internal
C _{org}	MJ/kg	47,6		chemical tables - internal
C ₂ H ₄	MJ/kg	48,2		chemical tables - internal
C ₂ H ₆	MJ/kg	47,1		chemical tables - internal
C ₃ H ₈	MJ/kg	47,5		chemical tables - internal
Natural Gas	MJ/kg	36,8		boundary conditions
RME	MJ/kg	37,1		[FNR, 2006]
Naphtha	MJ/kg	43,7		Eucar study 2006, fixed by working partner VW
Temperatures				
ambient temperature	°C	20		boundary conditions
Additional efficiencies				
PE to electricity		0,392		[EU, 2006]
Electricity Transmission		0,961		[EWI, 2005]
PE to Biodiesel		0,35		internal assumption: IE Leipzig
PE to naphtha		0,924		[Oeko, 2006]
PE to methanol		0,807		[Ullmann, 2006]
PE to propanol		0,807		Assumption: same as MeOH
PE to butanol		0,807		Assumption: same as MeOH
PE to pentanol		0,807		Assumption: same as MeOH
PE to (district) heat		0,862		[EWI, 2005]
Others				
El. Energy Equivalent of Oxygen INPUT	kWh_el/kg_O ₂	0,45		[Jungbluth, 2006]
El. Energy Equivalent of Oxygen (Gutschrift - Surplus) OUTPUT	kWh_el/kg_O ₃	0,769		[Althaus et. al, 2004]
El. Energy Equivalent of Hydrogen	kWh_el/kg_H ₂	53,3		[Jungbluth, 2006]
Efficiency Indicator Freight transport	toe/Mtkm	54,6	53,7	[EU, 2006]

Table 9-6: Constants for Efficiency Calculations

9.3.5 Calculation of Conversion Plant Efficiency

Here, the definitions of chapter 9.3.1 to 9.3.4 are applied to BtL-conversion technologies for

- the overall plant in chapter 9.3.5.1
- the gasification unit in chapter 9.3.5.2
- the gas cleaning and gas conditioning unit in chapter 9.5.3.3

Hydrogen Supply. Some concepts of BtL-conversion technologies do not include product

upgrading. Hydrogen is needed for this final step. In this technical assessment, Hydrogen is assumed to be produced by electrolysis. The electricity required for electrolysis is added to the electricity input ($P_{el,ext}$) in terms of hydrogen mass flow times the electrical energy equivalent for hydrogen.

$$P_{el,H_2} = \dot{m}_{H_2} \cdot E_{el} Equ$$

Equation 9-10

Oxygen. The surplus oxygen produced by electrolysis will be allocated for electricity (regarding the conventional way of oxygen production – by an air separation unit).

$$P_{el,surplus,O_2} = \dot{m}_{surplus,O_2} \cdot E_{el} Equ$$

Equation 9-11

The additional oxygen delivered ‘over the fence’ is taken into account by multiplication with an electrical power generation equivalent.

$$P_{el,add,O_2} = \dot{m}_{add,O_2} \cdot E_{el} Equ$$

Equation 9-12

External Electricity.

External Electricity is defined as electricity consumption and thus positive.

$$P_{el,ext} = P_{el,input} + P_{el,H_2} + P_{el,add,O_2}$$

Equation 9-13

Surplus Electricity.

External Electricity is defined as electricity generation and thus negative (subtracted from the external electricity).

$$P_{el,surplus} = P_{el,output} + P_{el,surplus,O_2}$$

Equation 9-14

Net Electricity. In calculations, only net electricity will be used. The net electricity is the sum of the electricity consumed the allocated electricity for hydrogen production and the allocated electricity for oxygen production minus the sum of the electricity produced and the allocated electricity for oxygen surplus.

$$P_{el,net} = P_{el,ext} - P_{el,surplus}$$

Equation 9-15

9.3.5.1 Overall Plant

System boundary: BtL-plant including product upgrading unit

System boundary: BtL-plant including product upgrading unit
(Plant gate: Biomass in; BtL out)

Target energy: BtL (FT-Diesel; DME; Ethanol)

Figure 9-10 includes all possible variations of BtL-production. Some implementations do not include every in- and output but in order to be able to compare all different approaches this definition is used.

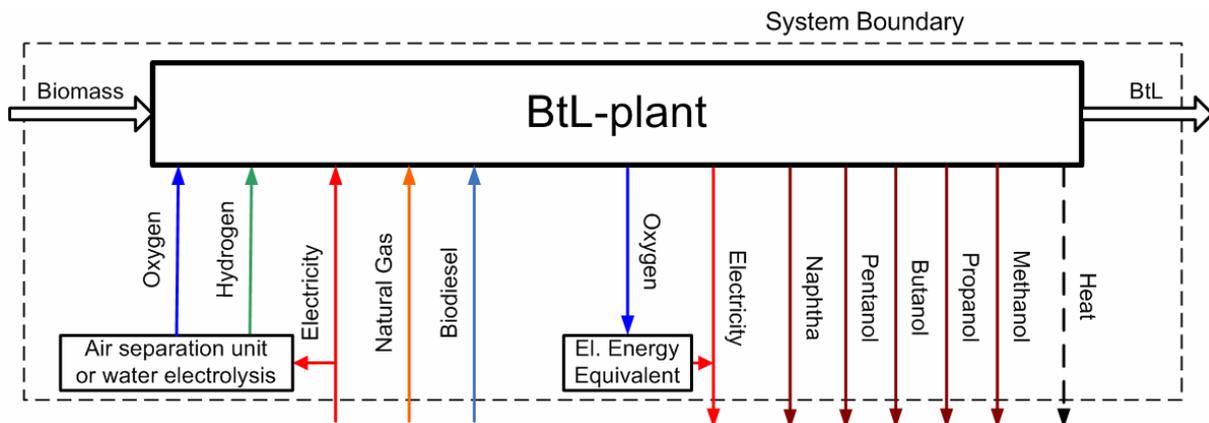


Figure 9-10: Definition of Overall Plant Efficiency – Conversion Plant

Overall Efficiency – Main Fuel.

Conventional Method. The overall efficiency ‘main fuel’ according to scenario paper, i.e. without heat is calculated as the fraction of the BtL fuel power referred to the sum of the fuel power of the biomass entering the plant, the external electrical power consumption and the fuel power of natural gas reduced by the naphtha fuel power, other alcohols power and the surplus electrical power.

$$\eta_{overall-heat} = \frac{\dot{m}_{BtL} \cdot LHV_{BtL}}{\dot{m}_{biomass} \cdot LHV_{biomass} + P_{el,ext} + \dot{m}_{NG} \cdot LHV_{NG} - \dot{m}_{naphtha} \cdot LHV_{naphtha} - \sum \dot{m}_{other_alcohols} \cdot LHV_{other_alcohols} - P_{el,surplus}}$$

Equation 9-16

Overall Efficiency – All Liquids.

Conventional Method. The overall efficiency ‘all liquids’ is calculated as the fraction of the sum of BtL fuel power, naphtha fuel power and other alcohols power referred to the sum of the fuel power of biomass entering the plant, external electrical power consumption and the fuel power of natural gas reduced by surplus electrical power.

$$\eta_{\text{overall-heat}} = \frac{\dot{m}_{\text{BtL}} \cdot \text{LHV}_{\text{BtL}} + \dot{m}_{\text{naphtha}} \cdot \text{LHV}_{\text{naphtha}} + \sum \dot{m}_{\text{other_alcohols}} \cdot \text{LHV}_{\text{other_alcohols}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}} + P_{\text{el,ext}} + \dot{m}_{\text{NG}} \cdot \text{LHV}_{\text{NG}} - P_{\text{el,surplus}}}$$

Equation 9-17

Overall Efficiency – CHP-F.

CHP-F method. The overall efficiency ‘CHP-F’ (or tri-generation) is calculated as the fraction of the sum of BtL fuel power, naphtha fuel power, other alcohols power, the produced electrical power and the surplus thermal power; referred to the sum of the fuel power of the biomass entering the plant, the external electrical power consumption and the NG fuel power.

$$\eta_{\text{overall+heat}} = \frac{\dot{m}_{\text{BtL}} \cdot \text{LHV}_{\text{BtL}} + \dot{m}_{\text{naphtha}} \cdot \text{LHV}_{\text{naphtha}} + \sum \dot{m}_{\text{other_alcohols}} \cdot \text{LHV}_{\text{other_alcohols}} + P_{\text{el,surplus}} + P_{\text{district_heat}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}} + P_{\text{el,ext}} + \dot{m}_{\text{NG}} \cdot \text{LHV}_{\text{NG}}}$$

Equation 9-18

Conversion Rate: Biomass to Main Fuel.



Figure 9-11: Definition of the Conversion Rate Biomass to Main Fuel

The energetic conversion rate from ‘biomass to main fuel’ is calculated as the fraction of BtL fuel power to the fuel power of biomass entering the plant. The result is a figure representing the fraction of biomass input, which was converted into BtL fuel (see Figure 9-11).

A mass-based criterion [kg of BtL / kg of Biomass] is not evaluated, since the heating values of the BtL products differ very much and thus such a criterion does not result in a utilizable information.

$$y_{\text{BM,BtL}} = \frac{\dot{m}_{\text{BtL}} \cdot \text{LHV}_{\text{BtL}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

Equation 9-19

Conversion Rate: Biomass to All Liquids.

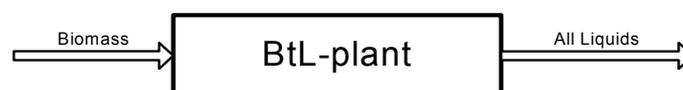


Figure 9-12: Definition of the Conversion Rate Biomass to All Liquids

The energetic conversion rate from ‘biomass to all liquids’ is calculated as the fraction of the sum of BtL fuel power, naphtha fuel power and other alcohols power to the fuel power of biomass entering the plant. The result is a figure representing the friction of biomass input, which was converted into BtL fuel (see Figure 9-12). A mass-based criterion [kg of BtL / kg of Biomass] is not evaluated, since the heating values of the BtL products differ very much and thus such a criterion does not result in a utilizable information.

$$y_{BM, fuels} = \frac{\dot{m}_{BtL} \cdot LHV_{BtL} + \dot{m}_{naphtha} \cdot LHV_{naphtha} + \sum \dot{m}_{other_alcohols} \cdot LHV_{other_alcohols}}{\dot{m}_{biomass} \cdot LHV_{biomass}}$$

Equation 9-20

9.3.5.2 Gasification

Two different system boundaries are investigated within this chapter.

Gasifier Efficiency – Gasification Media Based.

System: Gasification unit

System boundary: Gasification unit

Target energy: Raw Gas

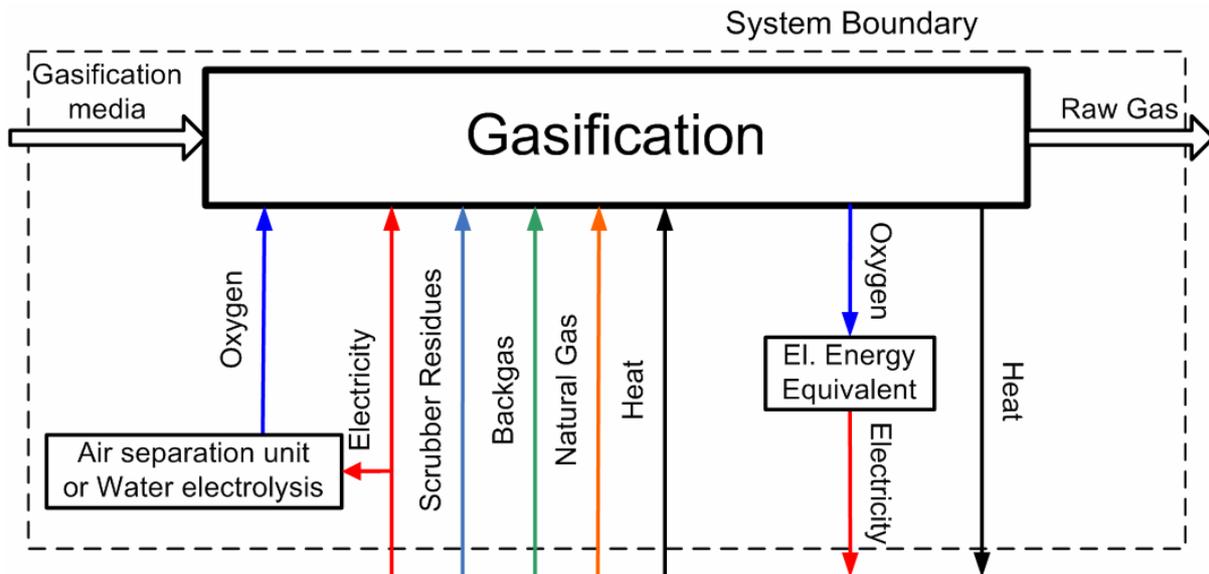


Figure 9-13: Definition of Gasification Efficiency – Gasification Media Based – Conversion Plant

Conventional method (target power = raw gas flux). The gasification efficiency (gasification media based) is calculated as the fraction of the fuel power of the raw gas (including tar) referred to the sum of the fuel power of the inputs gasification media, natural gas, liquid scrubber residues (used biodiesel) and backgas, the electrical power consumption for gasification and the thermal power entering the unit reduced by the surplus electrical power and the surplus thermal power leaving the unit. The energetic efficiency is gasification media based (for illustration see Figure 9-13).

$$\eta_{\text{gasif}} = \frac{\dot{m}_{RG} \cdot LHV_{RG}}{\dot{m}_{\text{gasif_media}} \cdot LHV_{\text{gasif_media}} + \dot{m}_{\text{scrub_res.}} \cdot LHV_{\text{scrub_res.}} + \dot{m}_{\text{backgas}} \cdot LHV_{\text{backgas}} + \dot{m}_{NG} \cdot LHV_{NG} + P_{\text{el,gasif}} + \dot{Q}_{\text{Heat_gasif}} - P_{\text{el,gasif_surplus}} - \dot{Q}_{\text{Surplus}}}$$

Equation 9-21

Gasifier Efficiency – Biomass Based.

System: Gasification unit including preparation (drying, pyrolysis, etc.)

System boundary: Gasification unit including preparation (drying, pyrolysis, etc.)

Target energy: Raw gas

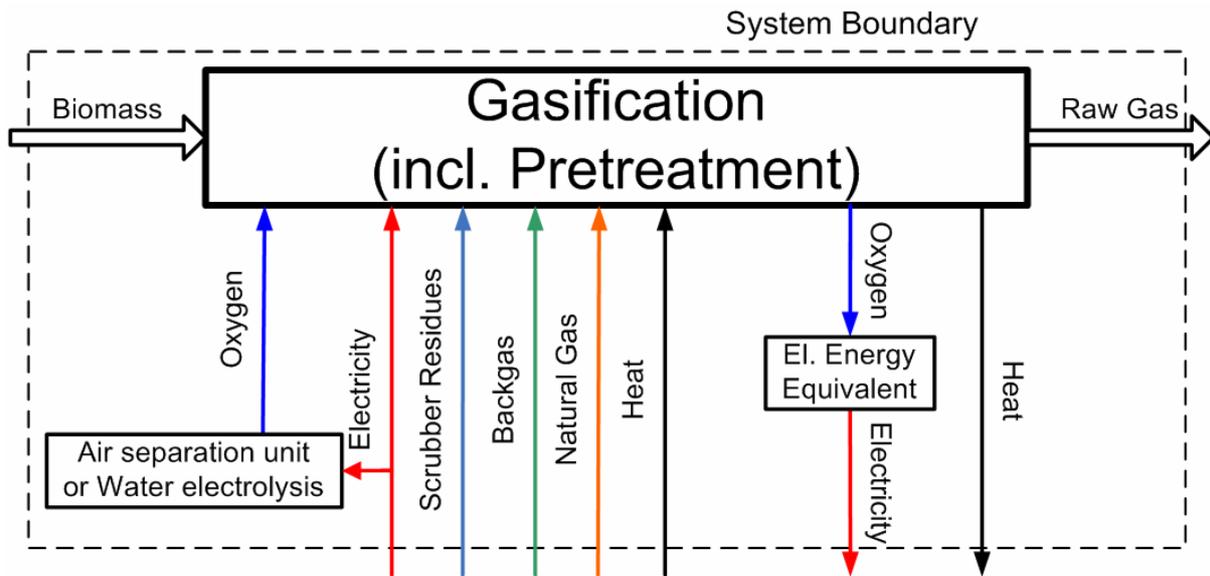


Figure 9-14: Definition of Gasification Efficiency – Biomass Based – Conversion Plant

Conventional method (target power = raw gas flux). The gasification efficiency (biomass based) is calculated in the same way as the gasification efficiency based on gasification media with only two differences:

- biomass is considered as main input instead of gasification media,
- heat and electricity necessary for biomass pretreatment is also included in the calculations (see also Figure 9-14).

$$\eta_{\text{gasif}} = \frac{\dot{m}_{RG} \cdot LHV_{RG}}{\dot{m}_{\text{biomass}} \cdot LHV_{\text{biomass}} + \dot{m}_{\text{scrub_res.}} \cdot LHV_{\text{scrub_res.}} + \dot{m}_{\text{backgas}} \cdot LHV_{\text{backgas}} + \dot{m}_{NG} \cdot LHV_{NG} + P_{\text{el,gasif}} + \dot{Q}_{\text{Heat_gasif}} - P_{\text{el,gasif_surplus}} - \dot{Q}_{\text{Surplus}}}$$

Equation 9-22

Cold Gas Conversion Rate (Gasification Media Based).



Figure 9-15: Definition of Cold Gas Conversion Rate (Gasification Media Based)

The cold gas conversion rate (sometimes referred also as cold gas ‘efficiency’ or ‘chemical efficiency’) is generally defined as the amount of chemical energy, which can be transferred from fuel power in the gasification media into the fuel power of the output gas of a thermo-chemical conversion process (Figure 9-15) [Bolhár-Nordenkamp, 2004], [Kaltschmitt, 2003]. The gasification media in this particular definition is the gasification media can be solid (e.g. willow-salix) or liquid (e.g. black liquor).

$$y_{gasif / RG} = \frac{\dot{m}_{RG} \cdot LHV_{RG}}{\dot{m}_{gasif_media} \cdot LHV_{gasif_media}} \quad \text{Equation 9-23}$$

Syngas Conversion Rate (Gasification Media Based).



Figure 9-16: Definition of Syngas Conversion Rate (Gasification Media Based)

The gasification media based syngas conversion rate is calculated as the fraction of the fuel power of hydrogen and CO (part of the syngas) referred to the fuel power of the gasification media input (Figure 9-16). The gasification media in this particular definition is the gasification media can be solid (e.g. willow-salix) or liquid (e.g. black liquor).

$$y_{gasif / H_2 \& CO} = \frac{\dot{m}_{H_2} \cdot LHV_{H_2} + \dot{m}_{CO} \cdot LHV_{CO}}{\dot{m}_{gasif_media} \cdot LHV_{gasif_media}} \quad \text{Equation 9-24}$$

9.3.5.3 Gas Cleaning and Gas Conditioning

System: Gas cleaning unit & Gas conditioning unit
 System boundary: Gas cleaning unit & Gas conditioning unit
 Target energy: Syngas

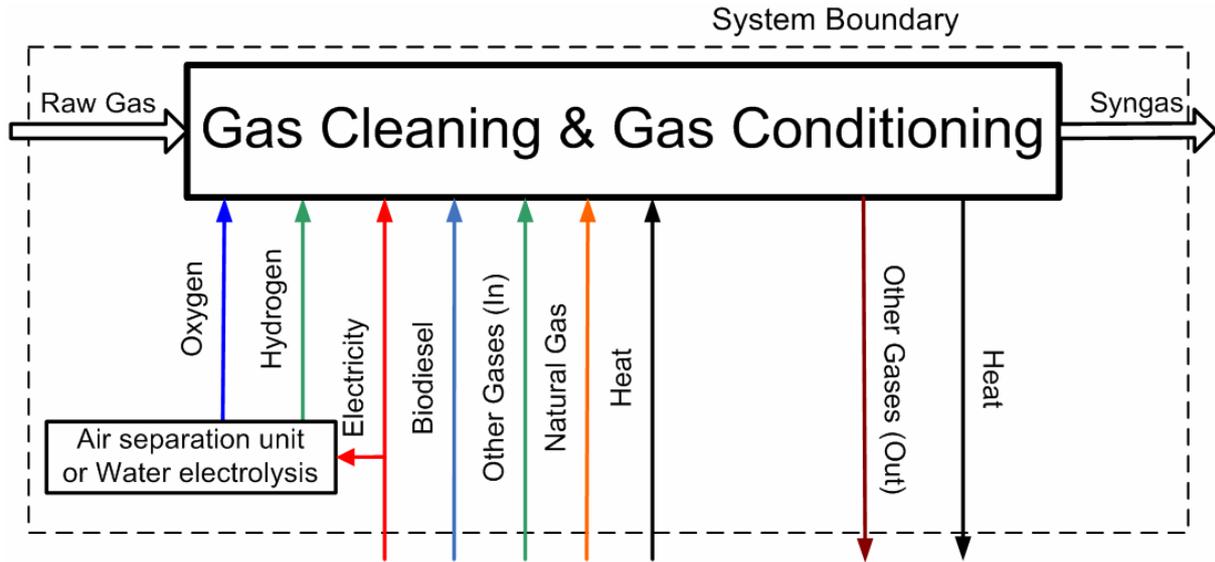


Figure 9-17: Definition of Gas Cleaning and Gas conditioning System Boundaries – Conversion Plant

Gas Cleaning and Gas Conditioning Efficiency.

Conventional method (target power = syngas flux). The gas cleaning and gas conditioning efficiency is calculated as the fraction of the fuel power of the syngas referred to the sum of the fuel power of the inputs raw gas, biodiesel, other gases (in) and natural gas, the electrical power consumption for gas cleaning / conditioning and the thermal power entering the unit reduced by the sum of the fuel power of other gases (out) surplus thermal power leaving the unit (Figure 9-17).

Other gases as input are different from other gases as output. As input other gases are purge gas, recycle gas, relax gas and light ends. Surplus gas, back gas and H₂S are defined as output.

$$\eta_{C\&C_overall} = \frac{\dot{m}_{SG} \cdot LHV_{SG}}{\dot{m}_{RG} \cdot LHV_{RG} + \dot{m}_{Biodiesel} \cdot LHV_{Biodiesel} + \dot{m}_{NG} \cdot LHV_{NG} + \dot{m}_{other(IN)} \cdot LHV_{other(IN)} + P_{el,C\&C} + \dot{Q}_{Heat_C\&C} - \dot{m}_{other(OUT)} \cdot LHV_{other(OUT)} - \dot{Q}_{surplus}}$$

Equation 9-25

Syngas Conversion Rate.

System: Gasification, Gas cleaning unit & Gas conditioning unit

System boundary: Gasification, Gas cleaning unit & Gas conditioning unit

Target energy: Syngas



Figure 9-18: Definition of Syngas Conversion Rate

The syngas conversion rate (Figure 9-18) includes the units

- gas cleaning
- gas conditioning
- gasification, considering the overall process which includes all 4 steps (drying, pyrolysis, combustion, gasification)
- preparation of gasification media (in some plants, the preparation of the gasification media is decentralized. Therefore the transport power has to be accounted as well)
- external HYDROGEN is not included in this conversion rate, although it is added additionally to the syngas output from electrolysis in some scenarios. The correct way would be to consider also the biomass used to generate this external hydrogen (by power generation and electrolysis for example).

$$\eta_{\text{syngas}} = \frac{\dot{m}_{\text{H}_2} \cdot \text{LHV}_{\text{H}_2} + \dot{m}_{\text{CO}} \cdot \text{LHV}_{\text{CO}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}}}$$

Equation 9-26

9.3.6 Calculation of Primary Energy Based Efficiency

Here, the definitions of chapter 9.3.1 to 9.3.4 are applied to BtL-conversion technologies with relation to the first conversion of primary energy for

- the overall plant in chapter 9.3.6.1

The PE-equivalent efficiency of the gasification as well as of the gas cleaning and gas conditioning units will be discussed in chapter 9.3.6.2.

Thereby the aspect of hydrogen supply is considered similar to chapter 9.3.5.

9.3.6.1 Overall plant

System: BtL-plant

System boundary: First Conversion of Primary Energy into Secondary Energy

Target energy: BtL (FT-Diesel; DME; Ethanol)

Figure 9-19 includes all possible variations of BtL-production. Some implementations do not include every in- and output but in order to be able to compare all different approaches this definition is used.

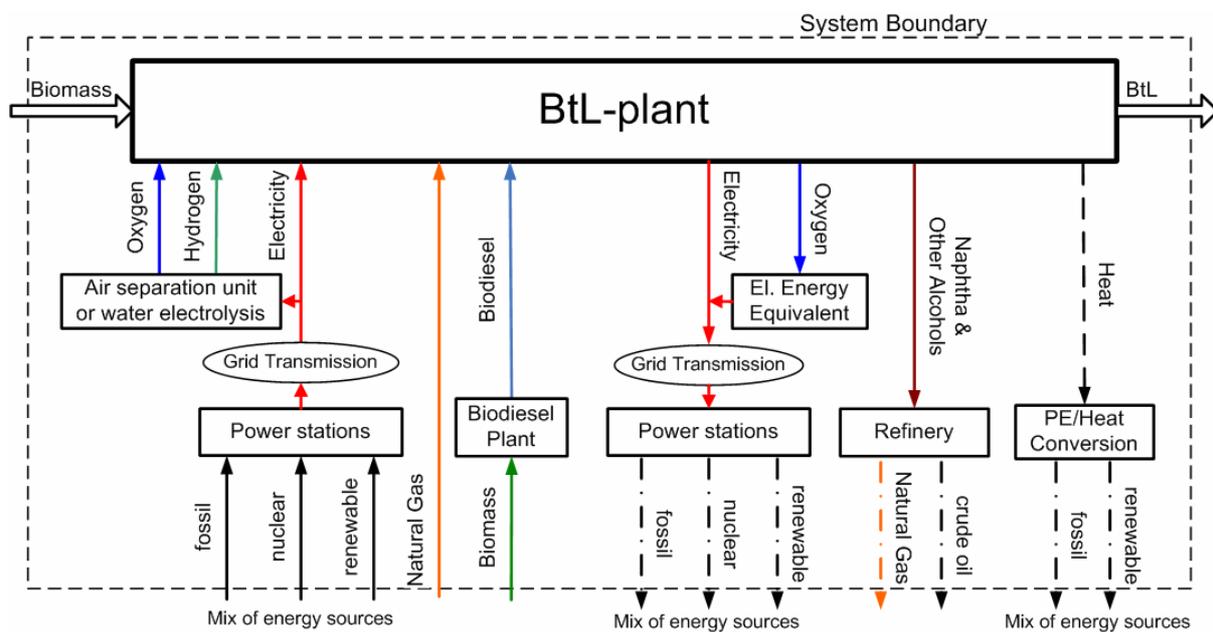


Figure 9-19: Definition of Overall Plant Efficiency – Primary Energy Based PE-equivalent Overall Efficiency – Main Fuel.

Conventional Method. The PE-equivalent overall efficiency 'main fuel' according to scenario paper, i.e. without heat is calculated as the fraction of BtL fuel power referred to the sum of the fuel power of the biomass entering the plant, the fuel power of natural gas, the biodiesel fuel power over the efficiency of converting biomass to biodiesel and the external electrical power consumption over the product of the primary energy sources mix conversion efficiency and the electrical transmission efficiency; reduced by the sum of NN fuel power over the efficiency of converting a mix of primary energy sources (crude oil and natural gas) to NN fuel; and the produced electrical power over the product of the primary energy sources mix conversion efficiency and the electrical transmission efficiency.

The energetic content of the by-products are calculated 'virtually' back to the original primary energy in order to keep the system boundaries.

$$\eta_{\text{overall-heat}} = \frac{\dot{m}_{\text{BiL}} \cdot \text{LHV}_{\text{BiL}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}} + \frac{P_{\text{el,ext}}}{\eta_{\text{PE_el_conv}} \cdot \eta_{\text{trans_el}}} + \dot{m}_{\text{NG}} \cdot \text{LHV}_{\text{NG}} + \frac{\dot{m}_{\text{Biodiesel}} \cdot \text{LHV}_{\text{Biodiesel}}}{\eta_{\text{PE_Biodiesel_conv}}} - \sum \frac{\dot{m}_{\text{NN}} \cdot \text{LHV}_{\text{NN}}}{\eta_{\text{PE_NN_conv}}} - \frac{P_{\text{el,surplus}}}{\eta_{\text{PE_el_conv}} \cdot \eta_{\text{trans_el}}}}$$

Equation 9-27

NN fuel. The liquid by-products are many (namely naphtha, methanol, (1)-propanol, (1)-butanol and (1)-pentanol) and will be abbreviated with NN in this and following formulas.

Mix of energy sources. The mix of energy sources is based on the conversion rate of PE into SE today and for 2020 [EU, 2006]

Electricity: the produced electricity per annum over the PE input per annum
 $\frac{MWh_{\text{el}} / a}{MWh_{\text{PE}} / a}$

PE-equivalent Overall Efficiency – All Fuels.

Conventional Method. The PE-equivalent overall efficiency 'all fuels' according to scenario paper, i.e. without heat is calculated in the same way as the PE-equivalent overall efficiency 'main fuel'. The only difference is that the fuel by-products (NN fuels) are considered as 'target energy' and moved from the denominator to the nominator (added to the main fuel output and not subtracted from the effort).

$$\eta_{\text{overall-heat}} = \frac{\dot{m}_{\text{BiL}} \cdot \text{LHV}_{\text{BiL}} + \sum \frac{\dot{m}_{\text{NN}} \cdot \text{LHV}_{\text{NN}}}{\eta_{\text{PE_NN_conv}}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}} + \frac{P_{\text{el,ext}}}{\eta_{\text{PE_el_conv}} \cdot \eta_{\text{trans_el}}} + \dot{m}_{\text{NG}} \cdot \text{LHV}_{\text{NG}} + \frac{\dot{m}_{\text{Biodiesel}} \cdot \text{LHV}_{\text{Biodiesel}}}{\eta_{\text{PE_Biodiesel_conv}}} - \frac{P_{\text{el,surplus}}}{\eta_{\text{PE_el_conv}} \cdot \eta_{\text{trans_el}}}}$$

Equation 9-28

Overall Efficiency – CHP-F.

CHP-F method. The overall efficiency with heat is calculated in the same way as the PE-equivalent overall efficiency 'all fuels' with two differences:

- (surplus) electricity output is considered as 'target energy' (moved from the denominator to the nominator)
- Surplus thermal power is also considered as 'target energy' and added to the power output (added in the nominator). The surplus thermal power is divided by the product of a primary energy sources mix conversion efficiency.

$$\eta_{\text{overall-heat}} = \frac{\dot{m}_{\text{BiL}} \cdot \text{LHV}_{\text{BiL}} + \sum \frac{\dot{m}_{\text{NN}} \cdot \text{LHV}_{\text{NN}}}{\eta_{\text{PE_NN_conv}}} + \frac{P_{\text{el,surplus}}}{\eta_{\text{PE_el_conv}} \cdot \eta_{\text{trans_el}}} + \frac{\dot{Q}_{\text{surplus}}}{\eta_{\text{PE_heat_conv}}}}{\dot{m}_{\text{biomass}} \cdot \text{LHV}_{\text{biomass}} + \frac{P_{\text{el,ext}}}{\eta_{\text{PE_el_conv}} \cdot \eta_{\text{trans_el}}} + \dot{m}_{\text{NG}} \cdot \text{LHV}_{\text{NG}} + \frac{\dot{m}_{\text{Biodiesel}} \cdot \text{LHV}_{\text{Biodiesel}}}{\eta_{\text{PE_Biodiesel_conv}}}}$$

Equation 9-29

9.3.6.2 Gasification and Gas Cleaning and Gas Conditioning

PE-equivalent definitions for efficiencies of gasification and gas cleaning and gas conditioning can be further indicators for technical assessment. They were defined and calculated but due to many indicators they were kept out of the technical assessment.

9.4 Literature Review on Gas Cleaning and Gas Conditioning

The biomass gasification process is quite similar to that of coal gasification, yielding in both cases a mixture of gases with the same main components. However, due to the higher reactivity and the milder reaction conditions of biomass the gas composition is different for biomass and coal. In general pressurized gasification favours the production of methane and carbon dioxide, whereas increasing the temperature tends to increase the concentration of hydrogen and carbon monoxide. Undesirable by-products and emissions encountered in the product gas, such as particulates and tar, are the main complications for its use in downstream synthesis or electricity production. Steam is often used as the gasification agent for syngas production. Blended with oxygen or air, it promotes the formation of H₂ and CO. The use of catalysts (e.g. Ni) in connection with steam gasification additionally contributes to increasing the hydrogen content due to the catalytic conversion of tar.

Using high-temperature oxygen-blown gasification, the tar content can be reduced to even lower levels. There are several options for gasification available or in development. However, only a few of them are suitable for biomass applications for producing hydrogen and synthesis gas. Gasifiers can work either with *direct heating*, in which the biomass is partially oxidised in order to supply the heat for the gasification or with *indirect heating*, using heat exchangers or heat carriers for the heat supply. For synthesis gas generation from biomass, the indirectly heated reactors or the directly heated, oxygen-blown reactors with partial oxidation are preferred. In both cases, the product gases show low proportions of inert gas (N₂) with a relatively high hydrogen concentration.

9.4.1 Fuel Synthesis

The general reaction of fuel synthesis is the formation of hydrocarbon chains from synthesis gas as follows: $\text{CO} + 2 \text{H}_2 \rightarrow \text{-(CH}_2\text{)-} + \text{H}_2\text{O}$.

The reaction is exothermic and needs a catalyst. Process conditions of the main fuel synthesis are listed exemplarily in Table 9-7. Most synthesis forming hydrocarbon chains –CH₂– and H₂O need a ratio of the educts H₂/CO of 2/1.

The use of catalysts requires a very clean synthesis gas. Therefore, high-priority research efforts focus on gas cleaning and on technologies with gas cleaning/conditioning (e.g. catalytic and thermal tar cracking), which yield synthesis-grade gases. The general purity requirements for synthesis gas suitable for fuel synthesis are listed in Table 9-8.

	Product	Pressure	Temp.	Catalyst	H ₂ :CO
Methane	CH ₄	1-30 bar	300-400 °C	Ni	3:1
Methanol	CH ₃ OH	50-100 bar	250-280 °C	Cu/ZnO	2:1
Fischer-Tropsch	- CH ₂ -	3-25 bar	190-240 °C	Co	2:1
Fischer-Tropsch	- CH ₂ -	3-25 bar	250-300 °C	Fe	2:1
Direct DME**	CH ₃ -O-CH ₃	50 bar	260 °C	special	1:1

Table 9-7: Exemplary Process Conditions of Fuel Synthesis and Stoichiometric Synthesis Gas Ratio*

* Optimal synthesis gas ratio H₂/CO used in technical application can differ from stoichiometric value depending on reactor type, process conditions, and catalyst

** Dimethylether can be produced via methanol dehydration technology (termed as the two-step or indirect method starting from syngas). This indirect path is currently state-of-the-art and consists of a conventional methanol synthesis step followed by the downstream catalytic conversion of methanol. An alternative technology is the production directly from syngas in a single-step DME synthesis with specially designed catalysts. This technology was successfully demonstrated at some pilot plants (e.g. a 30 t/d plant from Mitsubishi Gas Chemicals, Japan).

Component	Permissible Concentration /see Lit. above/	/Uhde ThyssenKrupp/
H ₂ S and other sulphur comp.	< 0.1 mg/Nm ³	0.1-15 ppm
Particles	< 0.2 mg/Nm ³	~ 0 mg/Nm ³
Tar	< 1.0 mg/Nm ³	
Alkalis	< 0.25 mg/Nm ³	
NH ₃ , HCN	< 0.1 mg/Nm ³	HCN 1-7ppm NH ₃ 1-5ppm
Cl, F	< 0.1 mg/Nm ³	HCl 0.5-5 ppm

Table 9-8: Permissible Sulphur and Other Impurities Concentrations of a Synthesis Gas Suitable for Methanol and Hydro Carbon Fuel Synthesis Process /Specht et al. 2006; Beenackers 1984; Hasler 1994; Boerrigter 2002, Ullmann's 2002/

Table 9-8 summarises values for required synthesis gas quality which can be found in literature. It has to be kept in mind that Fisher-Tropsch Synthesis can be realised using different process conditions (see Table 9-7), different catalyst, and different reactor types. Using a slurry reactor where the catalyst is in liquid suspension it can be assumed that a continuous catalyst purge or regeneration is possible. Thus higher concentration of impurities may be tolerated. At last the supplier who guaranty for the performance of the catalyst has to determine the permissible values which can be significant higher than those given in Table 9-8.

9.4.2 Gas Cleaning and Gas Conditioning Using Rectisol/Selexol

The process behind the trademarks rectisol (Lurgi, Linde) and selexol (Dow Chemical) is a gas-liquid scrubbing processes using different liquid solvents and process conditions. The sorption process of the gas impurities can be physical, chemical, or a combination of both. Examples of commercial available scrubbing processes are given in Table 9-9.

Process (supplier)	Ad-/Absorbat	Sorbent (Solvent)	Conditions	Synthesis gas quality
Physical absorption				
Pressurized water (Flotech)	H ₂ S, CO ₂ , NH ₃	H ₂ O	P > 10bar, T 3 to 30 °C	
Rectisol (Lurgi, Linde)	H ₂ S, COS, org.S, CO ₂ , NH ₃ , HCN, Aromatic HC	Methanol	P > 20 bar, T -70 to -10 °C	0.1-1ppm (H ₂ S+COS) 10-50ppm (CO ₂) > 10 000m ³ /h
Selexol (Allied Chem.Corp./Dow Chemical)	H ₂ S, COS, org.S, CO ₂ , NH ₃ , HCN, Aromatic HC	Polyethylen Glycoldimethyether	P 20-30 bar, T 0 to 40 °C	1ppm (H ₂ S) > 10 000m ³ /h
Chemical absorption				
Catacarb (Lurgi)	SO ₂ , H ₂ S, COS, HCN, CO ₂	K ₂ CO ₃ lye + catalyst	P 22 -70bar, T 70 to 120 °C	
Phy.& chem. absorption				
Amisol (Lurgi)	H ₂ S, COS, org.S, CO ₂ , NH ₃ , HCN, Aromatic HC	Methanol + MEA or DEA, DIPAM		0.1 ppm (H ₂ S)
Genosorb (Clariant)	H ₂ S, COS, CS ₂ , CH ₃ SH, NH ₃ , optimised for CO ₂	Polyethylen Glycoldimethyether + Amine	P > 20 bar, T 20 to 40 °C	

Table 9-9: Examples of Commercial Available Scrubbing Processes and the Main Process Parameters for Synthesis Gas Cleaning and Upgrading /Ullmann's 2002, Clariant 2002, Lurgi 2005/

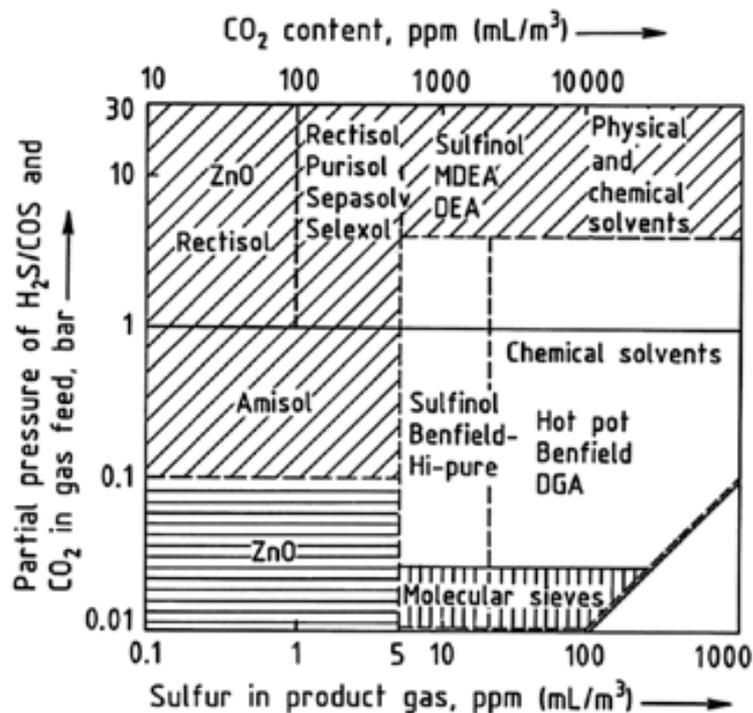


Figure 9-20: Selection of Appropriate Gas Purification Process for Simultaneous H₂S/COS and CO₂ Removal /Ullmann's 2002/

9.4.2.1 Rectisol Scrubbing

The rectisol process is a commercial available gas cleaning and gas conditioning process with a world wide installed capacity of 200 Mio. m³/d for cleaning raw gases of residual oil, waste, and coal gasification. The world biggest CtL (coal to liquid) plant in South Africa (Sasol) is equipped with rectisol technology with subsequent Fischer-Tropsch synthesis.

The rectisol process is very flexible and can be adapted for the requirements of different gas cleaning and gas conditioning tasks depending on raw gas and requirements of the synthesis. Like the most scrubbing processes (see Table 9-9) the rectisol wash is a multi component absorption which can be done in one unit. Oxygen blown biomass gasification produces less H₂ and much CO that have to be shifted to CO₂ which have to be removed before FT-synthesis. The components H₂S and CO₂ show different solubility in the solvent (Methanol). This offers the possibility to make the ab- and desorption stepwise which can be used for residual product separation. The solubility of H₂S is higher than that of CO₂. Therefore CO₂ is released by expansion of the solvent while desorption of H₂S needs cooking of the solvent (energy intensive). However this is only one example of process flexibility but on the other hand the flexibility increases complexity and costs. For that reason rectisol is suitable for gas flows > 10000 m³/h.

Applying rectisol wash for black liquor gasification and DME synthesis (Chemrec) offers further advantages. The used Methanol solvent is (intermediate) product of DME synthesis. Black liquor gasification produces high concentration of sulphur compounds in the raw gas. Rectisol offers the possibility to separate a sulphur rich acidic gas which can be recycled in the paper mill (for white liquor production).

9.4.2.2 Selexol Scrubbing

Except minor differences the selexol and other scrubbing technologies have the same performance. Referring to Figure 9-20, the selexol solvent remove H_2S down to 1 ppm. According to Table 9-8, this is not sufficient for synthesis catalyst (ThyssenKrupp gives a range from 0.1 to 15 ppm). As mentioned gas impurities and type of catalyst determine at last the catalyst lifetime. To find an economic solution is more a question of optimisation than of given threshold values. Coming back to biomass gasification with low sulphur content in the raw gas it seems not beneficial to separate H_2S as a residual product as it was mentioned as an advantage of rectisol. If no deep desulphurisation is necessary using selexol or other solvents may become more economic because of the moderate process conditions in comparison to rectisol ($-70\text{ }^{\circ}C$).

9.4.3 Other Fine Cleaning Methods

Besides rectisol/selexol scrubbing which is commercial available proven technology there are other concepts using dry methods for fine cleaning to achieve syngas quality. The capability of the two dry H_2S absorbents ZnO and molecular sieves are shown in Figure 9-20. The advantage of dry absorbents is that they can operate at higher temperatures than liquid solvents and that there is no waste water produced. Nevertheless the absorbents have to be regenerated or purged. The use of activated or special impregnated carbon as final police filter offers the possibility to recycle the purge to the gasifier. This causes not necessary the enrichment of impurities because they can abandon the process with the ash or in previous gas cleaning steps. Especially when smaller plant size is envisaged dry solid absorbents can be an economic alternative for final gas cleaning because they are less complex than rectisol/selexol units.

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9.5 Indicators for Efficiency

The following indicators ‘efficiency’ and ‘conversion rate’ show different efficiencies and conversion rates for all scenarios and units, as described and defined in detail in chapter 9.3.

9.5.1 Overall Efficiencies and Conversion Rates – Conversion Plant

The next table lists the overall efficiencies and conversion rates ‘conversion plant’, calculated according to the definitions in chapter 9.3.5.1. These indicators will be evaluated in chapter 5.1.1.

Concept	cEF-D			dEF-D		BLEF-DME	EF-E			CFB-D				ICFB-D				CFB-E	
	SP	SP	MF	SP/SS	MF	SP/SS	SP/SS	MF	MF	SP/SS	SP/SS	MF	MF	SP	SP	MF	MF	SP/SS	MF
Scenario	willow	straw	willow	straw	straw	willow	willow	willow	willow	willow	straw	willow	straw	willow	misc.	willow	misc.	willow	willow
Biomass type	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	50 MW	50 MW	500 MW	500 MW	500 MW	500 MW					
Biomass power																			
Conventional Method (target power = fuel (BtL))																			
Overall Efficiency - main fuel	48%	48%	49%	38%	38%	69%	20%	29%	34%	30%	37%	35%	24%	23%	52%	54%	23%	29%	
Overall Efficiency - all liquids	53%	53%	53%	45%	46%	69%	34%	46%	41%	37%	45%	42%	30%	29%	60%	61%	37%	45%	
CHP-F Method (target power=heat, electr., fuel)																			
Overall Efficiency - CHP-F	54%	53%	53%	45%	46%	69%	41%	47%	41%	37%	45%	42%	82%	84%	63%	64%	38%	45%	
Conversion Rates																			
Conversion Rate - biomass to main fuel	44%	44%	90%	33%	67%	69%	15%	25%	30%	28%	42%	41%	19%	19%	41%	42%	19%	28%	
Conversion Rate - biomass to all liquids	53%	53%	108%	45%	91%	69%	30%	50%	40%	38%	57%	56%	26%	26%	55%	57%	36%	57%	

Table 9-10: Overall Efficiencies and Conversion Rates – Conversion Plant

9.5.2 Overall Efficiencies– Primary Energy Based

The next table lists the efficiencies and conversion rates ‘primary energy based’, calculated according to the definitions in chapter 9.3.6.1. These indicators will be evaluated in chapter 5.1.1.

Concept	cEF-D			dEF-D		BLEF-DME	EF-E			CFB-D				ICFB-D				CFB-E	
	SP	SP	MF	SP/SS	MF	SP/SS	SP/SS	SP/SS	MF	SP/SS	SP/SS	MF	MF	SP	SP	MF	MF	SP/SS	MF
Scenario	willow	straw	willow	straw	straw	willow	willow	willow	willow	willow	straw	willow	straw	willow	misc.	willow	misc.	willow	willow
Biomass type	willow	straw	willow	straw	straw	willow	willow	willow	willow	willow	straw	willow	straw	willow	misc.	willow	misc.	willow	willow
Biomass power	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	50 MW	50 MW	500 MW	500 MW	500 MW	500 MW					
Conventional Method - PE based (target power = fuel (BtL))																			
Overall Efficiency- main fuel	50%	50%	26%	38%	20%	69%	29%	33%	34%	29%	27%	24%	31%	30%	64%	65%	26%	28%	
Overall Efficiency - all fuels	55%	55%	30%	46%	26%	69%	49%	53%	42%	36%	34%	31%	39%	38%	71%	72%	43%	47%	
CHP-F Method - PE based (target power=heat, electr., fuel)																			
Overall Efficiency - CHP-F	56%	56%	30%	46%	26%	69%	65%	56%	44%	36%	34%	31%	108%	110%	77%	77%	46%	47%	

Table 9-11: Overall Efficiencies – Primary Energy Based

9.5.3 Gasification Efficiencies and Conversion Rates

The next table lists the gasification efficiencies and conversion rates, calculated according to the definitions in chapter 9.3.5.2. These indicators will be evaluated in chapter 5.1.2.

Concept	cEF-D			dEF-D		BLEF-DME	EF-E		CFB-D				ICFB-D				CFB-E	
Scenario	SP	SP	MF	SP/SS	MF	SP/SS	SP/SS	MF	SP/SS	SP/SS	MF	MF	SP	SP	MF	MF	SP/SS	MF
Biomass type	willow	straw	willow	straw	straw	willow	willow	willow	willow	straw	willow	straw	willow	misc.	willow	misc.	willow	willow
Biomass power	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	50 MW	50 MW	500 MW	500 MW	500 MW	500 MW					
Conventional Method (target power = raw gas incl. tar)																		
Gasifier Efficiency - Gasification media based	89%	90,9%	89%	90%	90%	77%	84%	84%	85%	83%	87%	90%	83%	84%	79%	79%	70%	70%
Gasifier Efficiency - Biomass based	85%	90,2%	85%	85%	85%	91%	67%	67%	84%	77%	87%	83%	83%	85%	79%	79%	62%	62%
Conversion Rate																		
Conversion Rate - cold gas - Gasification media based	84%	85,6%	84%	85%	85%	80%	72%	72%	81%	84%	85%	89%	79%	81%	78%	79%	74%	74%
Conversion Rate - 'syngas' - Gasification media based	75%	76,7%	75%	85%	85%	73%	72%	72%	59%	57%	62%	63%	44%	45%	45%	46%	46%	46%

Table 9-12: Gasification Efficiencies and Conversion Rates

9.5.4 Gas Cleaning and Gas Conditioning Efficiencies and Conversion Rates

The next table lists the gas cleaning and gas conditioning efficiencies and conversion rates, calculated according to the definitions in chapter 9.3.5.3. These indicators will be evaluated in chapter 5.1.3.



Concept	cEF-D			dEF-D		BLEF-DME	EF-E		CFB-D				ICFB-D				CFB-E	
	SP	SP	MF	SP/SS	MF	SP/SS	SP/SS	MF	SP/SS	SP/SS	MF	MF	SP	SP	MF	MF	SP/SS	MF
Scenario																		
Biomass type	willow	straw	willow	straw	straw	willow	willow	willow	willow	straw	willow	straw	willow	misc.	willow	misc.	willow	willow
Biomass power	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	500 MW	50 MW	50 MW	100 MW	100 MW	500 MW	500 MW					
Conventional Method (target power = syngas)																		
Energetic efficiency	90%	89%	77%	83%	67%	111%	63%	69%	73%	73%	70%	72%	77%	78%	101%	103%	85%	80%
Conversion Rate																		
Conversion Rate - Syngas	75%	74%	151%	78%	142%	89%	63%	109%	61%	57%	82%	84%	44%	43%	81%	83%	84%	144%

Table 9-13: Gas Cleaning and Gas Conditioning Efficiencies and Conversion Rates

9.6 Indicators for Maturity

The following indicators on maturity show different parameters and their evaluation for all concepts and scenarios.

9.6.1 Maturity of the Overall Plant

The relevant indicators on maturity for the overall plant are listed, described and evaluated below. A summary on these indicators will be given in chapter 0.

9.6.1.1 Development stage 'Single Components'

This indicator describes which and how many of the system components for the foreseen overall concepts (e.g. 500 MW) are already applied under practical conditions (i.e. components which are generally available on the market or applied in other plants too). Before this background the indicator describes not explicit the development status at the test location of technology developers but the question if one could purchase the components 'off the shelf' on the conventional market.

The evaluation will be distinguished between the following: (Evaluation)

- (i) **Mature / commercial technology:** +++
- (ii) and technology dedicated for biomass conversion:
 - **lab/test plant** (feasibility test, scale [mg – kg/h]): -
 - **pilot plant** (basis for scale-up, technology variation needed, additional measurement, scale [kg - t/h]): +
 - **demo** (continuous operation, no technology variation needed or reference plant, scale [10^0 - 10^2 t/h]): ++

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D wood/straw	ICFB-D 50/500 MW	CFB-E
Mechanical/thermal Pretreatment	+++	+++	+++	+++	+++	+++	+++
Thermochemical Pretreatment	- ... +	-	n.e.	-	n.e.	n.e.	n.e.
Gasification	++	++	+	++ ²	+/-	++/++	-
Gas cleaning	++	+++	+++	++	- ... + ³	+/ ³	- ³
Gas conditioning	+++	+++	+++	+++	+++	n.e./+++	+++
Synthesis	+++	+++	+++	-	+++	+++	-
Product upgrading	+++	+++	+++	+++	n.e.	n.e.	+++
% of +++ ¹	0,84	0,86	0,92	0,71	0,78 / 0,73	0,81 / 0,85	0,63

Table 9-14: Indicator ‘Development Stage ‘Single Components’

n.e. – not existing, ¹calculated based on maximum points (- = 1 pt., + = 2 pts, ++ = 3 pts, +++ = 4 pts), ² assumed to apply the same reactor as dEF-D, ³ tar cracker only in lab scale, biodiesel-washer only in t/h-scale.

Comment:

- In terms of electricity generation, the 50MW gasifier of the ICFB-D concept is a demonstration plant; in terms of fuel production the gasifier of the 500 MW ICFB-D concepts is a pilot plant

9.6.1.2 Development stage ‘R&D-Facilities’

The indicator ‘development stage R&D-facilities’ points out which stage of development has been accomplished by the existing R&D-technology, regarding a ‘running overall process’.

The R&D facilities refer to available technology at the test facilities (explicit at test location) of the technology developers.

The evaluation will be distinguished between the following: (Evaluation)

- Foreseen / idea / **principal option** -
- **lab/test plant** (feasibility test, scale [mg – kg/h]): +
- **pilot plant** (basis for scale-up, technology variation needed, additional measurement, scale [kg - t/h]): ++
- **demo** (continuous operation, no technology variation needed or reference plant (not economic but in terms of a commercialisation meaningful, scale [10⁰-10²t/h]): +++

Concept	cEF-D α-/β- plant	dEF-D	BLEF- DME	EF-E	CFB-D wood/straw	ICFB-D 50/500 MW	CFB-E
Mechanical/thermal Pretreatment	++/+++	+ ...++	++	-	+	+++	-
Thermochemical Pretreatment	++/+++	+	n.e.	-	n.e.	n.e.	n.e.
Gasification	++/+++	+++	++	-	+	+++/-	-
Gas cleaning	++/+++	-	-	-	+	+++/-	-
Gas conditioning	++/-	-	-	-	+	n.e./-	-
Synthesis	++/-	-	-	-	+	-/-	-
Product upgrading	++/-	-	-	-	+	-/-	-
% of +++ ¹	0,75/0,68 0,72 ²	0,45	0,42	0,25	0,5	0,7 / 0,38	0,25

Table 9-15: Indicator 'Development Stage 'R&D-Facilities'

.e. – not existing, ¹calculated based on maximum points (- = 1 point, + = 2 points, ++ = 3 points, +++ = 4 points), ² since β-plant is not yet operated the result is calculated from average of α and β-plant

Comment:

- one problem of this indicator is the aim of technology development: Companies want to have the facilities for demonstration whereas the institutes are focused on research tasks (including the preference of small scale)
- no information on operation time is included in this indicator which is a disadvantage

9.6.1.3 Upscale Steps

The indicator 'upscale steps' reflects how many [numbers] of outstanding upscale steps are necessary for the gas production based on the available technology at the test facilities.

If more than one component needs an upscale, the 'weakest point/lowest maturity' will be taken as basis.

The evaluation will be distinguished between the following: (Evaluation Points)

- | | |
|---|---|
| • One upscale step necessary | 5 |
| • One and a half upscale step necessary | 3 |
| • Two upscale step necessary | 1 |

Concept ^D	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Thermochemical Pretreatment	<u>con. agr</u>	<u>2 → 100</u>					
Gasification	<u>con. agr</u>	130 → 500	<u>50 → 170?</u>	<u>n.i.</u>	<u>0,4 → con. agr.</u>	<u>8 → 50/500</u>	<u>n.i.</u>
Steps	1,5	1	1,5	1 ^B	2	1/2	2 ^C
Points ^A	3	5	3	5	1	5/3	3

Table 9-16: Indicator ‘Upscale Steps’

n.e.= not existing, weakest points are underlined and bold, n.i. = no information; ^A Maximum fulfillment 5 points, Minimum fulfillment 1 point; ^B assumed to be the same as dEF-D; ^C assumed to be the same as ICFB-D (500 MW); ^D the plant scale is given in MW

Comments:

- The following problems exist with this indicator:
 - 1) Different development aims: Companies want to have the facilities for demonstration vs. the institutes want to use them for research.
 - 2) the indicator goes in the same direction (is very similar to) like the indicator ‘Development stage of R&D facilities’
 - 3) different operation times already achieved at the test facilities/demonstration plants are not considered

9.6.1.4 Investment Cost Data

The ‘investment cost data’ indicator reflects the question whether an investment cost specification can be given for the different system components and the overall system [+/- indicator]. Therewith this indicator shows how close the concepts are in regard to a realistic implementation.

The evaluation will be done as follows:

(Evaluation)

- no information: -
- information on overall system: +
- information on specific system components: ++
- information on system components and overall system: +++

Concept Information on costs	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Pretreatment	Yes	No	Yes	No	No	Yes	No
Gasification	Yes	No	Yes	No	Yes	Yes	No
Gas cleaning	Yes	No	Yes	No	Yes	Yes	No
Gas conditioning	Yes	No	Yes	No	No	Yes/No	No
Synthesis	Yes	No	Yes	No	No	Yes/No	No
Product upgrading	Yes	No	Yes	No	n.e.	n.e.	No
Overall concept	Yes	Yes	Yes	No	No	Yes	No
Assessment	+++	+	+++	-	++	+++/++	-
% of +++ ¹	1	0,5	1	0,25	0,75	1 /0,75	0,25

Table 9-17: Indicator 'Investment Cost Data'

¹ calculated based on maximum points (- = 1 point, + = 2 points, ++ = 3 points, +++ = 4 points)

9.6.1.5 Technical Design

The +/- indicator 'technical design' specifies the kind of technical design of the concepts (rough estimation, simulation, simulation under implementation of commercial plant data).

The evaluation will be done as follows:

(Evaluation)

- neglected: -
- rough estimation: +
- simulation / calculation: ++
- simulation under implementation of data
- from practical plant realization and operation: +++

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Mechanical/thermal Pretreatment	++	+	+++?	++	++	+++	++
Thermochemical Pretreatment	+++	+++	n.e.	++	n.e.	n.e.	n.e.
Gasification	+++	+++	+++?	++	+++	+++?	++
Gas cleaning	++	-	+++?	++	++(+)	+++	++
Gas conditioning	++	+	+++?	++	++	n.e./++	++
Synthesis	++	+	+++?	++	++	++	++
Product upgrading	++	+	+++?	++	n.e.	n.e.	++
Power generation etc.	++	+	+++?	++	++	++	++
% of +++ ¹	0,81	0,59	1	0,75	0,81	0,9 / 0,88	0,75

Table 9-18: Indicator 'Technical Design'

¹ calculated based on maximum points (- = 1 point, + = 2 points, ++ = 3 points, +++ = 4 points)

9.6.1.6 Investment Costs of the Concept

The indicator 'investment costs of the concept' reflects whether a technological breakthrough of the concepts is delayed by economic restraints. Thereby two aspects are of importance:

- 1) The 'total costs' are an indicator for a real-time feasibility (reflecting the restraint of high investment costs).
- 2) On the other hand the 'specific costs' are an indicator for profitability (Economy of Scale)

The evaluation will be distinguished between the following: (Evaluation Points)

- - Lowest Investment Effort 5
- - Highest Investment Effort 1

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Total costs [Mio €]	ca. 360	ca. 370	ca. 250	ca. 370 ¹	ca. 460	ca. 70 / ca. 460 ²	ca. 460 ²
	1,2	1,2	1,6	1,2	1,0	5,0 / 1,0	1,0
Specific costs [T€/MW]	ca. 720	ca. 740	ca. 500	ca. 740 ¹	ca. 920	ca. 1400 / ca. 920 ²	ca. 920 ²
Points ³	3,1	3,0	5,0	3,0	2,2	1,0 / 2,2	2,2

Table 9-19: Indicator 'Investment Costs of the Concept'

¹ same costs assumed as for dEF-D, ² same costs assumed as for CFB-D, ³ Maximum fulfillment 5 points, Minimum fulfillment 1 point

9.6.2 Maturity of the Gasification Unit

The relevant indicators on maturity for the gasification unit are listed, described and evaluated below. A summary on these indicators will be given in chapter 0.

9.6.2.1500 MW Single Line

The indicator '500 MW Single Line' describes the number of gasifiers needed for a 500 MW gasification concept.

It evaluates how large the gasification unit can be built (to a maximum). This aspect is relevant, since all concepts go for large scale (as an effect of economies of scale). Therefore it is economically not feasible to built units in parallel, but singular large ones.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D atm./press.	CFB-E
Thermochemical Pretreatment	13 -16	1	1 (pulp mill)	10 ¹	n.e.	n.e.	n.e.
Gasification	1	1	1	1	1	5/1	5
Points ²	3	5	5	3	5	3/5	3

Table 9-20: Indicator '500 MW Single Line'

n.e.= not existing, ¹ assumption; ² Maximum fulfillment 5 points; Minimum fulfillment 1 point

9.6.2.2 Maximum Pressure

The indicator 'Maximum pressure' indicates the limitation of pressurized gasifier operation. The combination of high pressure synthesis is only reasonable, if it goes along with a pressurized gasification (reduction of the compression and gas cleaning effort). Therefore, this indicator points out the limits of a pressurized operation.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D	CFB-E
Thermochemical Pretreatment	30 bar?	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant	Not relevant
Gasification	n.a.?	80 bar	80 bar?	80 bar?	n.a.	n.a.	n.a.
Points ²	1	5	5	5	3 ¹	3 ¹	3 ¹

Table 9-21: Indicator 'Maximum Pressure'

¹ guess: pressurized feeding system required but no separate pre-treatment under pressure needed; thus, maximum pressure is assumed between limitation of pressurized thermo-chemical pretreatment and entrained flow gasification of pumpable feedstock; ² Maximum fulfillment 5 points, Minimum fulfillment 1 point

9.6.2.3 Functionality of the Feeding System

The indicator 'functionality of the feeding system' shows the state of development for feeding systems.

The evaluation will be done as follows:

- | | (Evaluation) |
|---|--------------|
| • commercial techniques: | +++ |
| • technically available but known as problematic: | ++ |
| • under development: | + |

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D	CFB-E
Woody biomass				+++	+++	+++	+++
Herbac. biomass					++	++	++
Pumpable feedstocks	+++	+++	+++				
Assessment	+++	+++	+++	+++ ^A	++(+)	++(+)	++(+) ^B
Points ^C	5	5	5	5	3	3	3

Table 9-22: Indicator 'Functionality of the Feeding System'

^A assumed to be the same as dEF-D; ^B assumed to be the same as ICFB-D (500 MW); ^C Maximum fulfillment 5 points, Minimum fulfillment 1 point

Comment:

- This indicator, esp. what is part of the feeding system and what not, has to be discussed with the gasifier developers. Based on this a discussion with feeding system providers (like e.g. Krupp) is needed.

9.6.3 Maturity of the Gas Cleaning and Gas Conditioning Unit

The relevant indicators on maturity for the gas cleaning and gas conditioning unit are listed, described and evaluated below. A summary on these indicators will be given in chapter 0.

9.6.3.1 Effort on Gas Cleaning and Gas Conditioning

This indicator reproduces the technical effort in form of the capital expenditure for gas cleaning and gas conditioning in 1000 EUR per installed MW biomass input.

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Main steps of GC&GC	-Water scrubber -water scrubber -WGS-reactor -selexol washing system -ZnO-adsorber -steam reforming - PSA	-heat exchanger -water scrubber -rectisol washing system -WGS-reactor -rectisol washing system -ATR -PSA	-heat exchanger -water scrubber -rectisol I -shift -rectisol II - compress.	-heat exchanger - ZnO absorber - LO-Cat - WGS-reactor - selexol washing system - compress.	-hot gas dedusting -WGS-Reactor -tar cracker -heat exchanger -quench -water scrubber -FAME scrubber -compression (two-stage) -catalytical hydrogenation -sulfur removal -selexol washing system -ZnO-adsorber	-hot gas filter -heat exchanger -pre-coat filter -RME-scrubber -booster -cooling -compress. -adsorber	- tar reformer -heat exchanger - ZnO absorber - LO-Cat - WGS-reactor - selexol washing system - compress.
Assessment [T€/MW] biomass input	149	188	179	179 ¹	245	716/ 245 ²	245 ²
Points ³	5,0	4,0	4,2	4,2	3,0	1,0 / 3,0	3,0

Table 9-23: Indicator 'Effort on Gas Cleaning and Gas Conditioning'

¹ assumed to be same as BLEF-DME; ² assumed to be same as CFB-D; ³ Maximum fulfillment 5 points, Minimum fulfillment 1 point

9.6.3.2 Experiences/Ratio of Commercial Systems

This indicator points out, whether the gas cleaning and gas conditioning system is approved

- (i) in commercial conversion plants
- (ii) respectively for syngas production

The evaluation will be done as follows: (Evaluation)

- approved in commercial syngas plants (e.g. CtL): +++
- mature for gas cleaning on high quality (like e.g. gas motor fuel quality): ++

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
	-Water scrubber -water scrubber -WGS-reactor -selexol washing system -ZnO-adsorber -steam reforming - PSA	-heat exchanger -water scrubber -rectisol washing system -WGS-reactor -rectisol washing system -ATR -PSA	-heat exchanger -water scrubber -rectisol I -shift -rectisol II -compress.	-heat exchanger - ZnO absorber - LO-Cat - WGS-reactor - selexol washing system - compress.	-hot gas dedusting -WGS-Reactor -tar cracker -heat exchanger -quench -water scrubber -FAME scrubber -compression (two-stage) -catalytical hydrogenation -sulfur removal -selexol washing system -ZnO-adsorber	-hot gas filter -heat exchanger -pre-coat filter -RME-scrubber -booster -cooling -compress. -adsorber	- tar reformer -heat exchanger - ZnO absorber - LO-Cat - WGS-reactor - selexol washing system - compress.
Assessment	+++?	+++?	+++?	++?	++?	++?	++?
Points ¹	3	5	5	3	3	3	3

Table 9-24: Indicator 'Experiences/Ratio of Commercial Systems'

¹ Maximum fulfillment 5 points, Minimum fulfillment 1 point

9.7 Indicators for Feedstock and Product Quality

The following indicators on feedstock and product quality show different parameters and their evaluation for all concepts and scenarios.

9.7.1 Feedstock and Product Quality of the Overall Plant

The relevant indicators on feedstock and product quality for the overall plant are listed, described and evaluated in the following. A summary on these indicators will be given in chapter 0.

9.7.1.1 Feedstock Flexibility

The indicator 'feedstock flexibility' reflects the percentage of the European biomass potential usable in a BtL plant, limiting the process by the feedstock or gasification media.

Ressource	Tech. Potential	Flexibility						
		cEF-D	dEF-D	BLEF-DME	EF-E ⁵	CFB-D	ICFB-D	CFB-E ⁶
Forrest Wood	2.830	1	1	0	1	1	1	1
Residues								
Black Liquor	500	0	0	1	0	0	0	0
Woody ind. Res. / Gehölzschnitt	760	1	1	0	1	1	1	1
Manure, Wet Residues from Agriculture and Industry	1.050	0	0	0	0	0	0	0
Straw	1.300	1	1	0	1	1 ⁴	1 ⁴	1 ⁴
Waste Wood / MSW ³	1.150	0,5 ¹	0,5 ¹	0	0,5 ¹	0,5 ¹	0,5 ¹	0,5 ¹
Energy Crops								
Grain / Perennials	2.810	1	0 - 0,5 ¹	0	1	1	1	1
Other ²	610	0	0	0	0	0	0	0
Sum	11.000	8.275	6.168	500	8.275	8.275	8.275	8.275
Share (%)		75	56	5	75	75	75	75

Table 9-25: Indicator 'Feedstock Flexibility'

¹ the factor 0,5 means, only one out of two biomass potentials is utilizable (depending on energy crops (annual or perennial)), ² Other energy crops' are used for biogas processes, ³ MSW – municipal solid waste, ⁴ measures required to increase the ash melting point (additives), ⁵ assumed to be the same as cEF-D, ⁶ assumed to be the same as ICFB-D

9.7.1.2 Infrastructure for Feedstock Provision

The +/- indicator 'infrastructure for feedstock provision' identifies the availability of provision concepts (infrastructure) assessed regarding feedstock-kind and amount.

The evaluation will be done as follows:

(Evaluation) Points

- mature provision chain: ++ 5
- provision chain available but not applied
- for this feedstock / amount (dedication needed): + 3
- concept state: - 1

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Pretreatment	+	++	+	+	+	++/+	+
Gasification		-					
Assessment	+	++	+	+	+	++/+	+
Points ¹	3	5	3	3	3	5/3	3

Table 9-26: Indicator 'Infrastructure for Feedstock Provision'

¹ Maximum fulfillment 5 points, Minimum fulfillment 1 point

Comment:

- Some facts have to be considered: also for a pulp mill itself huge amounts of biomass have to be supplied; on the other hand if the plant is very huge, only one admission is necessary and not several.

9.7.1.3 Infrastructure for Product Distribution

The +/- indicator 'infrastructure for feedstock provision' shows the availability / the development status of provision concepts (infrastructure) for product distribution. Thereby 'product' means the main output of the concept as described by the technology developers.

The evaluation will be done as follows: (Evaluation)

- matured provision chain (blendable): ++
- provision chain available but not applied for this product/product mix (dedication needed?): +
- concept state (R&D or engineering-required): -

Concepts	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Main fuel	Diesel	Diesel	DME	Ethanol	Diesel	Diesel	Ethanol
Assessment*	++	++	+	+...++	++	++	+...++
Points ¹	5	5	1	3	5	5	3

Table 9-27: Indicator 'Infrastructure for Product Distribution'

¹ Maximum fulfillment 5 points, Minimum fulfillment 1 point

Comment:

- the question how to distribute the different (raw) products to the market (cEF-D, dEF-D, BLEF-DME, EF-E, CFB-E) or to the next upgrading steps (CFB-D, ICFB-D) needs to be assessed by mineral oil industry partners and Volvo (for DME).

9.7.1.4 Product Quality

The indicator ‘product quality’ reflects on the availability and necessity of commercial concepts/techniques for product upgrading on motor fuel quality.

The evaluation will be done as follows: (Evaluation)

- No further upgrading / only additives needed: +++
- matured upgrading techniques sufficient: ++
- upgrading techniques could be available in principle but not commercially applied for this product/product mix (dedication needed?): +
- concept state: -

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
Main fuel	Raw-Diesel	Raw-Diesel	DME	Ethanol	FT-product (mixture)	FT-product (mixture)	Ethanol
Assessment	+++	+++	+++	+++	+	+	+++
Points ¹	5	5	5	5	1	1	5

Table 9-28: Indicator ‘Product Quality’

¹ Maximum fulfillment 5 points, Minimum fulfillment 1 point

Comment:

- The question how to upgrade the fuels on motor quality needs to be assessed by mineral oil industry partners and Volvo (for DME).

9.7.2.1 Effort on Preparation of Gasification Media

The indicator ‘effort on preparation of gasification media’ describes the demand of basic operations.

The evaluation will be done as follows: (Evaluation)

- only mechanical conditioning required: +++
- mechanical conditioning and drying and others (e.g. pelletising): ++
- thermo-chemical conversion: +

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D Wood/straw	ICFB-D	CFB-E
Assessment	+	+	+++ ²	+	+++ / ++	+++	+++
Points ¹	1	1	5	1	5/3	5	5

Table 9-30: Indicator ‘Effort on Preparation of Gasification Media’

¹ Maximum fulfillment 5 points, Minimum fulfillment 1 point. ² Black liquor is considered as available residue; i.e. the effort within the pulp and paper mill is not considered

9.7.2.2 Limitation for Ash Content

The indicator ‘limitation for ash content’ shows the limits for the feedstock’s ash content in [%]. The feedstock usable within the respective gasification systems is also limited by maximum or minimum ash content.

Comment:

- This indicator has to be discussed with the gasifier developers.

Concept	cEF-D	dEF-D	BLEF-DME	EF	CFB-D	ICFB-D 50/500 MW	CFB-E
Assessment	MAX. 15	1 -30	MIN. 15	1 -30 ²	MAX. 40 ¹	MAX. 40	MAX. 40 ¹
Points ³	3	3	3?	3	5	5	5

Table 9-31: Indicator 'Limitation for Ash Content'

¹ assumed to be the same as IFCB-D; ² assumed to be the same as dEF-D; ³ Maximum fulfillment 5 points, Minimum fulfillment 1 point

9.7.3 Feedstock and Product Quality of the 'Gas Cleaning and Gas Conditioning' Unit

The presently only relevant indicator on feedstock and product quality for the gas cleaning and gas conditioning unit is the 'syngas quality for fuel-synthesis'. It is described and evaluated below. In the summary of indicators it is mentioned in chapter 0.

Syngas Quality for Fuel-Synthesis. This indicator points out, whether the achieved synthesis gas quality fits to the requirements of the desired fuel synthesis. Relevant parameters in this context are: Amount and quality (flow, T, P, composition, impurities), H₂/CO ratio.

The evaluation will be done as follows: (Evaluation)

- Well adapted and proven (e.g. in commercial syngas plants CtL):
+++
- Well adapted and demonstrated (demonstration level)
++
- Adapted for tolerant synthesis catalyst (little risk concerning catalyst life time) +
- Unadapted H₂/CO ratio -

Concept	cEF-D	dEF-D	BLEF-DME	EF-E	CFB-D	ICFB-D 50/500 MW	CFB-E
	con.agr.	≈ 100% Rectisol	≈ 100% Rectisol	dedicated systems	con.agr.	dedicated systems	dedicated systems
Syngas quality	++	+++	+++	+	+	++/+	+
Points ¹	3	5	5	1	1	3/1	1

Table 9-32: Indicator 'Syngas Quality for Fuel-Synthesis'

¹ Maximum fulfillment 5 points, Minimum fulfillment 1 point

9.8 Ranking Matrices and Weighing Factors

In this chapter of the annex, the ranking matrices (modules) and weighing factors are listed, which are used for technical assessment and evaluation in chapter 6.

<p style="text-align: center;">HIGH TECHNICAL PERFORMANCE</p> <p style="text-align: center;">- Overall Plant - - Gasification - - Gas Cleaning and Gas Conditioning -</p>	Efficiency	Maturity	Feedstock and Product Quality	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	Efficiency		+	+	6	0,50	0,66	0,330
Maturity	-		0	3	0,25	0,66	0,165	0,250
Feedstock and Product Quality	-	0		3	0,25	0,66	0,165	0,250
Check Sum				12	1,00		0,66	1,00

Table 9-33: Ranking Matrix and Weighing Factors for PG1 'High Technical Performance'

GOOD INDUSTRIAL APPLICABILITY (close to Practical Realisation) - Overall Plant - - Gasification - - Gas Cleaning and Gas Conditioning -	Efficiency	Maturity	Feedstock and Product Quality	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	Efficiency	-	-	2	0,17	0,66	0,110	0,167
	Maturity	+	0	5	0,42	0,66	0,275	0,417
	Feedstock and Product Quality	+	0	5	0,42	0,66	0,275	0,417
	Check Sum			12	1,00		0,66	1,00

Table 9-34: Ranking Matrix and Weighing Factors for PG2 ‘Good Industrial Applicability’

Criteria for Efficiency - Overall Plant -	Overall Efficiency - Main Fuel	Overall Efficiency - All Liquids	Overall Efficiency - CHP-F	PE_equ. Overall Efficiency - Main Fuel	PE_equ. Overall Efficiency - All Liquids	PE_equ. Overall Efficiency - CHP-F	Conversion Rate - Biomass to Main Fuel	Conversion Rate - Biomass to All Liquids	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	FINAL WEIGHING FACTORS (incl. data security factor)
	Overall Efficiency - Main Fuel	+	0	-	0	-	+	+	15	0,13	1	0,134
	Overall Efficiency - All Liquids	-	-	-	-	-	+	+	11	0,10	1	0,098
	Overall Efficiency - CHP-F	0	+	-	0	-	+	+	15	0,13	1	0,134
	PE_equ. Overall Efficiency - Main Fuel	+	+	+	+	0	+	+	20	0,18	1	0,179
	PE_equ. Overall Efficiency - All Liquids	0	+	0	-	-	+	+	15	0,13	1	0,134
	PE_equ. Overall Efficiency - CHP-F	+	+	+	0	+	+	+	20	0,18	1	0,179
	Conversion Rate - Biomass to Main Fuel	-	-	-	-	-	-	+	9	0,08	1	0,080
	Conversion Rate - Biomass to All Liquids	-	-	-	-	-	-	-	7	0,06	1	0,063
	Sum check								112	1,00		

Table 9-35: Ranking Matrix and Weighing Factors for SG ‘High Efficiency’ – Overall Plant

Criteria for Efficiency - Gasification -	Gasifier Efficiency - Gasification Media Based	Gasifier Efficiency - Biomass Based	Conversion Rate - Cold Gas (GM Based)	Conversion Rate - 'Syngas' (GM Based)	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	FINAL WEIGHING FACTORS (incl. data security factor)
	Gasifier Efficiency - Gasification Media Based	-	+	+	7	0,29	1	0,292
	Gasifier Efficiency - Biomass Based	+	-	+	9	0,38	1	0,375
	Conversion Rate - Cold Gas (GM Based)	-	-	-	3	0,13	1	0,125
	Conversion Rate - 'Syngas' (GM Based)	-	-	+	5	0,21	1	0,208
Sum check				24	1,00			

Table 9-36: Ranking Matrix and Weighing Factors for SG 'High Efficiency' – Gasification

Criteria for Efficiency - Gas Cleaning & Gas Conditioning -	Gas Cleaning & Conditioning Efficiency	Conversion Rate - 'Syngas' (Raw Gas Based)	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	FINAL WEIGHING FACTORS (incl. data security factor)
	Gas Cleaning & Conditioning Efficiency	+	3	0,75	1	0,750
	Conversion Rate - 'Syngas' (Raw Gas Based)	-	1	0,25	1	0,250
	Sum check		4	1,00		

Table 9-37: Ranking Matrix and Weighing Factors for SG 'High Efficiency' – Gas Cleaning and Gas Conditioning

Criteria for Maturity - Overall Plant -	Development Stage 'Single Components'	Development Stage 'R&D-facilities'	Upscale Steps	Investment Cost Data	Technical Design	Total Investment Cost of the Concept	Specific Investment Cost of the Concept	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	Development Stage 'Single Components'	0	+	+	0	0	0	14	0,17	0,66	0,110	0,185
	Development Stage 'R&D-facilities'	0	+	+	0	0	0	14	0,17	1	0,167	0,280
	Upscale Steps	-	-	+	0	0	0	11	0,13	0,33	0,043	0,073
	Investment Cost Data	-	-	-	+	-	-	6	0,07	1	0,071	0,120
	Technical Design	0	0	0	+	+	0	13	0,15	0,66	0,102	0,171
	Total Investment Cost of the Concept	0	0	0	+	0	+	13	0,15	0,33	0,051	0,086
	Specific Investment Cost of the Concept	0	0	0	+	0	0	13	0,15	0,33	0,051	0,086
	Check Sum							84	1,00		0,60	1,00

Table 9-38: Ranking Matrix and Weighing Factors for SG 'High Maturity' – Overall Plant

Criteria for Maturity - Gasification -	500 MW Single Line	Maximum Pressure	Functionality of the Feeding System	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	500 MW Single Line	-	-	2	0,17	0,33	0,055	0,118
	Maximum Pressure	+	0	5	0,42	0,66	0,275	0,588
	Functionality of the Feeding System	+	0	5	0,42	0,33	0,138	0,294
	Check Sum				12	1,00	0,47	1,00

Table 9-39: Ranking Matrix and Weighing Factors for SG 'High Maturity' – Gasification – with supplementation from 'Overall Plant'

Criteria for Maturity - Gasification - with supplementation from 'overall'	Development Stage 'Single Components'	Development Stage 'R&D-facilities'	Investment Cost Data	Technical Design	500 MW Single Line	Maximum Pressure	Functionality of the Feeding System	ranking numbers r	Weighting - related to 1	data security factor	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)	
	Development Stage 'Single Components'	0	+	0	+	+	+	16	0,19	0,66	0,126	0,174	
	Development Stage 'R&D-facilities'	0		+	0	+	+	16	0,19	1	0,190	0,264	
	Investment Cost Data	-	-		-	0	-	-	7	0,08	1	0,083	0,115
	Technical Design	0	0	+		0	-	-	11	0,13	0,66	0,086	0,120
	500 MW Single Line	-	-	0	0		-	-	8	0,10	0,33	0,031	0,044
	Maximum Pressure	-	-	+	+	+		0	13	0,15	0,66	0,102	0,142
	Functionality of the Feeding System	-	-	+	+	+	0		13	0,15	0,33	0,102	0,142
Check Sum							84	1,00			0,72	1,00	

Table 9-40: Ranking Matrix and Weighing Factors for SG 'High Maturity' – Gas Cleaning and Gas Conditioning

Criteria for Maturity - Gas Cleaning and Gas Conditioning -	Effort on Gas Cleaning and Gas Conditioning	Experience/Ratio of Commerical Systems	ranking numbers r	Weighting - related to 1	data security factor	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	Effort on Gas Cleaning and Gas Conditioning	0	2	0,50	0,66	0,330	0,398
	Experience/Ratio of Commerical Systems	0	2	0,50	1	0,500	0,602
	Check Sum		4	1,00		0,83	1,00

Table 9-41: Ranking Matrix and Weighing Factors for SG 'High Maturity' – Gas Cleaning and Gas Conditioning – with supplementation from 'Overall Plant'

Criteria for Maturity - Gas Cleaning and Gas Conditioning - with supplementation from 'overall'	Development Stage 'Single Components'	Development Stage 'R&D-facilities'	Investment Cost Data	Technical Design	Effort on Gas Cleaning and Gas Conditioning	Experience/Ratio of Commerical Systems	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	Development Stage 'Single Components'	0	+	0	-	0	10	0,17	0,66	0,110	0,147
	Development Stage 'R&D-facilities'	0	+	0	-	0	10	0,17	1	0,167	0,222
	Investment Cost Data	-	-	-	-	0	6	0,10	1	0,100	0,133
	Technical Design	0	0	+	-	0	10	0,17	0,66	0,110	0,147
	Effort on Gas Cleaning and Gas Conditioning	+	+	+	+	0	14	0,23	0,66	0,154	0,205
	Experience/Ratio of Commerical Systems	0	0	0	0	0	10	0,17	0,33	0,110	0,147
	Check Sum						60	1,00		0,75	1,00

Table 9-42: Ranking Matrix and Weighing Factors for SG 'High Feedstock and Product Quality' – Overall Plant

Criteria for Feedstock and Product Quality - Overall Plant -	Feedstock Flexibility	Infrastructure for Feedstock Provision	Infrastructure for Product Distribution	Product Quality	Ash Recycling Concept	ranking numbers r	Weighing - related to 1	data security factor 1,00 - sure 0,67 - quite sure 0,33 - uncertain	WEIGHING FACTORS - proportional (incl. data security factor)	FINAL WEIGHING FACTORS (incl. data security factor)
	Feedstock Flexibility	+	0	+	+	11	0,28	1	0,275	0,344
	Infrastructure for Feedstock Provision	-	-	0	0	6	0,15	0,33	0,050	0,062
	Infrastructure for Product Distribution	0	+	+	+	11	0,28	1	0,275	0,344
	Product Quality	-	0	-	0	6	0,15	1	0,150	0,188
	Ash Recycling Concept	-	0	-	0	6	0,15	0,33	0,050	0,062
	Check Sum					40	1,00		0,80	1,00

Table 9-43: Ranking Matrix and Weighing Factors for SG 'High Feedstock and Product Quality' – Gasification

List of Figures

Figure 0-1: Production Process Chain of Synthetic Biofuels (Basic Steps)	66
Figure 0-2: Scale of industrial/planned XtL-plants in comparison with world diesel consumption	67
Figure 0-3: Similarities and differences between BtL and Gtl/CtL (red-differences, green-similarities).....	67
Figure 0-4: Main technical differences between Renew concepts defined to technical assessment (*Industrial integration concepts as studied in RENEW: integration of mass- and energy flows of the BtL-plant with other industrial plants / consumers)	68
Figure 0-5: Overall Efficiency of the Renew-concepts based on the conventional calculation method (main fuel and all liquids); *For Trigeneration Concept ICFB SP-scenario only conversion rate from biomass to fuel is presented – i.e. district heat output has not been considered within the efficiency calculation; el-electrical; NG-Natural Gas; ext-external.....	71
Figure 0-6: Overall Efficiency of the Renew-concepts based on the CHP-F method; el-electrical; NG-Natural Gas; ext-external	72
Figure 0-7: Comparison of Renew-concepts from viewpoint of selected industrial criteria (Scale up factors: number of steps/needed from actual status up to commercial scale; mass balances: knowledge regarding the changes of process conditions under start up/end run; cat. Provider: number of commercial providers contracted for synthesis catalyst provision in future plants; CAPEX/OPEX: knowledge of capital- and operation-related costs for the main equipment with preliminary sizing data; plot and water flow plan, HSE issues: developments status of project specific plant design assessed by availability of a plot plan and water flow plan and HAZID and/or HAZOP studies; modelling quality: knowledge of quality of data sources of SP5; n.a.-not available)	74
Figure 0-8: Plant sizes and efficiencies of the Renew-concepts.....	77
Figure 0-9: General development steps of bioenergy technologies and classification of technology developers which are responsible for data provision for the renew concepts (UET-data provider for cEF-D concept, FZK--data provider for dEF-D concept, TÜV-data provider for ICFB-D concept, CUTEC-data provider for CFB-D concept, Chemrec-data provider for BLEF-DME concept, Abengoa-data provider for EF-E and CFB-E concept).....	78
Figure 2-1: Process Chains of GtL, CtL and BtL.....	95
Figure 2-2: Thermochemical Pretreatment - 'Low-Temperature Gasifier' (NTV) (LEFT), Pyrolysis Plant with a Twin Screw Mixer [FZK 1, 2006] (RIGHT); Legend: Holzspäne = Wood Chips; Koks = Char; Antriebswelle = Driveshaft.....	97
Figure 2-3: Classification of Gasifiers	100
Figure 2-4: Gasifiers in Fixed Bed and Fluidized Bed Design (SFB and CFB)	101
Figure 2-5: Design of a Internally Fluidized Bed Gasifier (Twin-Bed Gasifier) [Hofbauer, 2007] (LEFT), Design of an Entrained Flow Gasifier (EF) (RIGHT).....	102
Figure 2-6: Molar H/C ratio of different feedstocks and diesel	105

Figure 2-7: FT Product Distribution (Product Weight Fraction [% wt]) for Different α , Calculated Using Equation 2-10 [Boerrigter, 2003]..... 109

Figure 2-8: Tubular Fixed Bed Reactor [Dry, 2002] (LEFT) vs. Slurry Bubble Column Reactor[Dry, 2002] (RIGHT) 111

Figure 2-9: ICI quench reactor [Cheng, 1994] (LEFT) vs. Fixed Bed Reactor for MeOH/DME synthesis [Mii, 2001] (RIGHT) 113

Figure 2-10: Experiences of commercial syngas technologies, existing plants > 1000 barrels per day (bbl/d)..... 117

Figure 3-1: BtL-Concepts Considered within the Technical Assessment 124

Figure 3-2: Simplified Process Flow of the cEF-D-Concept (Starting Point)..... 127

Figure 3-3: Simplified Sankey Diagram of the cEF-D-Concept (Starting Point, willow); Figures in MW 130

Figure 3-4: Simplified Sankey Diagram of the cEF-D-Concept (Maximum Biofuel, willow); Fig. in MW..... 130

Figure 3-5: Simplified Process Flow of the dEF-D-Concept..... 134

Figure 3-6: Simplified Sankey Diagram of the dEF-D-Concept (Starting Point, straw); Figures in MW 135

Figure 3-7: Simplified Sankey Diagram of the dEF-D-Concept (Maximum Biofuel, straw); Figures in MW 136

Figure 3-8: Simplified Process Flow of the BLEF-DME-Concept; Figures in MW 140

Figure 3-9: Simplified Sankey Diagram of the BLEF-DME Concept..... 140

Figure 3-10: Simplified Process Flow of the EF-E-Concept (Starting Point)..... 145

Figure 3-11: Simplified Sankey Diagram of the EF-E-Concept (Starting Point); Figures in MW 147

Figure 3-12: Simplified Sankey Diagram of the EF-E-Concept (Maximum Biofuel); Figures in MW 147

Figure 3-13: Simplified Process Flow of the CFB-D-Concept 150

Figure 3-14: Simplified Sankey Diagram of the CFB-D-Concept (Starting Point, willow); Figures in MW 151

Figure 3-15: Simplified Sankey Diagram of the CFB-D-Concept (Maximum Biofuel, willow); Fig. in MW..... 152

Figure 3-16: Simplified Process Flow of the ICFB-D-Concept 156

Figure 3-17: Simplified Sankey Diagram of the ICFB-D-Concept (Starting Point, willow); Figures in MW 156

Figure 3-18: Simplified Process Flow of the ICFB-D-Concept (Maximum Biofuel, willow); Figures in MW 157

Figure 3-19: Simplified Sankey Diagram of the ICFB-D-Concept (Maximum Biofuel, willow); Fig. in MW..... 157

Figure 3-20: Simplified Process Flow of the CFB-E-Concept 161

Figure 3-21: Simplified Sankey Diagram of the CFB-E-Concept (Starting Point); Figures in MW 161

Figure 3-22: Simplified Sankey Diagram of the CFB-E-Concept (Maximum Biofuel); Figures in MW 162

Figure 4-1: Values in Technical Action [VDI 3780, 2000] 166

Figure 4-2: General Assessment Procedure..... 167

Figure 4-3: Various Kinds of Criteria and Their Relations..... 168

Figure 4-4: Criteria and Goal System as Basis of Technical Assessment 171

Figure 4-5: Evaluation Numbers of the Criteria Overall Efficiency 172

Figure 4-6: Example on Weighting of Criteria for Gasification Efficiency..... 173

Figure 4-7: Example for Ranking Matrix and Weighing Factors – Efficiency – Overall Plant 175

Figure 4-8: Incomplete Process Chain 178

Figure 5-1: Overall Efficiency – Conversion Plant (upper part) and Deviation from Average Overall Efficiencies (lower part)..... 183

Figure 5-2: Overall Efficiency – Primary Energy Based (upper part) and Overall Efficiency – Difference Between the ‘Primary Energy Based’ Calculations and the ‘Conversion Plant’ Calculations (lower part) 186

Figure 5-3: Overall Efficiency – Conversion Rates 188

Figure 5-4: Gasification Efficiencies & Conversion Rates..... 188

Figure 5-5: Gas Cleaning and Gas Conditioning Efficiency & Conversion Rates 191

Figure 5-6: Comparison of Renew-concepts from viewpoint of selected industrial criteria (Scale up factors: number of steps/needed from actual status up to commercial scale; mass balances: knowledge regarding the changes of process conditions under start up/end run; cat. Provider: umber of commercial providers contracted for synthesis catalyst provision in future plants; CAPEX/OPEX: knowledge of capital- and operation-related costs for the main equipment with preliminary sizing data; plot and water flow plan, HSE issues: developments status of project specific plant design assessed by availability of a plot plan and water flow plan and HAZID and/or HAZOP studies; modelling quality: knowledge of quality of data sources of SP5; n.a.-not available) 195

Figure 6-1: Overall Plant – Secondary Goals ‘Efficiency, Maturity, Feedstock and Product Quality’ 205

Figure 6-2: Overall Plant – Primary Goal ‘High Technical Performance’ 207

Figure 6-3: Overall Plant – Primary Goal ‘Industrial Applicability’ 208

Figure 6-4: Overall Plant – Sensitivity of Primary Goals – Weighing Factors 209

Figure 6-5: Overall Plant – Sensitivity of Primary Goals – Data Security Factors PG1210 209

Figure 6-6: Gasification – Secondary Goals ‘Efficiency, Maturity, Feedstock and Product Quality’ 211

Figure 6-7: Gasification – Primary Goal ‘High Technical Performance’ 213

Figure 6-8: Gasification – Primary Goal ‘Industrial Applicability’ 214

Figure 6-9: Gasification – Sensitivity of Primary Goals – Weighing Factors 215

Figure 6-10: Gasification – Sensitivity of Primary Goals – Data Security Factors PG1216

Figure 6-11: Gas Cleaning and Gas Conditioning – Secondary Goals ‘Efficiency, Maturity, Feedstock and Product Quality’	218
Figure 6-12: Gas Cleaning and Gas Conditioning – Primary Goal ‘High Technical Performance’	220
Figure 6-13: Gas Cleaning and Gas Conditioning – Primary Goal ‘Industrial Applicability’	220
Figure 6-14: Gas Cleaning and Gas Conditioning – Sensitivity of Primary Goals – Weighing Factors.....	221
Figure 6-15: Gas Cleaning and Gas Conditioning – Sensitivity of Primary Goals – Data Security Factors PG1.....	222
Figure 9-1: Simplified Flow Sheet of the Upgrading Process.....	243
Figure 9-2: Distribution of a Fischer-Tropsch Product Before and After Selective Hydrocracking [3].....	245
Figure 9-3: Plausibility Check for Energy Consumption of Upgrading Process [16]	248
Figure 9-4: General Definition of System Boundary for Efficiency Calculations.....	252
Figure 9-5: General Definition of System Boundary for Conversion Rate Calculations.....	253
Figure 9-6: Definition of Conversion Plant System Boundary for Efficiency Calculations	254
Figure 9-7: Definition of Primary Energy Based System Boundary for Efficiency Calculations	255
Figure 9-8: Definition of Auxiliary Power Integration.....	256
Figure 9-9: Definition of By-Product Power Integration.....	256
Figure 9-10: Definition of Overall Plant Efficiency – Conversion Plant	260
Figure 9-11: Definition of the Conversion Rate Biomass to Main Fuel	261
Figure 9-12: Definition of the Conversion Rate Biomass to All Liquids.....	261
Figure 9-13: Definition of Gasification Efficiency – Gasification Media Based – Conversion Plant	262
Figure 9-14: Definition of Gasification Efficiency – Biomass Based – Conversion Plant	263
Figure 9-15: Definition of Cold Gas Conversion Rate (Gasification Media Based).....	264
Figure 9-16: Definition of Syngas Conversion Rate (Gasification Media Based).....	264
Figure 9-17: Definition of Gas Cleaning and Gas conditioning System Boundaries – Conversion Plant	265
Figure 9-18: Definition of Syngas Conversion Rate.....	266
Figure 9-19: Definition of Overall Plant Efficiency – Primary Energy Based.....	267
Figure 9-20: Selection of Appropriate Gas Purification Process for Simultaneous H ₂ S/COS and CO ₂ Removal /Ullmann’s 2002/	272

List of Tables

Table 3-1: Concept Background and Intension of the cEF-D-concepts	131
Table 3-2: Data Quality of the cEF-D-concepts	132
Table 3-3: Concept Background and Intension of the dEF-D-concepts	137
Table 3-4: Data Quality of the dEF-D-concepts	138
Table 3-5: Concept Background and Intension of the BLEF-DME-concept	141
Table 3-6: Data Quality of the BLEF-DME-concepts	142
Table 3-7: Concept Background and Intension of the EF-E-concepts	146
Table 3-8: Data Quality of the EF-E-concepts	148
Table 3-9: Data Quality of the CFB-D-concepts	151
Table 3-10: Concept Background and Intension of the CFB-D-concepts	153
Table 3-11: Concept Background and Intension of the ICFB-D-concepts	158
Table 3-12: Data Quality of the ICFB-D-concepts	159
Table 3-13: Concept Background and Intension of the CFB-E-concepts	163
Table 3-14: Data Quality of the CFB-E-concepts.....	164
Table 4-1: Example on Evaluation Numbers for the Criteria ‘Overall Efficiency’	172
Table 5-1: Indicators on Maturity for the Overall Plant.....	197
Table 5-2: Indicators on Maturity for the Gasification Unit	198
Table 5-3: Indicators on Maturity for the Gas Cleaning and Gas Conditioning Unit.....	200
Table 5-4: Indicators on Feedstock and Product Quality for the Overall Plant.....	202
Table 5-5: Indicators on Feedstock and Product Quality for the Gasification Unit.....	202
Table 5-6: Indicator on Feedstock and Product Quality for the Gas Cleaning and Gas Conditioning Unit	203
Table 9-1: Product Fractions Before and After Mild-Severity Hydrocracking	245
Table 9-2: H ₂ Demand	246
Table 9-3: Conditions of the C ₅ + Fraction.....	247
Table 9-4: Calculation of Energy Demand and Yields	249
Table 9-5: Calculation of Energy Demand and Yields Relating to 1 kg FT Raw Product	250
Table 9-6: Constants for Efficiency Calculations	258
Table 9-7: Exemplary Process Conditions of Fuel Synthesis and Stoichiometric Synthesis Gas Ratio*.....	270
Table 9-8: Permissible Sulphur and Other Impurities Concentrations of a Synthesis Gas Suitable for Methanol and Hydro Carbon Fuel Synthesis Process /Specht et al. 2006; Beenackers 1984; Hasler 1994; Boerrigter 2002, Ullmann’s 2002/	270

Table 9-9: Examples of Commercial Available Scrubbing Processes and the Main Process Parameters for Synthesis Gas Cleaning and Upgrading /Ullmann's 2002, Clariant 2002, Lurgi 2005/	271
Table 9-10: Overall Efficiencies and Conversion Rates – Conversion Plant	275
Table 9-11: Overall Efficiencies – Primary Energy Based	276
Table 9-12: Gasification Efficiencies and Conversion Rates	277
Table 9-13: Gas Cleaning and Gas Conditioning Efficiencies and Conversion Rates	278
Table 9-14: Indicator ‘Development Stage ‘Single Components’	280
Table 9-15: Indicator ‘Development Stage ‘R&D-Facilities’	281
Table 9-16: Indicator ‘Upscale Steps’	282
Table 9-17: Indicator ‘Investment Cost Data’	283
Table 9-18: Indicator ‘Technical Design’	284
Table 9-20: Indicator ‘Investment Costs of the Concept’	285
Table 9-20: Indicator ‘500 MW Single Line’	285
Table 9-21: Indicator ‘Maximum Pressure’	286
Table 9-22: Indicator ‘Functionality of the Feeding System’	287
Table 9-23: Indicator ‘Effort on Gas Cleaning and Gas Conditioning’	288
Table 9-24: Indicator ‘Experiences/Ratio of Commercial Systems’	289
Table 9-25: Indicator ‘Feedstock Flexibility’	291
Table 9-26: Indicator ‘Infrastructure for Feedstock Provision’	292
Table 9-27: Indicator ‘Infrastructure for Product Distribution’	292
Table 9-28: Indicator ‘Product Quality’	293
Table 9-29: Indicator ‘Ash Recycling Concept’	294
Table 9-30: Indicator ‘Effort on Preparation of Gasification Media’	295
Table 9-31: Indicator ‘Limitation for Ash Content’	296
Table 9-32: Indicator ‘Syngas Quality for Fuel-Synthesis’	297
Table 9-33: Ranking Matrix and Weighing Factors for PG1 ‘High Technical Performance’	297
Table 9-34: Ranking Matrix and Weighing Factors for PG2 ‘Good Industrial Applicability’	298
Table 9-35: Ranking Matrix and Weighing Factors for SG ‘High Efficiency’ – Overall Plant	298
Table 9-36: Ranking Matrix and Weighing Factors for SG ‘High Efficiency’ – Gasification	299
Table 9-37: Ranking Matrix and Weighing Factors for SG ‘High Efficiency’ – Gas Cleaning and Gas Conditioning	299
Table 9-38: Ranking Matrix and Weighing Factors for SG ‘High Maturity’ – Overall Plant	300

Table 9-39: Ranking Matrix and Weighing Factors for SG ‘High Maturity’ – Gasification – with supplementation from ‘Overall Plant’300

Table 9-40: Ranking Matrix and Weighing Factors for SG ‘High Maturity’ – Gas Cleaning and Gas Conditioning301

Table 9-41: Ranking Matrix and Weighing Factors for SG ‘High Maturity’ – Gas Cleaning and Gas Conditioning – with supplementation from ‘Overall Plant’301

Table 9-42: Ranking Matrix and Weighing Factors for SG ‘High Feedstock and Product Quality’ – Overall Plant302

Table 9-43: Ranking Matrix and Weighing Factors for SG ‘High Feedstock and Product Quality’ – Gasification302