ANNEX to Chapter 3 of
ANNEX "Full Background Report"

to the

GM Well-to-Wheel Analysis of
Energy Use and Greenhouse Gas Emissions
of Advanced Fuel/ Vehicle Systems -
A European Study

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A 3 ANNEX TO CHAPTER 3

A 3.1 Crude Oil Refinery with Gasoline WTT Analysis [LBST Calculation]

A 3.1.1 Crude oil supply EU (well-to-refinery-input)

Primary source of information is GEMIS (Global Emission Model of Integrated Systems). GEMIS is a computer program developed in 1987-1989 as a tool for the comparative assessment of environmental effects of energy by the Öko-Institut (Institute for applied ecology) in Germany and the Gesamthochschule Kassel (GhK). Since then, the model was continuously upgraded and updated. This work is sponsored by several donors, especially the Ministry for Environment in Hesse, Germany, and was done in close cooperation with partners (i.e. German Environmental Agency, Environment Agency Vienna, Austria, Eidgenössische Technische Hochschule (ETH) in Zurich/Switzerland). Since version 3.0 (1996), GEMIS is freely available as public domain software which can be copied and distributed without restriction. Meanwhile the version 4.1 is available.

According to GEMIS 4.1 [GEMIS 2001] the crude oil consumption is supplied by crude oil from the North Sea, from Russia and from OPEC. The crude oil supply shares are shown in Tab. 1.

Tab. 1: Shares of crude oil supply in the EU

	North Sea [%]	Siberia, Russia [%]	Mix OPEC [%]
Primary off-shore oil extraction	17.5		
Secondary off-shore oil extraction	17.5		
On-shore oil extraction		25.0	
Primary on-shore oil extraction			32.0
Secondary on-shore oil extraction			8.0
Total	**35**	**25**	**40**

The energy consumption and emission of greenhouse gases of crude oil supply in the EU is shown in Tab. 2.

Tab. 2: Energy consumption and greenhouse gas emissions related to the LHV of the supplied crude oil, without construction material [GEMIS 2001]

Energy (non renewable) [kWh/kWh]	Energy (renewable) [kWh/kWh]	CO_2 [g/kWh]	CH_4 [g/kWh]	N_2O [g/kWh]
1.06	0.00	18.8	0.257	0.0004

The sulfur content of the crude oil ranges between 0.1 and 2.5 %-mass, depending on the region where the crude oil comes from (Tab. 3).

Tab. 3: Sulfur content and density of crude oil used in the EU

Region	North Sea	Siberia, Russia	Mix OPEC	Mix EU
S-content [%-mass]	0.3	0.6 – 1.8	0.1 – 2.5	0.3 – 1.6
Density [t/m^3]	0.84	n. d. a. [1)]	0.80 – 0.87	n. d. a.

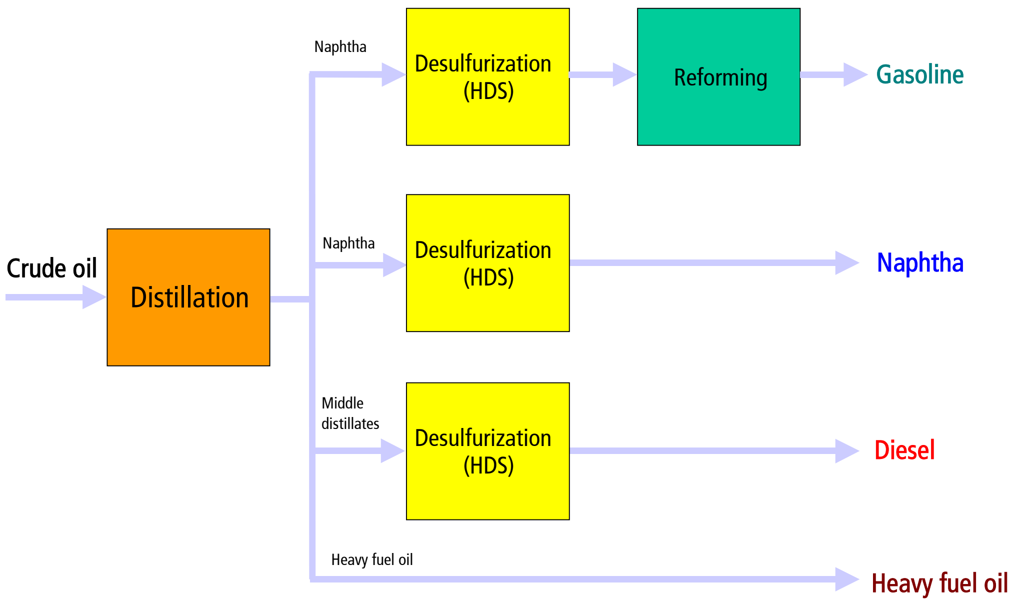
[1)] no data available

A 3.1.2 Refinery

General Model

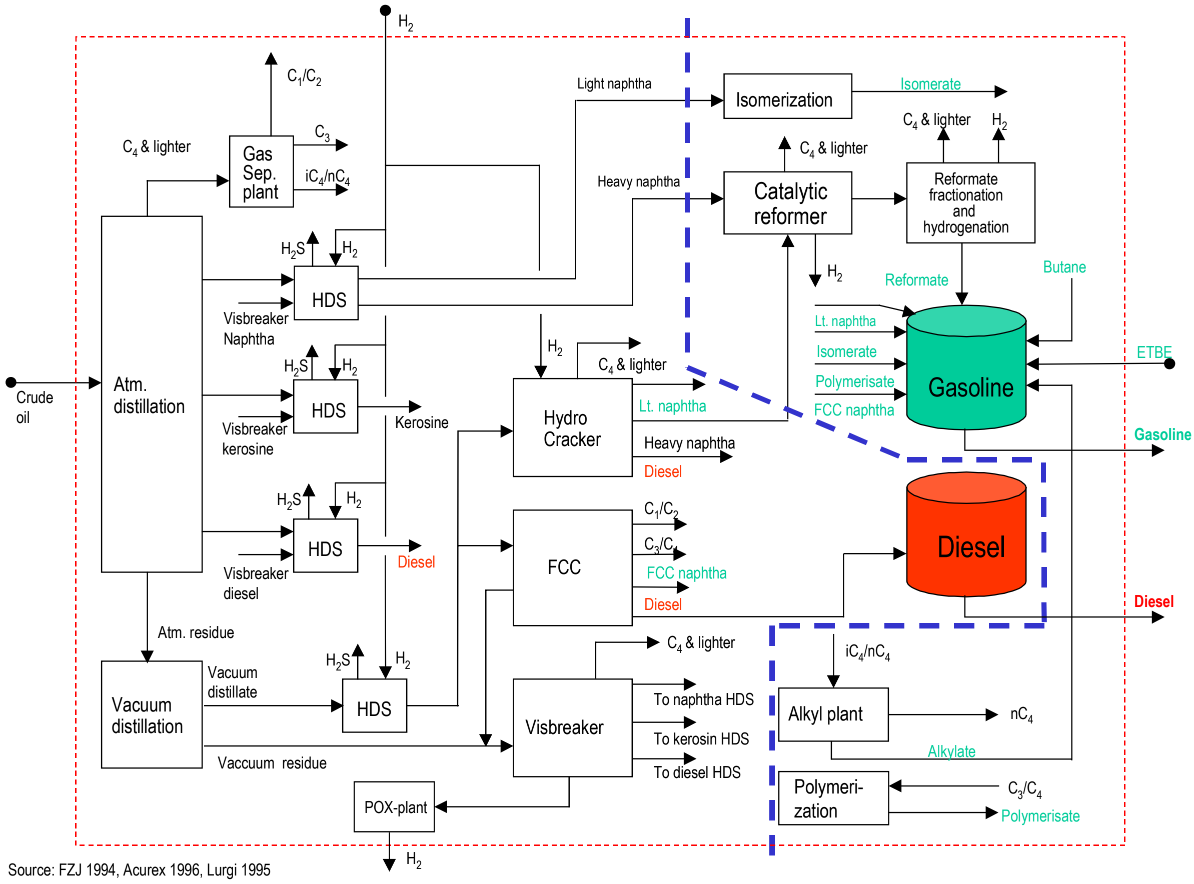
The target is, to calculate the energy consumption and emissions of greenhouse gases and ambient air pollutants caused by gasoline, diesel and naphtha supply. The emissions and energy consumption is influenced by the crude oil quality (density, sulfur content) and the required property of the final fuel. The sulfur content of the crude oil can be considered in the calculation as far as the desulfurization is concerned. The density of the crude oil influences the share of heavy products, which need more processing for conversion to light products (e.g. gasoline and diesel). This leads to a higher energy consumption and therefore to higher emissions. Crude oil refineries are very complex plants. The most general representation of the refinery process is shown in Fig. 3.1-1.

Fig. 3.1-1: Basic layout of a refinery process



At first there is an atmospheric distillation, which separates the crude oil into several components. There is a large variety of different outputs, which have to be processed further (see Fig. 3.1-2).

Fig. 3.1-2: Refinery for gasoline and diesel supply (low sulfur and low benzene content)



Source: FZJ 1994, Acurex 1996, Lurgi 1995

The light ends are treated in a gas separation plant to separate the different components of the gases. The naphtha is desulfurized and then processed in a catalytic reformer to get gasoline components with a high octane number. The diesel and kerosene fraction can be used directly after desulfurization.

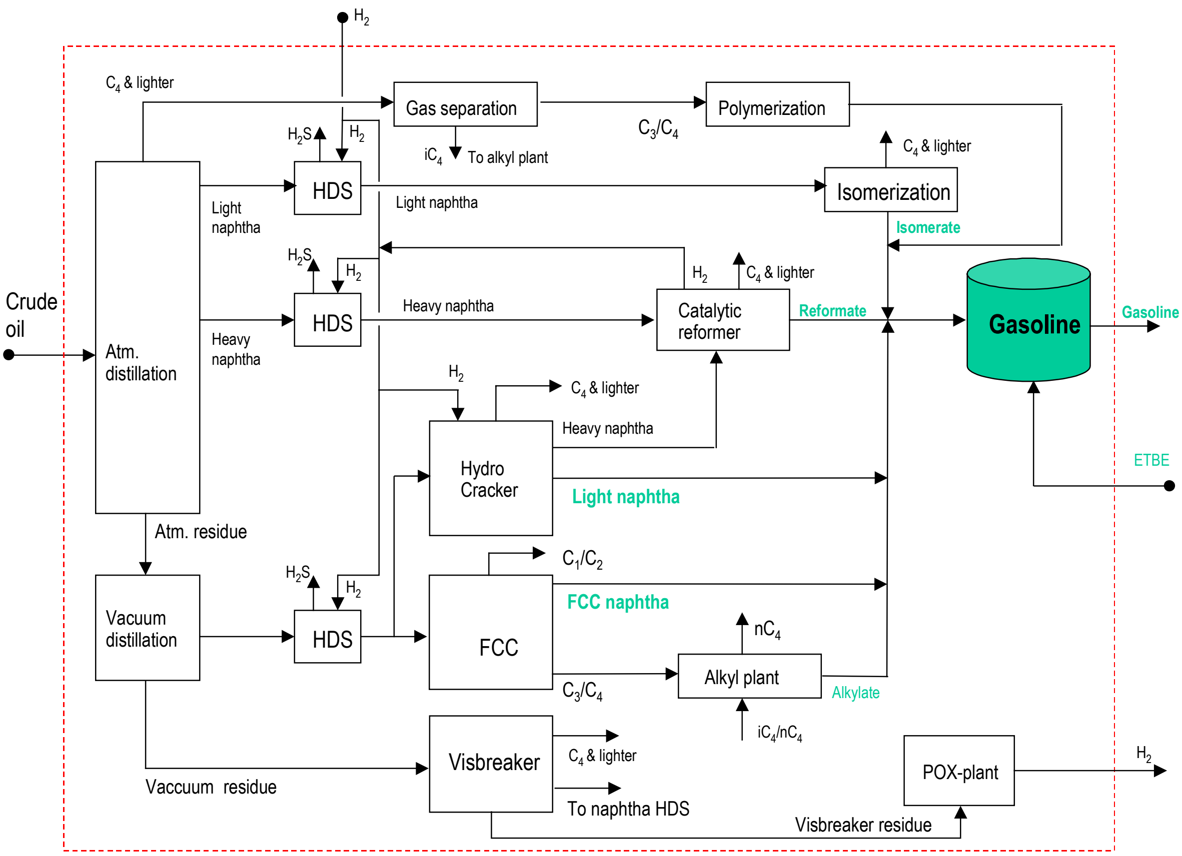
The residue of the atmospheric distillation is processed further in the vacuum distillation tower. The vacuum distillate is desulfurized and subsequently processed in cracking plants. As well as hydro cracker and fluid catalytic cracker (FCC) can be used.

For the conversion of the vacuum residue a coker, a visbreaker or a thermal cracker can be used. In the EU the use of visbreakers is more common. In the USA often cokers are used. For the sake of calculation the refinery is subdivided into one for gasoline production and one for diesel production. The products of the visbreaker are sent to the desulfurization units before they can be processed further.

At the end of the refinery process there are also different products. The question is which additional consumption of energy and additional emissions are caused by the production of gasoline. As shown in Fig. 3.1-2 all processes on the right of the blue dotted line are required for gasoline production. In a first approach the energy requirements for diesel and naphtha supply can be assumed as equivalent. The processes at the left of the blue dotted line are required both for gasoline, naphtha and diesel production.

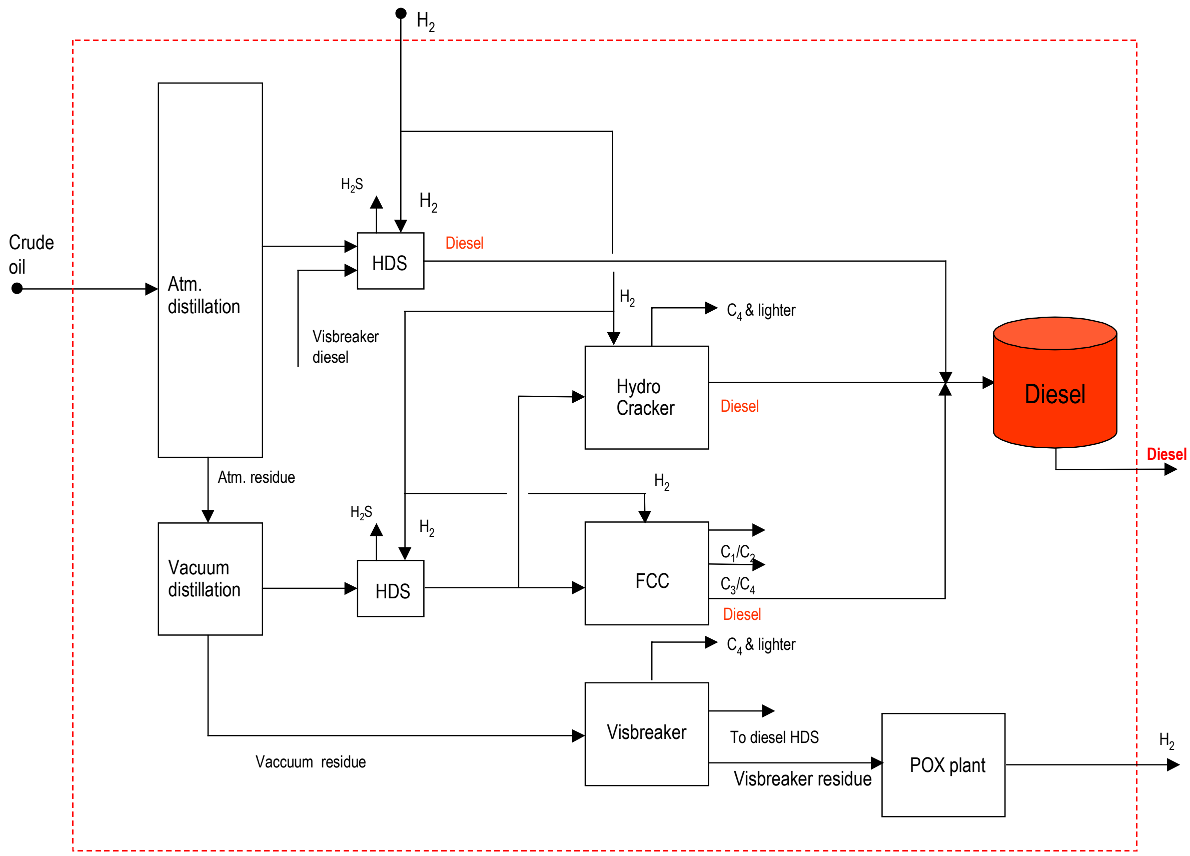
In order to allocate the energy consumption and the emissions of greenhouse gases of the total refinery to a certain product (e.g. gasoline) the refineries has to be separated into a "gasoline refinery" and a "diesel refinery" (see Fig. 3.1-3 and Fig. 3.1-4).

Fig. 3.1-3: "Gasoline refinery"



Source: FZJ 1994, Acurex 1996, Lurgi 1995

Fig. 3.1-4: "Diesel refinery"



Source: FZJ 1994, Acurex 1996, Lurgi 1995

For several processes the processes are further split up to model different outputs. The different products from the atmospheric distillation are distributed to the different downstream plants for further processing (e.g. desulfurization plants, vacuum distillation etc).

Different process chains lead to gasoline and diesel (see Fig. 3.1-2). The mass streams of each single process are connected together in a reasonable way to a chain by means of excel spreadsheets. The output of the first process is the input of the second process whose output itself is the input of the next process etc.. The resulting energy and emission data of gasoline (or diesel) production are calculated by adding all the different production chains used in the refinery which have a gasoline component (or a diesel component) as output.

Most of the processes e.g. the "vacuum distillation" have also different products. Every product is connected with the required plant for further processing. The final product of the different chains are subsequently converted to an energy based value to get the energy content of the refinery output.

Sometimes two different processes are connected in parallel. E.g. if the refinery has a hydro cracker as well as a fluid catalytic cracker (FCC), the share of the different streams of the vacuum distillate has to be known. As a first approach it was assumed that 50% of the vacuum distillate is processed in a FCC and 50% of the vacuum distillate is processed in a hydro cracker.

In reality there are refineries which have an FCC but no hydro cracker and there are refineries which have a hydro cracker and no FCC. A mix of these two kinds of cracking plants represents a mix of refineries. According to the oil based fuel producing companies in the EU about 60% of the refineries will have FCC-plants and about 40% will have hydro cracking plants in the year 2010 (see below).

Refinery processes

In the following the input assumptions and the mass streams for several processes of the refinery are described which are used for diesel and for gasoline production.

Atmospheric distillation:

The composition of the different products of the atmospheric distillation depends on the density of the crude oil feedstock. The shares of the different products can be calculated by the equations as shown in Tab. 4 (ρ = density).

Tab. 4: Material balance of atmospheric distillation [FZJ 1994]

	Unit	Equation
C4 & lighter	%-mass of crude oil feedstock	$15\text{-}15 \cdot \rho_{crude\ oil}$
Light naphtha	%-mass of crude oil feedstock	$32 - 31 \cdot \rho_{crude\ oil}$
Heavy naphtha	%-mass of crude oil feedstock	$114 - 112 \cdot \rho_{crude\ oil}$
Middle distillates (total)	%-mass of crude oil feedstock	$117 - 102 \cdot \rho_{crude\ oil}$
Kerosene	%-mass of middle distillates (MD)	$108 - 85 \cdot \rho_{MD}$
Atmospheric residue	%-mass of crude oil feedstock	$-178 + 260 \cdot \rho_{crude\ oil}$

The equations in Tab. 4 are valid for crude oil densities up to 1.0 t/m^3. The sulfur content of the crude oil is assumed to be 0.3 – 1.6 %-mass, the density to be 0.83 – 0.85. This leads to the following input and output data at the atmospheric distillation tower (see Tab. 5 and Tab. 6).

Tab. 5: Input and output data of atmospheric distillation (S-content: 0.3 %; density: 0.83 t/m3) [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Crude oil	4,940,000		-
Fuel (refinery gas)		702.5	-
Electric power	-	72.4	-
C_4 and lighter	-	-	125,970
Light naphtha	-	-	309,738
Heavy naphtha	-	-	1,039,376
Kerosene	-	-	598,300
Other middle distillate	-	-	999,296
Atmospheric Residue	-	-	1,867,320
Total	-	-	4,940,000
CO_2	-	-	148,200

Tab. 6: Input and output data of atmospheric distillation (S-content: 1.6 %; density: 0.85 t/m3) [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Crude oil	4,940,000		-
Fuel (refinery gas)		702.5	-
Electric power	-	72.4	-
C_4 and lighter	-	-	111,150
Light naphtha	-	-	279,110
Heavy naphtha	-	-	928,720
Kerosene	-	-	535,113
Other middle distillate	-	-	961,707
Atmospheric Residue	-	-	2,124,200
Total	-	-	4,940,000
CO_2	-	-	148,200

Tab. 7 shows the emissions of air pollutants of the atmospheric distillation tower in a typical modern refinery (derived from the data of the refinery of ELF in Leuna, erected in 1997).

Tab. 7: Emissions of air pollutants at the atmospheric distillation tower per t of crude oil feedstock [IPPC 1999]

SO_2 [kg/t_{feed}]	NO_x [kg/t_{feed}]	CO [kg/t_{feed}]	Dust [kg/t_{feed}]
0.004	0.012	0.012	0.001

Vacuum distillation

The atmospheric residue is processed in a downstream vacuum distillation tower. In the vacuum distillation the output stream is divided into two outputs, the vacuum distillate and the vacuum residue. Tab. 8 shows the mass streams and energy requirements in this part of the refinery in case of the use of crude oil with a density of about 0.83 t/m³ and Tab. 9 in case of the use of a crude oil with a density of about 0.85 t/m³.

Tab. 8: Vacuum distillation, downstream the atmospheric distillation for crude oil with a density of 0.83 t/m³ and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Atmospheric Residue	1,867,320		-
Fuel (refinery gas)		265.4	-
Electric power	-	27.3	-
Vacuum distillate (S-content: 0.4%)	-	-	1,155,124
Vacuum residue (S-content: 1.1%)	-	-	712,196
CO_2	-	-	56,917

Tab. 9: Vacuum distillation, downstream the atmospheric distillation for crude oil with a density of 0.85 t/m³ and a S-content of 1.6%[FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Atmospheric Residue	2,124,200		-
Fuel (refinery gas)		301.9	-
Electric power	-	31.1	-
Vacuum distillate (S-content: 1.2%)	-	-	1,204,421
Vacuum residue (S-content: 5.8%)	-	-	919,779
CO_2	-	-	64,747

In case of the heavier crude oil (0.85 t/m³) the processed amount of atmospheric residue is higher because more heavy fractions occur in the outlet of the atmospheric distillation tower.

The emissions of air pollutants of a typical vacuum distillation plant are indicated in [IPCC 1999]. The emission data of vacuum distillation plants are shown in Tab. 10.

Tab. 10: Emissions of air pollutants at the vacuum distillation plant per t of atmospheric residue feedstock [IPPC 1999]

SO_2 [kg/t_{feed}]	NO_x [kg/t_{feed}]	CO [kg/t_{feed}]	Dust [kg/t_{feed}]
0.004	0.013	0.013	0.001

Gas separation

The gaseous products (light ends) of the atmospheric distillation are fed into the gas separation plant, where the C_1/C_2-fraction (a mixture of methane and ethane) is separated from the C_3/C_4-fraction (a mixture of propane and butane).

Tab. 11: Gas separation, downstream the atmospheric distillation for crude oil with a density of 0.83 t/m³ and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Fuel (refinery gas)		253.8	
Electric power		26.2	
C_1	82,340		82,340
C_2	82,340		82,340
C_3	155,179		155,179
C_4	126,605		126,605
CO_2	-	-	53,670

Tab. 12: Gas separation, downstream the atmospheric distillation for crude oil with a density of 0.85 t/m^3 and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Fuel		245.6	
Electric power		25.3	
C_1	79,320		79,320
C_2	79,320		79,320
C_3	151,641		151,641
C_4	121,848		121,848
CO_2	-	-	51,947

As shown in Tab. 11 and Tab. 12 the amount of gases are slightly higher in case of the use of the lighter crude oil than in case of the use of the heavier crude oil.

Hydro-desulfurization (HDS)

By means of hydrogen and a catalyst sulfur containing components are cracked according to the following formula (cracking of mercaptanes).

$$R\text{-}SH + H_2 \rightarrow R\text{-}H + H_2S$$

The produced H_2S has to be fed into a Claus plant, where the H_2S is converted to solid sulfur.

$$H_2S + 3/2\ O_2 \rightarrow SO_2 + H_2O$$

$$2\ H_2S + SO_2 \rightarrow 3\ S + 2\ H_2O$$

$$3\ H_2S + 3/2\ O_2 \rightarrow 3\ S + 3\ H_2O$$

Cracker naphtha contains olefins, which are saturated with hydrogen during desulfurization. This leads to a higher hydrogen requirement than for the desulfurization of paraffins. In case of naphtha the content of olefins has a greater effect on the amount of hydrogen required than the sulfur content. The hydrogen consumption is stated with about 1 kg per t of naphtha for straight-run naphtha and 10 kg/t for naphtha from cracking plants [FZJ 1994].

In case of the middle and the vacuum distillates there is a linear correlation between sulfur content and hydrogen consumption .

Furthermore, the hydrogen consumption depends on the required sulfur content in the final product.

The hydrogen consumption for desulfurization of middle distillates from straight-run-middle distillates is given by

$$H_2 - consumption = 0.8 + 1.75 \cdot (X_{S,MD,in} - X_{S,MD,out}) \qquad \text{in [kg } H_2/t_{MD}]$$

The hydrogen consumption for desulfurization of middle distillates from crackers can be calculated by:

$$H_2 - consumption = 6.4 + 2.1 \cdot (X_{S,MD,in} - X_{S,MD,out}) \qquad \text{in [kg } H_2/t_{MD}]$$

The hydrogen consumption for desulfurization of vacuum distillates can be calculated by:

$$H_2 - consumption = 0.6 + 2.1 \cdot (X_{S,VD,in} - X_{S,VD,out}) \qquad \text{in [kg } H_2/t_{MD}]$$

where: $X_{S,MD,in}$: sulfur content of the input middle distillate (share of the mass)

$X_{S,MD,out}$: sulfur content of the output middle distillate (share of the mass)

Tab. 13: Specific energy consumption and CO_2-emissions for hydro-desulfurization (HDS) incl. sulfur recovery at the claus plant [FZJ 1994], [LBST calculation]

	Fuel [kWh/kWh$_{output}$]	Electric power [kWh/kWh$_{output}$]	H_2 [kWh/kWh$_{output}$]	CO_2-emission [g/kWh$_{output}$]
Straight run naphtha	0.0116	0.0012	0.0027	2.5
Cracker naphtha	0.0120	0.0012	0.0281	2.5
Straight run middle distillates [1)]	0.0150	0.0015	0.0023	3.2
Straight run middle distillates [2)]	0.0157	0.0016	0.0023	3.3
Cracker middle dis-tillates [1)]	0.0150	0.0015	0.0181	3.2
Cracker middle dis-tillates [2)]	0.0157	0.0016	0.0182	3.3

[1)] from 0.13 %-mass to 10 ppm-mass (or for crude oil with a sulfur content of 0.3 % at the atmospheric distillation respectively); [2)] from 0.74 %-mass to 10 ppm-mass (or for crude oil with a sulfur content of 1.6 % at the atmospheric distillation respectively)

Tab. 14: Specific energy consumption and CO_2-emissions for hydro-desulfurization (HDS) incl. sulfur recovery at the Claus plant of vacuum distillation [FZJ 1994], [LBST calculation]

	Fuel [kWh/kg$_{out}$]	Electric power [kWh/kg$_{out}$]	H_2 [kWh/kg$_{out}$]	CO_2-emission [kWh/kg$_{out}$]
From 0.4 %-mass to 10 ppm-mass [1)]	0.2350	0.0242	0.0203	49.5
From 1.2 %-mass to 10 ppm-mass [2)]	0.2445	0.0252	0.0208	51.5

[1)] or for crude oil with a sulfur content of 0.3 % at the atmospheric distillation respectively; [2)] or for crude oil with a sulfur content with 1.6 % at the atmospheric distillation respectively

The CO_2-emissions are caused by the fuel for heating. The emissions of ambient air pollutants are shown in Tab. 15.

Tab. 15: Emissions of air pollutants at the HDS and the Claus plant per t of feedstock [IPPC 1999]

	Feedstock	SO_2 [kg/t_{feed}]	NO_x [kg/t_{feed}]	CO [kg/t_{feed}]	Dust [kg/t_{feed}]
Naphtha HDS	Naphtha	0.005	0.014	0.014	0.001
Middle distillate HDS	Gasoil	0.002	0.007	0.007	0.000
Vacuum distillate HDS	Vacuum distillate	0.007	0.02	0.02	0.001
Claus plant	Sulfur	12.5	0.58	0.29	0.15

There is a lot of uncertainty whether the equations for hydrogen consumption (see above) are also valid for extremely low sulfur contents (e.g. 0.4 ppm in case of the naphtha supply path).

Hydro cracker

In the hydro cracker the vacuum distillate is converted to lighter products by addition of hydrogen. The Outputs of the hydro cracker are light ends (C_1/C_2 and C_3/C_4), light naphtha, heavy naphtha and middle distillates (optional). The composition of the several products depends on the mode of operation (maximum gasoline production or maximum diesel production). It is assumed that 50% of the vacuum distillate is processed in the hydro cracker. The other 50% are processed in the FCC (see below).

Tab. 16: Hydro Cracker, maximum gasoline production mode, in case of a crude oil density of 0.83 t/m³ and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Vacuum distillate	577,562		
H_2	21,481		
Fuel		271.6	
Electric power	-	28.0	
Light Naphtha	-	-	136,994
Heavy Naphtha	-	-	343,092
C_1/C_2	-	-	29,283
C_3			31,107
C_4	-	-	31,107
CO_2	-	-	57,391

Tab. 17: Hydro Cracker, maximum gasoline production mode, in case of a crude oil density of 0.85 t/m³ and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Vacuum distillate	602,211		
H_2	22,398		
Fuel		283.1	
Electric power	-	29.2	
Light Naphtha	-	-	142,840
Heavy Naphtha	-	-	357,734
C_1/C_2	-	-	30,533
C_3			32,435
C_4	-	-	32,435
CO_2	-	-	59,841

Fluid catalytic cracker (FCC)

Like the hydro cracker the FCC converts the vacuum distillate to lighter products. In contrast to the hydro cracker no hydrogen is added. Similar to the hydro cracker the composition of the different products at the outlet of a fluid catalytic cracker (FCC) depends on the mode of operation (maximum gasoline production or maximum diesel production). Tab. 19 shows the input and output data of a typical fluid catalytic cracker. The feedstock (vacuum distillate) has to be desulfurized before it is fed into the FCC.

Coke deposits at the surface of the catalyst material. Therefore regeneration is required.

As mentioned above it is assumed that 50% of the vacuum distillate is processed in the FCC.

Tab. 18: Fluid catalytic cracker (FCC), maximum gasoline production mode, in case of a crude oil density of 0.83 t/m^3 and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Desulfurized vacuum distillate	577,562		-
Fuel		328.5	-
Electric power		33.9	-
FCC-Naphtha	-	-	329,210
Middle distillate	-	-	80,859
Fuel oil / heavy	-	-	40,429
C_1/C_2	-	-	11,551
C_3	-	-	28,574
C_3	-	-	58,060
CO_2	-	-	124,125

Tab. 19: Fluid catalytic cracker (FCC), maximum gasoline production mode, in case of a crude oil density of 0.85 t/m³ and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Desulfurized vacuum distillate	602,211		-
Fuel		342.5	-
Electric power		35.3	-
FCC-Naphtha	-	-	343,260
Middle distillate	-	-	84,309
Fuel oil heavy	-	-	42,155
C_1/C_2	-	-	12,044
C_3			29,794
C_4	-	-	60,538
CO_2	-	-	129,422

The fuel demand is partly supplied by the coke. The CO_2-emissions are caused by the combustion of the additional fuel and the combustion of the coke during regeneration.

Tab. 20: Emissions of air pollutants at the FCC-plant per t of feedstock [IPPC 1999]

Feedstock	SO_2 [kg/t_{feed}]	NO_x [kg/t_{feed}]	CO [kg/t_{feed}]	Dust [kg/t_{feed}]
Desulfurized vacuum distillate	0.79	0.33	0.08	0.033

Coker

The vacuum residue can be processed in a coker or a visbreaker. Cokers are often used in the USA. In the EU mainly visbreakers are used for the processing of visbreaker residues. In the refinery model in this study no coker is used (share of vacuum residue processed in the visbreaker is 100%, share of vacuum residue processed in the coker is 0%). Tab. 21 shows the input and output data of a typical coker (delayed coking process) as described in [FCJ 1994].

Tab. 21: Coker [FZJ 1994]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Vacuum residue	1,140,000		-
Fuel (Refinery gas)	-	349	-
Electric power	-	36	-
Naphtha	-	-	188,000
Middle distillate	-	-	251,000
Fuel oil heavy	-	-	217,000
Coke	-	-	352,000
C_1/C_2	-	-	64,300
C_3/C_4	-	-	66,000
CO_2	-	-	73,800
H_2S	-	-	17,000

The H_2S has to be further processed in a Claus plant to convert it into solid sulfur.

Visbreaker

In the visbreaker the vacuum residue (containing very heavy components) and the heavy fraction of the FCC are cracked. The product at the outlet of the visbreaker contains gases, crack naphtha, middle distillates and heavy fuel oil.

Tab. 22: Visbreaker, mass and energy streams in case of a crude oil density of 0.83 t/m3 and an S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Vacuum residue and heavy fraction from FCC	752,625		-
Fuel		123.2	-
Electric power	-	12.8	-
Naphtha	-	-	45,158
Middle distillate	-	-	105,368
Heavy fuel oil	-	-	579,918
C_1/C_2	-	-	11,091
C_3	-	-	5,942
C_4	-	-	5,942
CO_2	-	-	21,720

Tab. 23: Visbreaker, mass and energy streams in case of a crude oil density of 0.85 t/m³ and an S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Vacuum residue and heavy fraction from FCC	961,933		-
Fuel		157.5	-
Electric power	-	16.3	-
Naphtha	-	-	57,716
Middle distillate	-	-	134,671
Heavy fuel oil	-	-	741,195
C_1/C_2	-	-	14,176
C_3	-	-	7,594
C_4	-	-	7,594
CO_2	-	-	27,761

Refinery power station

The electric power consumed by the refinery is partly derived from the electric power mix and partly produced within the refinery. The electric power requirement of the refinery is produced within the plant by a steam turbine power station with steam co-generation, fueled with refinery gas (a mixture of CH_4 and C_2H_6), heavy fuel oil and coke. For the calculation preliminary no refinery power station is included.

Steam reforming plant

The hydrogen requirements are partly produced by a steam reforming plant (the other part of the required hydrogen comes from the reformer). The steam reforming plant is fueled by natural gas.

POX-reforming plant

The hydrogen requirement can also be supplied by partial oxidation (POX) of heavy fuel oil or the vacuum distillate residue. A POX-reforming plant is e.g. located at the refinery in Leuna in Germany. It uses the heavy fuel oil fraction at the outlet of a visbreaker. Using POX-plants for processing the visbreaker residue is necessary to built a "reside free refinery". The use of visbreaker residue as fuel in ships causes a lot of emissions of heavy metals and air pollutants like SO_2. In the future it might be possible that the use of visbreaker residue as fuel for ships in not longer permitted.

Additional refinery processes required for gasoline production

For gasoline production further processing stages are required. E.g. a part of the light naphtha fraction is further processed in the isomerization plant. The heavy naphtha fraction is fed into the catalytic reformer and the C_3/C_4-fraction is partly used in the alkyl and polymerization plant.

The following plants are only required for gasoline production. All the emissions and energy consumption values of this plants are added to the gasoline fraction of the refinery.

Reformer

The reformer produces gasoline components with high octane numbers. Linear hydrocarbons are converted to cyclo hydrocarbons and subsequently dehydrogenated.

Tab. 24: Catalytic reformer, mass streams and energy flow in case of a crude oil density of 0.83 t/m³ and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Heavy naphtha (from atmospheric distillation and FCC)	1,382,468		-
Fuel (Refinery gas)		786.2	-
Electric power	-	80.9	-
Reformate	-	-	1,180,191
H_2	-	-	36,381
C_1/C_2	-	-	49,769
C_3	-	-	58,064
C_4	-	-	58,064
CO_2	-	-	166,187

Tab. 25: Catalytic reformer, mass streams and energy flow in case of a crude oil density of 0.85 t/m³ and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Heavy naphtha (from atmospheric distillation and FCC)	1,286,454		-
Fuel		731.6	-
Electric power	-	75.3	-
Reformate	-	-	1,098,226
H_2	-	-	33,854
C_1/C_2	-	-	46,312
C_3	-	-	54,031
C_4	-	-	54,031
CO_2	-	-	154,645

The reformate is the main product. The by-product hydrogen can be used in the hydro-desulfurization plant or in the hydro cracker. The C_1/C_2-fraction is used as fuel and the C_3/C_4-fraction is used in the alkyl plant.

The emissions of ambient air pollutants are shown in Tab. 26.

Tab. 26: Emissions of air pollutants at the reformer per t of feedstock [IPPC 1999]

Feedstock	SO_2 [kg/t_{feed}]	NO_x [kg/t_{feed}]	CO [kg/t_{feed}]	Dust [kg/t_{feed}]
Heavy naphtha	0.024	0.069	0.069	0.003

To achieve a low benzene content (< 1 %-vol) in the final fuel a reformer with down-stream benzene removal may be required (input and output data see Tab. 27). Another possible way to reduce the benzene content in the final fuel is, to increase the share of al-kylate in the final fuel.

Tab. 27: Reformer with downstream benzene removal, not yet include within the refinery model [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Heavy naphtha	950,000		-
Fuel (Refinery gas)		786	-
Electric power	-	81	-
Reformate	-	-	779,000
H_2	-	-	25,000
C_1/C_2	-	-	34,200
C_3/C_4	-	-	79,800
Benzene	-	-	32,000
CO_2	-	-	166,200

Alkyl plant

In the alkyl plant i-C_4 is converted to liquid hydrocarbons with a higher octane number. Generally C_4 from the C_3/C_4-fraction at the outlet of the FCC is used as feedstock.

Tab. 28: Alkyl plant, mass streams and energy flow in case of a crude oil density of 0.83 t/m³ and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
C_4	58,060		-
Fuel		44.8	-
Electric power	-	4.6	-
Alkylate	-	-	52,531
n-C_4	-	-	5,530
CO_2	-	-	9,474

Tab. 29: Alkyl plant, mass streams and energy flow in case of a crude oil density of 0.85 t/m³ and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
C_4	60,538		-
Fuel		46.7	-
Electric power	-	4.8	-
Alkylate	-	-	54,772
n-C_4	-	-	5,766
CO_2	-	-	9,878

Isomerization

During isomerization the structure of the molecules are converted (e.g. n-hexane is converted to i-hexane).

Tab. 30: Isomerization plant, mass streams and energy flow in case of a crude oil density of 0.83 m^3/t and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Light naphtha from atmospheric distillation	309,738	-	-
H_2	1,858	-	-
Fuel		220.1	-
Electric power	-	22.7	-
Isomerate	-	-	309,738
CO_2	-	-	46,515

Tab. 31: Isomerization plant, mass streams and energy flow in case of a crude oil density of 0.85 m³/t and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
Light naphtha from atmospheric distillation	279,110	-	-
H_2	1,675	-	-
Fuel		198.3	-
Electric power	-	20.5	-
Isomerate	-	-	279,110
CO_2	-	-	41,915

Polymerization

In the polymerization plant C_3/C_4 are converted to hydrocarbons, which can be added as gasoline component.

Tab. 32: Polymerization plant, mass streams and energy flow in case of a crude oil density of 0.83 t/m³ and a S-content of 0.3% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
$C_{3/}C_4$-Olefins and C_3/C_4-Paraffins	174,646	-	-
Fuel (Refinery gas)		81.6	-
Electric power	-	8.6	-
Polymerisate	-	-	149,270
CO_2	-	-	17,284

Tab. 33: Polymerization plant, mass streams and energy flow in case of a crude oil density of 0.85 t/m³ and a S-content of 1.6% [FZJ 1994], [LBST calculation]

	Input		Output
		Energy	
	t/a	GWh/a	t/a
C_3/C_4-Olefins and C_3/C_4-Paraffins	159,821	-	-
Fuel (Refinery gas)		74.7	-
Electric power	-	7.9	-
Polymerisate	-	-	136,599
CO_2	-	-	15,817

Complete gasoline refinery

According to data in [IPPC 1999] the emissions of a complete modern refinery (e.g. Leuna, Germany) related to LHV of the crude oil feedstock (LHV = 11.6 kWh/kg) can be calculated as shown in Tab. 34 (without power station).

Tab. 34: Emissions of the refinery in Leuna [IPPC 1999]; [LBST calculation]

CO_2 [g/kWh_{feed}]	SO_2 [g/kWh_{feed}]	NO_x [g/kWh_{feed}]	CO [g/kWh_{feed}]	Dust [g/kWh_{feed}]
18.8	0.034	0.023	0.013	0.001

In Leuna crude oil from Russia is processed. For the calculation of the gasoline output related emissions an allocation of the emission data to the different refinery products has to be done. Another problem is, that the refinery probably produces gasoline with a sulfur content well above 30 ppm-mass (EU guidelines 2000: 150 ppm-mass).

The energy consumption and emissions of greenhouse gases and air pollutants of the refinery depends on the share of the different streams of gasoline supply in the refinery (or the share of the different components e.g. isomerate, reformate, FCC naphtha, ETBE in the final fuel respectively).

The composition of the different components in the final fuel depends on the crude oil (density, sulfur content) and the required properties (e.g. octane number) of the produced gasoline. According to EU guidelines 98/70/EU of the European parliament (October, 13th 1998) the sulfur content in the gasoline will be reduced to values below 30 ppm-mass until the year 2005. The content of benzene, which is identified as carcinogenic, has been already reduced below 1 %-vol in the year 2000.

For the calculation the sulfur content was reduced to 10 ppm, but preliminary no benzene removal was assumed.

According to [DGMK 1992] and [Acurex 1996] the typical composition of conventional gasoline was stated as shown in Tab. 35 and Tab. 41.

Tab. 35: Composition of conventional gasoline, share in %-mass, in case of a crude oil density of 0.83 t/m^3 and a S-content of 0.3% (maximum gasoline mode, 50% FCC, 50% hydro cracker)

	DGMK 1992 [%]	Acurex 1996 [%]	LBST [%]
Reformate	66.3	45.8	54.6
FCC naphtha	26.8	16.6	15.2
Coker naphtha	-	-	-
Hydrocrackate	-	5.2	6.3
Isomerate	5.7	18.2	14.3
Polymerisate	-	-	6.9
Alkylate	-	10.7	2.4
MTBE	-	-	-
Butane	1.2	3.5	0.3

Tab. 36: Composition of conventional gasoline, share in %-mass, in case of a crude oil density of 0.85 t/m³ and a S-content of 1.6% (maximum gasoline mode, 50% FCC, 50% hydro cracker)

	DGMK 1992 [%]	Acurex 1996 [%]	LBST [%]
Reformate	66.3	45.8	53.3
FCC naphtha	26.8	16.6	16.7
Coker naphtha	-	-	-
Hydrocrackate	-	5.2	6.9
Isomerate	5.7	18.2	13.5
Polymerisate	-	-	6.6
Alkylate	-	10.7	2.7
MTBE	-	-	-
Butane	1.2	3.5	0.3

[Acurex 1996] described a typical refinery in California, USA. [DGMK 1992] refers also to US refineries as source for the gasoline composition. There are no data for the typical composition of gasoline in the EU. The MTBE can be replaced by ETBE. For this study ETBE is used.

In case of the crude oil with a density of about 0.83 kg/m³ as well as in the case of a crude oil density of 0.85 t/m³ the LHV of the “LBST gasoline” is about 11.8 kWh/kg and the ROZ is about 97.

The connected single processes leads to the input and output data of the refinery which is itself a single process used in the E^2 database. The input and output data are shown in Tab. 37 - Tab. 40

Tab. 37: Input data for calculation in E^2-database (crude oil density: 0.83 t/m³; S-content: 0.3%), without POX, visbreaker residue is sold as fuel

Input Basic Assumptions			
Share VD into FCC	50%		
Share visbreaker residue to POX	0%		
Crude oil density	0.83	t/m3	
S-content crude oil	0.3%		
Specific input data (for E2-database)			
	Diesel kWh/kWh	Naphtha kWh/kWh	Gasoline kWh/kWh
Crude oil	1.034	1.034	1.143
H2	0.016	0.016	-0.031
Electric power	0.005	0.005	0.010
Specific emission data (for E2-database)			
	Diesel g/kWh	Naphtha g/kWh	Gasoline g/kWh
CO2	11.5	11.5	22.0
CH4	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000
SO2	0.0114	0.0114	0.0139
NOx	0.0079	0.0079	0.0124
CO	0.0047	0.0047	0.0089
NMVOC	0.0000	0.0000	0.0000
Dust	0.0006	0.0006	0.0008

Tab. 38: Input data for calculation in E^2-database (crude oil density: 0.85 t/m³; S-content: 1.6%), without POX, visbreaker residue is sold as fuel

Input Basic Assumptions			
Share VD into FCC	50%		
Share visbreaker residue to POX	0%		
Crude oil density	0.85	t/m3	
S-content crude oil	1.6%		
Specific input data (for E2-database)			
	Diesel kWh/kWh	Naphtha kWh/kWh	Gasoline kWh/kWh
Crude oil	1.034	1.034	1.149
H2	0.017	0.017	-0.029
Electric power	0.005	0.005	0.010
Specific emission data (for E2-database)			
	Diesel g/kWh	Naphtha g/kWh	Gasoline g/kWh
CO2	11.9	11.9	22.3
CH4	0.0000	0.0000	0.0000
N2O	0.0000	0.0000	0.0000
SO2	0.0168	0.0168	0.0200
NOx	0.0083	0.0083	0.0129
CO	0.0048	0.0048	0.0089
NMVOC	0.0000	0.0000	0.0000
Dust	0.0006	0.0006	0.0009

Tab. 39: Input data for calculation in E²-database (crude oil density: 0.83 t/m³; S-content: 0.3%), with POX, visbreaker residue is converted to hydrogen

Input Basic Assumptions			
Share VD into FCC	50%		
Share visbreaker residue to POX	100%		
Crude oil density	0.83	t/m3	
S-content crude oil	0.3%		
Specific input data (for E2-database)			
	Diesel kWh/kWh	Naphtha kWh/kWh	Gasoline kWh/kWh
Crude oil	1.172	1.172	1.296
H2	-0.083	-0.083	-0.132
Electric power	0.012	0.012	0.017
Specific emission data (for E2-database)			
	Diesel g/kWh	Naphtha g/kWh	Gasoline g/kWh
CO2	47.9	47.9	62.3
CH4	0.0057	0.0057	0.0064
N2O	0.0000	0.0000	0.0000
SO2	0.0139	0.0139	0.0167
NOx	0.0096	0.0096	0.0143
CO	0.0150	0.0150	0.0203
NMVOC	0.0000	0.0000	0.0000
Dust	0.0006	0.0006	0.0009

Tab. 40: Input data for calculation in E^2-database (crude oil density: 0.85 t/m^3; S-content: 1.6%), with POX, visbreaker residue is converted to hydrogen

Input Basic Assumptions			
Share VD into FCC	50%		
Share visbreaker residue to POX	100%		
Crude oil density	0.85 t/m3		
S-content crude oil	1.6%		
Specific input data (for E2-database)			
	Diesel kWh/kWh	Naphtha kWh/kWh	Gasoline kWh/kWh
Crude oil	1.219	1.219	1.354
H2	-0.114	-0.114	-0.165
Electric power	0.015	0.015	0.019
Specific emission data (for E2-database)			
	Diesel g/kWh	Naphtha g/kWh	Gasoline g/kWh
CO2	60.5	60.5	76.4
CH4	0.0077	0.0077	0.0085
N2O	0.0000	0.0000	0.0000
SO2	0.0211	0.0211	0.0247
NOx	0.0107	0.0107	0.0156
CO	0.0185	0.0185	0.0242
NMVOC	0.0000	0.0000	0.0000
Dust	0.0007	0.0007	0.0010

Negative values ("-") indicates an export of energy or material and leads to credit.

These inputs and outputs are connected with upstream and downstream processes. Hydrogen is produced in a natural gas fuel steam reformer. If excess hydrogen occur a credit has been taken into account whereas a natural gas steam reformer is used as reference system. Electricity input comes from the EU electricity mix. The crude oil input is connected with the crude oil supply. The gasoline and diesel output is connected with the transport.

A 3.1.3 Gasoline Distribution

The gasoline produced is distributed by truck (40 t), which meets the exhaust emission limits according to EURO 4 (average distance from the refinery: 150 km).

A 3.1.4 Complete conventional gasoline supply chain

Tab. 41 shows the greenhouse gas emissions of the supply of conventional gasoline in the EU.

Tab. 41: Energy consumption and greenhouse gas emissions related to the LHV of the final fuel (conventional gasoline)

	Energy [kWh/kWh]	CO_2 [g/kWh]	CH_4 [g/kWh]	N_2O [g/kWh]
Crude oil density 0.83 t/m^3, without POX	1.20	41	0.285	0.001
Crude oil density 0.85 t/m^3, without POX	1.21	42	0.288	0.001
Crude oil density 0.83 t/m^3, with POX	1.24	60	0.273	0.001
Crude oil density 0.85 t/m^3, with POX	1.26	67	0.271	0.001

The conversion of the visbreaker residue to hydrogen in a POX-plant causes more emissions of greenhouse gases than the variants without POX-plants. The reason is that the carbon content of the visbreaker residue (a kind of heavy fuel oil) is released at the plant site in case of the conversion to hydrogen. If the visbreaker residue leaves the refinery as product the CO_2 is emitted during combustion e.g. in a heavy fuel oil fueled ship.

According to [Lurgie 1995] the "bottom-of-the-barrel" disposal by blending of fuel oil with visbreaker residue can not be accepted in the future. Therefore the partial oxidation of this residues will increase.

A 3.1.5 Literature

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A 3.2 Farming Machines

Table 3.2-1: Diesel consumption of farming machines for sugar beet plantation (case 1 and 2) [FfE 1998]

	LL	L	SF	M	S	
Load	0%	30%	35%	50%	80%	
Diesel consumption	16	74	87	126	204	g/(h*kW_N)
LHV (Diesel)	42.7	42.7	42.7	42.7	42.7	MJ/kg
Sugar beet plantation						
	h/ha	h/ha	h/ha	h/ha	h/ha	kW
Seed praparation	0.22	0.15	0.06	0.45	0.00	55
Seeding by a single seed drill	0.17	0.80	0.03	0.00	0.00	55
Land application of fertilizer by a fertilizer broadcaster	0.21	0.16	0.06	1.04	0.00	55
Land application of pesticides	0.38	0.90	0.13	0.00	0.00	55
Upkeeping of sugar beets by a spring tine harrow	0.28	0.22	0.06	1.24	0.00	55
Upkeeping of sugar beets by a rotating hoe	0.28	0.22	0.06	1.24	0.00	55
Sugar beet harvesting	0.32	0.15	0.03	0.15	3.55	55
Ploughing in of beet top rake by a heavy no till drill	0.11	0.06	0.03	0.02	0.38	75
Tilling	0.25	0.09	0.03	0.08	1.45	75
Loading trailer	0.23	0.22	0.03	1.86	1.86	55
Total	2.45	2.97	0.52	6.08	7.24	
Sugar beet plantation						
	LL	L	SF	M	S	Total
	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha
Seed praparation	8	26	12	133	0	180
Seeding by a single seed drill	6	139	6	0	0	152
Land application of fertilizer by a fertilizer broadcaster	8	28	12	308	0	356
Land application of pesticides	14	156	27	0	0	197
Upkeeping of sugar beets by a spring tine harrow	11	38	12	367	0	428
Upkeeping of sugar beets by a rotating hoe	11	38	12	367	0	428
Sugar beet harvesting	12	26	6	44	1701	1789
Ploughing in of beet top rake by a heavy no till drill	6	14	8	8	248	285
Tilling	13	21	8	32	947	1022
Loading trailer	9	38	6	550	891	1495
Total	97	526	111	1810	3787	6331

Table 3.2-2: Diesel consumption of farming machines for rape seed plantation [FfE 1998]

	LL	L	SF	M	S	
Load	0%	30%	35%	50%	80%	
Diesel consumption	16	74	87	126	204	g/(h*kW_N)
LHV (Diesel)	42.7	42.7	42.7	42.7	42.7	MJ/kg
Rape seed plantation						
	h/ha	h/ha	h/ha	h/ha	h/ha	kW
Seed praparation	0.22	0.15	0.06	0.45	0.00	40
Seeding	0.12	0.47	0.03	0.00	0.00	40
Land application of fertilizer	0.21	0.16	0.06	1.04	0.00	40
Land application of pesticides	0.28	0.67	0.10	0.00	0.00	40
Rape seed harvesting	0.13	0.07	0.03	0.04	1.23	74
Ploughing in of crop residue	0.11	0.06	0.03	0.03	0.47	65
Tilling	0.25	0.09	0.03	0.08	1.45	65
Loading trailer	0.13	0.11	0.03	0.62	0.62	40
Total	1.45	1.78	0.37	2.26	3.77	
Rape seed plantation						
	LL	L	SF	M	S	Total
	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha
Seed praparation	6	19	9	97	0	131
Seeding	3	59	4	0	0	67
Land application of fertilizer	6	20	9	224	0	259
Land application of pesticides	8	85	15	0	0	107
Rape seed harvesting	7	16	8	16	793	840
Ploughing in of crop residue	5	12	7	10	266	301
Tilling	11	18	7	28	821	886
Loading trailer	4	14	4	133	216	371
Total	49	244	64	508	2096	2962

Table 3.2-3: Diesel consumption of farming machines for the reference system [FfE 1998]

	LL	L	SF	M	S	
Load	0%	30%	35%	50%	80%	
Diesel consumption	16	74	87	126	204	g/(h*kW_N)
LHV (Diesel)	42.7	42.7	42.7	42.7	42.7	MJ/kg
	h/ha	h/ha	h/ha	h/ha	h/ha	kW
Seeding (rye grass, egyptian clover)	0.19	0.07	0.03	0.02	0.49	40
Mulching by a mulching machine	0.11	0.11	0.03	0.84	0.00	40
Ploughing in stubbles by a heavy no till drill	0.11	0.06	0.03	0.02	0.38	65
Total	0.41	0.24	0.09	0.88	0.87	
	LL	L	SF	M	S	Total
	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha	MJ/ha
Seeding (rye grass, egyptian clover)	5	9	4	4	171	194
Mulching by a mulching machine	3	14	4	181	0	202
Ploughing in stubbles by a heavy no till drill	5	12	7	7	215	247
Total	13	35	16	192	386	642

A 3.3 Inputs and outputs for the supply of sugar beet derived ethanol

Ethanol from Sugar Beet, Variant 1a: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.135	kWh
Nuclear	0.009	kWh
Biomass	0	kWh
Coal / Brown	0.002	kWh
NG	0.067	kWh
Mineral Oil	0.006	kWh
Geothermal	0	kWh
Waste	0.001	kWh
Coal / Hard	0.004	kWh
Hydro Power	0.001	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.893	kWh
Material Source	0.026	kg
Energy Source	0.007	kWh
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Organic Energy	0.109	kWh

Ethanol from Sugar Beet, Variant 1b: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.135	kWh
Nuclear	0.04	kWh
Biomass	0	kWh
Coal / Brown	0.008	kWh
NG	0.508	kWh
Mineral Oil	0.009	kWh
Geothermal	0	kWh
Waste	0.007	kWh
Coal / Hard	0.023	kWh
Hydro Power	0.004	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.893	kWh
Material Source	0.029	kg
Energy Source	0.007	kWh
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Soybeans	-0.14	kg
Diesel Oil	-0.027	kWh
Fuel Oil / Heavy	-0.037	kWh
Coal	-0.002	kWh
Rape seed stofflich	0.06	kg

Ethanol from Sugar Beet, Variant 1c: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.292	kWh
Nuclear	0.041	kWh
Biomass	0	kWh
Coal / Brown	0.008	kWh
NG	0.366	kWh
Mineral Oil	0.009	kWh
Geothermal	0	kWh
Waste	0.007	kWh
Coal / Hard	0.02	kWh
Hydro Power	0.004	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.332	kWh
Material Source	0.018	kg
Energy Source	0.124	kWh
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Coke-mass	0.002	kg

Ethanol from Sugar Beet, Variant 2a: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.133	kWh
Nuclear	0.009	kWh
Biomass	0	kWh
Coal / Brown	0.002	kWh
NG	0.053	kWh
Mineral Oil	0.006	kWh
Geothermal	0	kWh
Waste	0.001	kWh
Coal / Hard	0.004	kWh
Hydro Power	0.001	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.893	kWh
Material Source	0.024	kg
Energy Source	0.005	kWh
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Organic Energy	0.109	kWh

Ethanol from Sugar Beet, Variant 2b: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.133	kWh
Nuclear	0.04	kWh
Biomass	0	kWh
Coal / Brown	0.008	kWh
NG	0.485	kWh
Mineral Oil	0.009	kWh
Geothermal	0	kWh
Waste	0.007	kWh
Coal / Hard	0.022	kWh
Hydro Power	0.004	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.893	kWh
Material Source	0.027	kg
Energy Source	0.005	kWh
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Soybeans	-0.14	kg
Diesel Oil	-0.027	kWh
Fuel Oil / Heavy	-0.038	kWh
Coal	-0.002	kWh
Rape seed stofflich	0.06	kg

Ethanol from Sugar Beet, Variant 2c: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.291	kWh
Nuclear	0.041	kWh
Biomass	0	kWh
Coal / Brown	0.008	kWh
NG	0.356	kWh
Mineral Oil	0.009	kWh
Geothermal	0	kWh
Waste	0.007	kWh
Coal / Hard	0.02	kWh
Hydro Power	0.004	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.332	kWh
Material Source	0.017	kg
Energy Source	0.123	kWh
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Coke-mass	0.002	kg

Ethanol from Sugar Beet, Variant 3a: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.11	kWh
Mineral Oil	0.015	kWh
Nuclear	0.007	kWh
Biomass	0	kWh
Coal / Brown	0.001	kWh
NG	0.046	kWh
Geothermal	0	kWh
Waste	0.001	kWh
Coal / Hard	0.004	kWh
Hydro Power	0.001	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.893	kWh
Material Source	0.009	kg
Energy Source	0.004	kWh
Energy Source / Renewable	0	kWh
Organic Energy	0.109	kWh

Ethanol from Sugar Beet, Variant 3b: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.12	kWh
Nuclear	0.039	kWh
Biomass	0	kWh
Coal / Brown	0.007	kWh
NG	0.477	kWh
Mineral Oil	0.009	kWh
Geothermal	0	kWh
Waste	0.006	kWh
Coal / Hard	0.021	kWh
Hydro Power	0.004	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.893	kWh
Material Source	0.012	kg
Energy Source	0.004	kWh
Energy Source / Renewable	0	kWh
Soybeans	-0.14	kg
Diesel Oil	-0.027	kWh
Fuel Oil / Heavy	-0.038	kWh
Coal	-0.002	kWh
Rape seed stofflich	0.06	kg
Material Source / Organic	0	kg

Ethanol from Sugar Beet, Variant 3c: per kWh of ethanol

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.279	kWh
Nuclear	0.04	kWh
Biomass	0	kWh
Coal / Brown	0.007	kWh
NG	0.351	kWh
Mineral Oil	0.008	kWh
Geothermal	0	kWh
Waste	0.006	kWh
Coal / Hard	0.019	kWh
Hydro Power	0.004	kWh
Wind Power	0	kWh
Steel	0	kg
Sugar Beet	1.332	kWh
Material Source	0.007	kg
Energy Source	0.122	kWh
Energy Source / Renewable	0	kWh
Coke-mass	0.002	kg

A 3.4 Inputs and outputs for the supply of bio-ester from rape seed (RME)

RME, Variant 1a, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.144	kWh
Nuclear	0.024	kWh
Biomass	0	kWh
Coal / Brown	0.005	kWh
NG	0.3	kWh
Mineral Oil	0.011	kWh
Geothermal	0	kWh
Waste	0.004	kWh
Coal / Hard	0.012	kWh
Hydro Power	0.002	kWh
Wind Power	0	kWh
Energy Source	0.022	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	0.028	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0.001	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 1b, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.144	kWh
Nuclear	-0.041	kWh
Biomass	0	kWh
Coal / Brown	-0.039	kWh
NG	0.097	kWh
Mineral Oil	-0.036	kWh
Geothermal	0	kWh
Waste	-0.001	kWh
Coal / Hard	0.007	kWh
Hydro Power	-0.002	kWh
Wind Power	0	kWh
Energy Source	0.022	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	-0.01	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0.001	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 2a, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.136	kWh
Nuclear	0.023	kWh
Biomass	0	kWh
Coal / Brown	0.005	kWh
NG	0.251	kWh
Mineral Oil	0.01	kWh
Geothermal	0	kWh
Waste	0.004	kWh
Coal / Hard	0.012	kWh
Hydro Power	0.002	kWh
Wind Power	0	kWh
Energy Source	0.016	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	0.023	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0.001	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 2b, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.136	kWh
Nuclear	-0.042	kWh
Biomass	0	kWh
Coal / Brown	-0.04	kWh
NG	0.048	kWh
Mineral Oil	-0.036	kWh
Geothermal	0	kWh
Waste	-0.002	kWh
Coal / Hard	0.007	kWh
Hydro Power	-0.002	kWh
Wind Power	0	kWh
Energy Source	0.016	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	-0.015	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0.001	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 3a, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.144	kWh
Nuclear	0.025	kWh
Biomass	0	kWh
Coal / Brown	0.005	kWh
NG	0.304	kWh
Mineral Oil	0.011	kWh
Geothermal	0	kWh
Waste	0.004	kWh
Coal / Hard	0.012	kWh
Hydro Power	0.002	kWh
Wind Power	0	kWh
Energy Source	0.023	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	0.028	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 3b, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.144	kWh
Nuclear	-0.041	kWh
Biomass	0	kWh
Coal / Brown	-0.039	kWh
NG	0.101	kWh
Mineral Oil	-0.036	kWh
Geothermal	0	kWh
Waste	-0.001	kWh
Coal / Hard	0.007	kWh
Hydro Power	-0.002	kWh
Wind Power	0	kWh
Energy Source	0.023	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	-0.01	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 4a, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.144	kWh
Nuclear	0.025	kWh
Biomass	0	kWh
Coal / Brown	0.005	kWh
NG	0.304	kWh
Mineral Oil	0.011	kWh
Geothermal	0	kWh
Waste	0.004	kWh
Coal / Hard	0.012	kWh
Hydro Power	0.002	kWh
Wind Power	0	kWh
Energy Source	0.023	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	0.028	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg

RME, Variant 4b, per kWh of RME

Faktor	Amount	Unit
Mineral Oil / TotalFinaElf	0.144	kWh
Nuclear	-0.041	kWh
Biomass	0	kWh
Coal / Brown	-0.039	kWh
NG	0.101	kWh
Mineral Oil	-0.036	kWh
Geothermal	0	kWh
Waste	-0.001	kWh
Coal / Hard	0.007	kWh
Hydro Power	-0.002	kWh
Wind Power	0	kWh
Energy Source	0.023	kWh
Steel	0	kg
Rape seed	1.735	kWh
Material Source	-0.01	kg
Energy Source / Renewable	0	kWh
Material Source / Organic	0	kg
Soybeans	-0.218	kg
Diesel Oil	-0.066	kWh
Fuel Oil / Heavy	-0.066	kWh
Coal	-0.003	kWh
Rape seed stofflich	0.093	kg