UCSB

Crude Oil Refining in US and California

Life Cycle Inventories (LCI) for Base Oil / Lubricants

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ACRONYMS -

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BTX	Benzene, Toluol, Xylene
EIA	US Energy Information Administration
EoL	End-of-Life
EP	Eutrophication Potential
EPA	US Environmental Protection Agency
FCC	Fluid Catalytic Cracking
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LFO	Light Fuel Oil
LPG	Liquefied Petroleum Gas
MTBE	Methyl-Tertiary- Butyl- Ether
NMVOC	Non-methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PE	PE INTERNATIONAL
POCP	Photochemical Ozone Creation Potential
RON	Research Octane Number

SECA	Sea Emission Control Area
US	Country code: USA
US-CA	Country code: California

GLOSSARY (ISO 14040/44:2006)

ISO 14040:2006, Environmental management - Life cycle assessment - Principles and framework, International Organization for Standardization (ISO), Geneva 2006.

ISO 14044 Environmental management -- Life cycle assessment -- Requirements and guidelines, International Organization for Standardization (ISO), Geneva 2006

Allocation

Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems

Functional Unit

Quantified performance of a product system for use as a reference unit

Closed loop & open loop

A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.

An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.

Cradle to grave

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of life.

Cradle to gate

Addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition until the end of the production process ("gate of the factory"). It may also include transportation until use phase.

Life cycle

A unit operations view of consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal. This includes all materials and energy input as well as waste generated to air, land and water.

Life Cycle Assessment - LCA

Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle

Life Cycle Inventory - LCI

Phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact assessment - LCIA

Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life Cycle Interpretation

Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

BACKGROUND

A detailed report was not foreseen within the project. However, we put all information together, documented all data sources used, and give explanations around PE INTERNATIONAL's LCA refinery model, etc, allowing UCSB to compile the official project report for the commissioner.

Based on that, this report should be seen as supporting document.

1 GOAL OF THE STUDY

The goal of the project is to set up of life cycle inventories (LCI) representing US and Californian average base oil production. Results generated within this project (PE INTERNATINAL acts as subcontractor for UCSB) slip in a bigger project managed by UCSB.

The goals in detail are:

1. - Set up of life cycle inventories for average virgin base oil production in US and California by using PE INTERNATIONAL's LCA refinery model,
2. - Use of these life cycle inventories as benchmark for the comparison with different used oil treatment options. This comparison is not part of this study and will be performed by UCSB.

The two life cycle inventories are set up as partly aggregated data sets, allowing the LCA practitioner to combine with country /region specific upstream processes, like crude oil mixes, the natural gas mixes, and electricity.

In addition, data sets for bitumen, heavy fuel oil, and bunker oil, and lubricants are modeled,

The audience is:

1. - CalRecycle (commissioner),
2. - and the oil and gas industry (stakeholders);

Since the results are intended to support comparative assertions (i.e., option A vs. option B) and are intended to be disclosed to the public (i.e., third parties other than commissioner and practitioner), a critical review is requested by ISO 14040. Since PE is acting as subcontractor, commissioned to provide LCI data sets it is in the responsibility of UCSB to prepare an ISO conform report and accompany the review panel.

2 Scope of the Study

The following section describes the general scope of the project to achieve the stated goals. This includes the identification of specific products to be assessed, the supporting product systems (e.g. refining, etc.), and the boundary of the study, allocation procedures and cut-off criteria.

2.1 Product System(s) to be studied

The data set covers the entire supply chain of the refinery products. This includes well drilling, crude oil production and processing as well as transportation of crude oil via pipeline respectively vessel to the refinery. Main technologies such as conventional crude oil (primary, secondary, tertiary) and unconventional oil production (oil sands, in-situ) are considered. For both parameters like energy consumption, crude oil processing technologies and transport distances are individually considered for each crude oil production country. Also considered are US and Californian specific downstream (refining) technologies, feedstock (crude oil) and product (diesel fuel, etc.) properties, like sulfur contents, as well as the output spectrum of the refineries. The inventory is mainly based on industry data taken from literature and is completed where necessary by secondary data.

2.2 Product Function(s), Functional Unit and Reference Flows

The reference flow is 1 kg of base oil (group II), at the refinery gate.

2.3 System Boundaries

The system boundaries of the modeled life cycle inventory are shown in the following figure. For all processes the resources needed, and emissions released are accounted for.

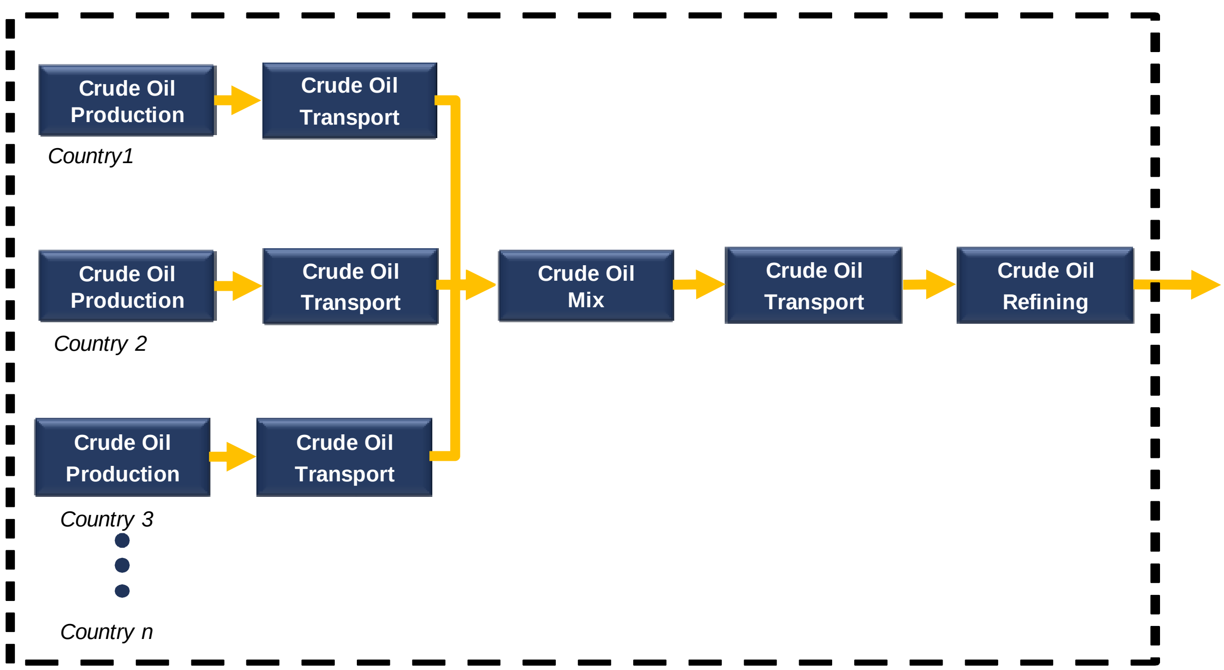

Figure 2-1: System boundaries of the base oil / lubricant supply

1.1.1 Time Coverage

All data refer to the year 2010. Data gaps are filled by data from previous years, e.g. 2008. Whenever non-2010 data are used, it is indicated clearly in the report respectively in the attached Excel spreadsheets.

1.1.2 Technology Coverage

An average refinery is considered for US and for the Californian refinery. The averaging is based on the throughput of each unit process capacity.

1.1.3 Geographical Coverage

The geographical coverage is US respectively California.

2.4 ALLOCATION

Allocation of downstream (refining) data (energy and materials):

- ✓ For all products of the refinery, allocation by mass and energy (based on net calorific value) is applied. The feedstock (crude oil) is allocated by energy, the refinery efforts (emissions) by mass to each product. The production route of every refinery product is modeled in detail, and therefore it is possible to track the energy efforts for operating each single unit process of the refinery. These energy demand and the corresponding emissions can be allocated causer-oriented to each refinery product.

- ✓ The feedstock of the respective unit process, which is necessary for the production of a product or an intermediate product, is allocated by energy (i.e. mass of the product * net calorific value of the product). In this way products with high caloric values, e.g. gasoline or gases are assigned to higher feedstock consumption and hence higher environmental upstream impacts compared with low caloric value products (e.g. asphalt, residual oil).

- ✓ The energy demand resp. the emissions released by supplying these energy (thermal energy, steam, electricity), of each unit process, e.g. atmospheric distillation, being required to create a product or an intermediate product, are allocated according to the share of the throughput of the unit process (mass allocation). In general, products that are more complex to produce and therefore pass a lot of refinery facilities e.g. gasoline, are assigned with higher energy consumption values (and hence higher emissions) compared with e.g. straight-run products. The higher the energy intensity of a process, the higher the assignment of the emissions.

- ✓ Summarized all emissions from the crude oil supply (crude oil mix) and all emissions from the refinery (bubble refinery emission) are allocated to the single refinery products.

Allocation of upstream data (energy and materials):

- ✓ For the combined crude oil, natural gas and natural gas liquids (NGL) production allocation is applied by net calorific value.

2.5 Cut-Off Criteria

The cut-off criteria for including or excluding materials, energy and emissions data of the study are as follows:

- ✓ Mass – If a flow is less than 1% of the cumulative mass of the model it may be excluded, - providing its environmental relevance is not a concern. -
- ✓ Energy – If a flow is less than 1% of the cumulative energy of the model it may be excluded, providing its environmental relevance is not a concern.
- ✓ Environmental relevance – If a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it was included. Material flows that leave the system (emissions) and whose environmental impact is greater than 1% of the whole impact of an impact category that has been considered in the assessment must be covered. This judgment was made based on experience and documented as necessary.
- ✓ Refining catalysts and other refining auxiliary materials are not considered as well as refining infrastructure.

The sum of the excluded material flows must not exceed 5% of mass, energy or environmental relevance.

2.6 Selection of LCIA Methodology and Types of Impacts

The model is set up to assess the most common used impact categories[1,2], like Global Warming Potential, Eutrophication, Acidification, and Photochemical Ozone Creation Potentials, and Ozone Depletion Potential. Additionally, the evaluation of human toxicity and ecotoxicity employing the USEtox characterization model can be done. The precision of the current USEtox characterization factors is within a factor of 100–1,000 for human health and 10–100 for freshwater ecotoxicity[3]. This is a substantial improvement over previously available toxicity characterization models, but still significantly higher than for the impacts noted above. Given the limitations of the characterization models for each of these factors, results are reported as 'substances of high concern', but are not to be used to make comparative assertions.

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[1] Bare, J: TRACI 2.0: the Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0. Clean Technology Environmental Policy, 2010.

[2] Guinée, J. B. (ed.): Handbook on life cycle assessment: Operational guide to the ISO-standards. Centre for Milieukunde (CML), Leiden 2001.

[3] Rosenbaum et al (2008): USEtox—the UNEP-SETAC toxicity model: recommended characterization factors for human toxicity and freshwater ecotoxicity in life cycle impact assessment, Int J Life Cycle Assess (2008) 13:532–546

In addition, the non-renewable and renewable primary energy demand as well as the water footprint can be assessed. The assessment itself is not a content of the study.

2.7 Data Quality Requirements

The data used to create the inventory model are precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data is considered to be of the highest precision, followed by calculated and estimated data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. Cut-off criteria apply and were defined in Chapter 2.5.
- Consistency refers to modeling choices and data sources. The goal is to ensure that differences in results occur due to actual differences between product systems, and not due to inconsistencies in modeling choices, data sources, emission factors, or other.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The geographical region under consideration is US resp. California.

An evaluation of the data quality with regard to these requirements is provided in the interpretation chapter of this report.

2.8 Assumptions and Limitations

The data sources for the complete product system are sufficiently consistent:

- The data on the energy carrier supply chains (crude oil, natural gas, etc.) are based on statistics with country-specific transport distances and energy carrier composition, as well as industry and literature data on the inventory of exploration, production and processing.
- Average infrastructure data for oil platforms are from literature.
- Refinery data (product slate, capacity, emissions, etc.) are also based on statistical data and measurements of refineries taken from literature, as well as secondary data.
- LCI modeling is fully consistent.

In terms of the country specific crude oil production and refining, missing data on certain parameters has been used from countries with a comparable technology. Data measured at a group of representative production facilities have been used to represent the national production.

2.9 Software and Database

The LCA model was created using the GaBi 5 Software system for life cycle engineering, developed by PE INTERNATIONAL AG. The GaBi 2011 LCI database provides the life cycle inventory data for several of the raw and process materials obtained from the background system.[4]

2.10 Critical Review

No external critical review is planned within this sub-contracting project.

[4] GaBi 5 dataset documentation for the software-system and databases, LBP-GaBi, University of Stuttgart and PE INTERNATIONAL AG, Leinfelden-Echterdingen, 2012 (http://documentation.gabi-software.com/)

3 Life Cycle Inventory (LCI) Analysis

3.1 Data Collection

1.1.4 Data Collection & Quality Assessment Procedure of the refining operations

Data used for modeling the supply chain for base oil products are mainly based on secondary data taken from literature. The main data used in the modeling and the corresponding data sources are listed below.

In the following table the feedstock and product properties of the refinery inputs and outputs are shown.

Table 3-1: US and Californian refinery feedstock and refinery product properties (2010)

Refinery feedstock and Product Properties	***US***	***US-CA***
Feedstock		
Crude oil sulfur content [wt.%]	1.39[5]	1.56[6]
Crude oil density [kg/dm³]	0.872[7]	0.903[8]
Products (Sulfur content)		
Gasoline [ppm]	30[9]	12[10]

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[5] Source: US EIA – Crude Oil Input Qualities: http://www.eia.gov/dnav/pet/pet_pnp_crq_a_EPC0_YCS_pct_a.htm, annual average, 2010

[6] Source: California Energy Commission (CEC) Petroleum Industry Information Reporting Act (PIIRA) database. Volume-weighted average for all refineries operating during calendar year, 2010.

[7] Source: US EIA – Crude Oil Input Qualities: http://www.eia.gov/dnav/pet/pet_pnp_crq_a_EPC0_YCG_d_a.htm, annual average, 2010

[8] Source: California Energy Commission (CEC) Petroleum Industry Information Reporting Act (PIIRA) database. Volume-weighted average for all refineries operating during calendar year 2010, (25.25 API gravity).

[9] Source: US EIA – Gasoline Sulfur Standards: http://www.epa.gov/otaq/standards/fuels/gas-sulfur.htm, Federal, Large Refiners, 2010.

[10] Source: California Energy Commission (CEC) confidential survey of California refineries. Volume-weighted average for all types of gasoline produced during 2006 was 11.9ppm. Sulfur content of gasoline produced for the California market was lower, averaging 9.6ppm.

Diesel fuel [ppm]	15[11]	5[12]
Kerosene / Jet A1 [wt.%]	0.07[13]	0.065[14]
Light fuel oil [wt.%]	0.05[15]	0.05[16]
Marine diesel [wt.%]	0.05[17]	0.0005[18]
HFO (inland) [wt.%]	0.31[19]	0.31[20]
HFO (marine, SECA) [wt.%]	1.0[21]	1.0[22]
HFO (marine, global) [wt.%]	4.5[23]	2.25[24]

[11] Source: US EIA – Highway, Nonroad, Locomotive, and Marine Diesel Fuel Sulfur Standards: http://www.epa.gov/otaq/standards/fuels/diesel-sulfur.htm, Large Refiners & Importers, 2010.

[12] Source: California Energy Commission (CEC) confidential survey of California refineries. Volume-weighted average for California and EPA ultra-low sulfur diesel fuel produced during 2006 was 4.4ppm.

[13] Source: Expert judgment by PE INTERNATIONAL based on international values, 2010.

[14] Source: California Energy Commission confidential survey of California refineries. Volume-weighted average for jet fuel (commercial Jet A) produced during 2006 was 654ppm.

[15] Source: Expert judgment by PE INTERNATIONAL based on international values, 2010.

[16] Source: Expert judgment by PE INTERNATIONAL based on international values, 2010.

[17] Source: US EIA – Highway, Nonroad, Locomotive, and Marine Diesel Fuel Sulfur Standards: http://www.epa.gov/otaq/standards/fuels/diesel-sulfur.htm, Large Refiners & Importers, 2010.

[18] Source: California regulations require all marine vessels within harbor and close proximity to shore use ULSD.

[19] Source: US EIA – Refinery & Blender Net Production http://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_a.htm, annual average 2010. (category of HFO 0.31 derived from EIA classification)

[20] Source: US value, (category of HFO 0.31 derived from EIA classification).

[21] Source: International Maritime Organization (IMO) - Prevention of Air Pollution from Ships. Second IMO GHG Study 2009. London, UK.

[22] Source: International Maritime Organization (IMO) - Prevention of Air Pollution from Ships. Second IMO GHG Study 2009. London, UK.

[23] Source: International Maritime Organization (IMO) - Prevention of Air Pollution from Ships. Second IMO GHG Study 2009. London, UK.

[24] Source: California Energy Commission (CEC) confidential survey of California refineries. Volume-weighted average for residual fuel oil produced during 2006 was 2.25 wt.%.

Table 3-2 shows the output slate of the US and Californian refineries in the year 2010. As displayed are the fuels consumed at the refineries to supply the necessary energy to run the refining operations.

Table 3-2: US and Californian refinery production (2010)[25]

Refinery Output	***US***[26] ***[vol.-%]***	***US-CA***[27] ***[vol.-%]***
Refinery gas	6.60	5.17
- Net production	3.48	0.84
- Fuel consumed at refineries	3.12	4.33
LPG	3.45	3.14
- Net production	3.43	3.03
- Fuel consumed at refineries	0.03	0.11
Naphtha	1.88	0.04
- Net production	1.88	0.04
- Fuel consumed at refineries	0.00	0.00
Gasoline	46.94	50.06
- Net production	46.94	50.06
- Fuel consumed at refineries	0.00	0.00
Aromatics / BTX (incl. in others)	-	-
Kerosene / Jet A1	7.53	12.70
- Net production	7.53	12.70
- Fuel Consumed at Refineries	0.00	0.00
Diesel fuel	17.82	16.89
- Net production	17.81	16.89
- Fuel Consumed at Refineries	0.01	0.00
Light fuel oil (LFO)	1.70	0.73

[25] A mapping index of terms used by EIA and PE INTERNATIONAL can be found in Annex 6

[26] Source: US EIA – Refinery & Blender Net Production and Fuel Consumed at Refineries: http://www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_a.htm, http://www.eia.gov/dnav/pet/pet_pnp_capfuel_dcu_nus_a.htm, both annual average, 2010.

[27] Source: The Californian Energy Commission (CEC) Petroleum Products Yielded from One Barrel of Crude Oil in California, personal communication between UCSB and CEC, annual average 2010.

Refinery Output	***US[26] [vol.-%]***	***US-CA[27] [vol.-%]***
- Net production	1.70	0.73
- Fuel Consumed at Refineries	0.00	0.00
Marine diesel	2.37	
- Net production	2.37	
- Fuel Consumed at Refineries	0.00	part of others
HFO (inland)	0.26	
- Net production	0.25	
- Fuel Consumed at Refineries	0.01	part of others
HFO (marine, SECA)	0.44	0.19
- Net production	0.44	0.19
- Fuel Consumed at Refineries	0.00	0.00
HFO (marine, global)	2.34	2.50
- Net production	2.34	2.50
- Fuel Consumed at Refineries	0.00	0.00
Lubricants	0.85	1.04
- Net production	0.85	1.04
- Fuel Consumed at Refineries	0.00	0.00
Waxes / Paraffins	0.04	0.00
- Net production	0.04	0.00
- Fuel Consumed at Refineries	0.00	0.00
Asphalt /Bitumen	1.96	1.14
- Net production	1.96	1.14
- Fuel Consumed at Refineries	0.00	0.00
Petrol Coke	5.39	6.40
- Net production	4.21	5.26
- Fuel Consumed at Refineries	1.18	1.13
Sulfur (incl. in others)	-	-
Other (like Sulfur, BTX, Hydrogen, etc.)	0.43	0.01
- Net production	0.39	0.01
- Fuel Consumed at Refineries	0.03	0.00
Total	**100.00**	**100.00**

Table 3-3: Purchased energy by US and Californian refineries (2010)

Purchased energy by refineries	***US***	***US-CA***
Purchased natural gas consumed at refineries (Million Cubic Feet)	756,062	154,974
Purchased coal consumed at refineries (Thousand Short Tons)	29	0
Purchased electricity consumed at refineries (Million Kilowatthours)	46,227	3,132
Purchased steam consumed at refineries (Million Pounds)	128,981	12,200

Refinery emission data are derived from three sources:

- US EPA – Greenhouse Gas Data Sets[28], with reference to 2010
- US EPA –The National Emissions Inventory[29], with reference to 2008
- US EPA – Toxics Release Inventory (TRI)[30], with reference to 2010

Detailed information on the refinery emission data can be found in the enclosed Excel file.

Refining process capacity data are listed in the following table. The model is set up in a way so that the capacities are related to the crude oil distillation unit. Therefore the absolute values are not the decisive factor but rather the ratios from all processes to the crude oil distillation (CDU) unit. Nevertheless the absolute capacities are presented in this documentation.

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[28] Source: US EPA – Greenhouse Gas Data Sets http://www.epa.gov/ghgreporting/ghgdata/datasets.html, annual average 2010.

[29] Source: US EPA – The National Emissions Inventory http://www.epa.gov/ttn/chief/net/2008inventory.html, annual average 2008. (since the annual emission data are related to the processed volume of crude oil, crude oil data from 2008 are considered to guarantee data consistency)

[30] Source: US EPA TRI Explorer: http://iaspub.epa.gov/triexplorer/tri_release.chemical, annual average, 2010.

Table 3-4: US and Californian refinery facility capacity (2010) [31]

Facility	*US [bbl/stream day]*	*US-CA [bbl/ stream day]*
Crude oil distillation (CDU)	18,581,089	2,134,000
Vacuum distillation	8,542,643	1,273,556
Coking	2,605,076	519,500
Visbreaking / Thermal Cracking	26,600	5,000
Catalytic cracking (FCC)	6,231,961	729,400
Catalytic reforming	3,700,463	434,100
Semi-regenerative	1,377,763	214,000
Continuous regeneration	2,322,700	220,100
Catalytic hydrocracking	1,819,700	484,300
Distillate	1,674,700	484,300
Residue	145,000	0
Catalytic hydrotreating	16,023,206	2,050,100
Cat. Reformer feed / naphtha desulph.	4,281,046	447,900
Kerosene/Jet desulphurisation	1,339,150	194,100
Middle destillate desulphurisation	4,336,882	445,300
HT FCC-feed desulphurisation	2,796,798	699,200
Residue desulphurisation	874,448	61,200
Post FCC naphtha treatment	2,394,882	202,400

[31] Source: US EIA - Number and Capacity of Petroleum Refineries and U.S. Production Capacity of Operable Petroleum Refineries http://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm and http://www.eia.gov/dnav/pet/pet_pnp_capprod_dcu_nus_a.htm, annual average, 2010.

Alkylation	1,248,514	182,026
Polymerization/Dimerization	0	0
Aromatics and BTX extraction	270,820	1,500
Isomerization	715,317	148,050
Base oil	239,760	39,800
Oxygenates	37,000	0
Hydrogen [MMcf]	2,985	1,140
Petrol coke	760,441	134,400
Sulfur [t]	34,058	4,847
Asphalt/Bitumen	844,078	75,433

In general, the quality of figures derived from US EIA , US EPA, and the Californian Energy Commission statistics was assumed to have a high level of quality. Any re-calculation of quantities and units needed to feed the PE INTERNATIONAL's LCA refining model was double checked internally. Consistency checks were performed whenever possible.

1.1.5 Fuels and Energy – Background Data

Refinery feedstock data sets were obtained from the GaBi 5 database 2011. They are based on national respectively regional averages. Table 3-5 shows the most relevant LCI datasets used in modeling the product systems.

Table 3-5: Key energy datasets used in inventory analysis

Geography	***Data set name***	***Primary source***	***Year***	***Project specific***
US	Electricity grid mix	PE	2008	No
US	Crude oil mix	PE	2008	No
US	Natural gas mix	PE	2008	No
US-West	Electricity grid mix	PE	2008	No
US-CA	Crude oil mix	PE	2010	Yes

US: Refining model:

Crude oil / natural gas: Both energy carriers are modeled according to the US average specific supply situation. The US energy carrier supply (share of imports and / or domestic supply) including the country-specific energy carrier properties (e.g. element and energy content) are accounted for. The exploration, production, processing and transport processes of the energy carrier supply chains are modeled according to the specific situation of each crude oil / natural gas producing country. The different production and processing techniques (emissions and efficiencies) in the different crude oil / natural gas producing countries are considered, e.g. different crude oil production technologies or different flaring rates at the oil platforms.

Electricity is modeled according to the individual US-specific situations. The US-specific modeling is achieved on multiple levels. Firstly, individual energy carrier specific power plants and plants for renewable energy sources are modeled according to the current national electricity grid mix. Modeling the electricity consumption mix includes transmission / distribution losses and the own use by energy producers (own consumption of power plants and "other" own consumption e.g. due to pumped storage hydropower etc.), as well as imported electricity. Secondly, the national emission and efficiency standards of the power plants are modeled as well as the share of electricity plants and combined heat and power plants (CHP). Thirdly, the country-specific energy carrier supply (share of imports and / or domestic supply) including the country-specific energy carrier properties (e.g. element and energy content) are accounted for. Fourthly, the exploration, mining/production, processing and transport processes of the energy carrier supply chains are modeled according to the specific situation of each electricity producing country. The different production and processing techniques (emissions and efficiencies) in the different energy producing countries are considered, e.g. different crude oil production technologies or different flaring rates at the oil platforms.

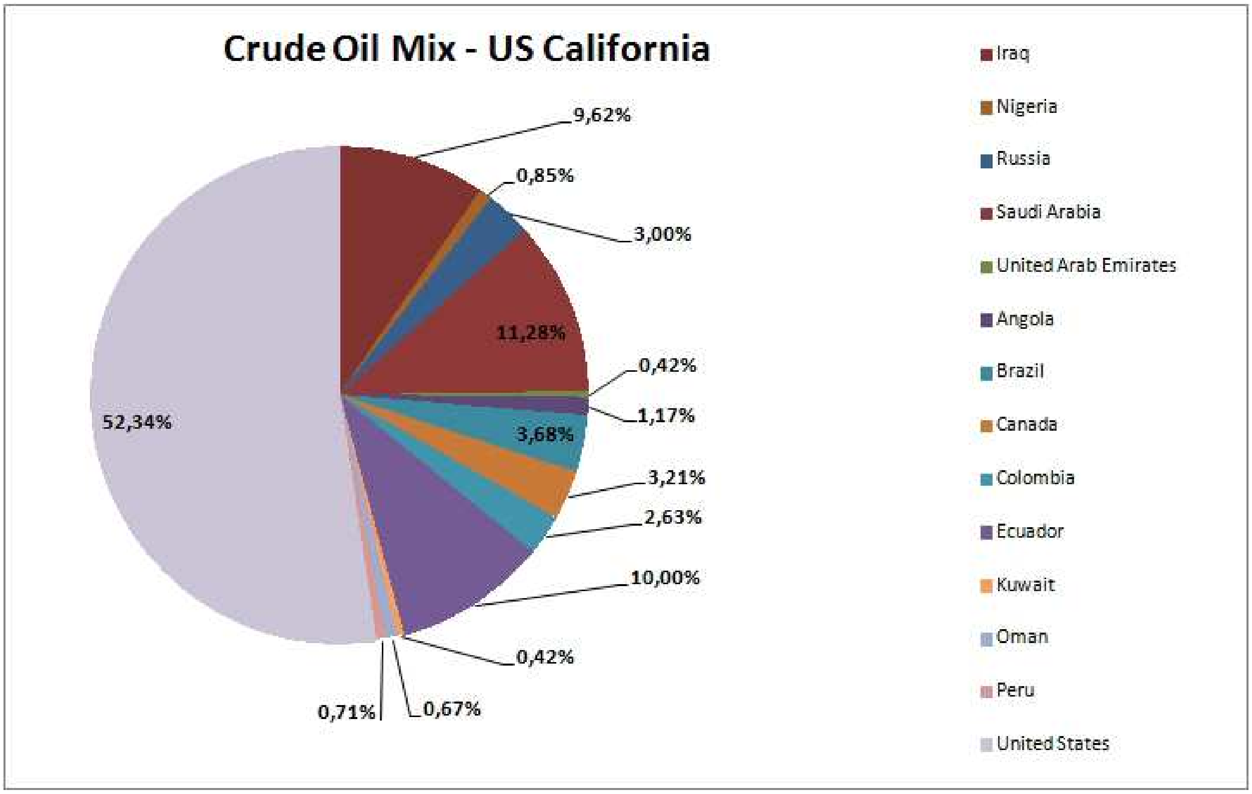
US-CA: Refining model:

The crude oil mix is modeled according to the Californian average specific supply situation. Since natural gas plays a minor role, the US specific average is used. Electricity is modeled according to the individual Western US-specific situations.

The Californian crude oil mix looks as follows[32][33]:

[32] Source: The Californian Energy Commission: http://www.energyalmanac.ca.gov/petroleum/statistics/2010_foreign_crude_sources.html, annual average 2010.

[33] Source: The Californian Energy Commission: http://www.energyalmanac.ca.gov/petroleum/statistics/crude_oil_receipts.html, annual average 2010.



1.1.6 Raw Materials and Processes – Background Data

Data for up- and downstream raw materials and unit processes were obtained from the GaBi 5 database 2011. Up- and downstream raw materials and processes are of minor relevance to the LCI modeling of the product system. Documentation for all non-project-specific datasets can be found at www.gabi-software.com/support/gabi/gabi-lci-documentation.

1.1.7 Transportation

Average transportation distances and modes of transport are included for the transport of crude oil and natural gas to the refineries. The GaBi database for transportation and fuels was used to model the ocean-going vessel, and continental pipeline transportation.

1.1.8 Emissions to Air, Water and Soil

All emissions reported by refinery operators for the refining are taken into account in the study (data used for official reporting). All gate-to-gate emissions data were obtained from publications of the US EPA. These include GHG, criteria emissions as well as others emissions. Minor data gaps were closed by using European data.

The energy supply emissions are provided by the GaBi LCI database.

Emission data (CO_2, etc.) for all feedstocks, crude oil, natural gas, electricity etc. are obtained from the GaBi 5 database 2011. This includes the energy carrier supply itself as all emissions associated with transportation. Energy use in transportation and the associated emissions were calculated using pre-configured transportation models from the GaBi 5 database 2011.

3.2 PRODUCT SYSTEM

1.1.9 Overview of Life Cycle

The data set covers the entire supply chain of virgin base oil. This includes well drilling, crude oil production and processing as well as transportation of crude oil via pipeline resp. vessel to the refinery. Main technologies such as conventional crude oil (primary, secondary, tertiary) and unconventional oil production (oil sands, in-situ) are considered. For both, parameters like energy consumption, crude oil processing technologies, and transport distances are individually considered for each crude oil production country. Also considered are US and Californian specific downstream (refining) technologies, feedstock (crude oil) and product (diesel fuel, etc.) properties, like sulfur contents, as well as output spectrum of the refineries.

1.1.10 Description of Process Flow

Petroleum refineries are complex plants. The combination and sequence of a large number of processes is usually very specific to the characteristics of the crude oil and the products to be produced. Additional influencing factors are the market demand for the type of products, the available crude oil quality and certain requirements set by authorities, the configuration and complexity of a refinery.

Simple hydro-skimming refineries can process only a few crude oil qualities and produce few high-quality products. Complex refineries with many conversion plants can process different crude oil types.

Petroleum refinery activities start with the reception of crude oil. After desalting, the crude oil is fed to the distilling column of the atmospheric distillation (fractionation of the crude oil by separation according to density/ boiling point/ condensation areas). The light ends (gases) go up to the head of the column and are employed to the liquid gas system to recover methane and ethane for use as refinery fuel and LPG (propane and butane) as saleable products. This light product separation is done in almost every refinery. These gases can also be used in a steam-reforming process to produce hydrogen, which is needed for the desulphurisation processes, the hydro cracking and to a lesser extent for the isomerisation unit. The straight-run naphtha of the atmospheric distillation, which is taken in the upper trays of the column are spitted and fed to three different processes. The light naphtha fraction is introduced to the chemical sweetening process. Some sweetened naphtha is directly blended in the gasoline pool, the main fraction is sent to the isomeriation unit where the aliphatic paraffins are converted into iso-paraffins with a high octane value. Often there is a de-isopentaniser (distillation) downstream to increase the gain of iso-components. These iso-paraffins are very valuable components for the gasoline production with high RON content. After desulphurisation the heavy naphtha fractions are sent to the reformer for catalytic transformation from aliphatic paraffins to iso-paraffins and from cyclo-paraffins to aromatic compounds, with a reduction of the net calorific value. The specific feature of this process is the production of hydrogen (the only hydrogen producer besides additional plants, like steam-reforming). The outputs of the isomerisation (often including a de-isopentaniser) and catalytic reforming go to the gasoline blending system and premium or regular gasoline follow as products. Kerosene is directly obtained from the atmospheric distillation and is separately treated from the rest of the middle distillates fraction. The main part of the middle distillates produced in the atmospheric distillation is employed into the hydrofiner (for desulphurisation). The desulphurised product is fed to the middle distillate blender. The residue from the atmospheric distillation is mainly introduced to the vacuum distillation. Here there is a distillation in light vacuum gas oil, vacuum gas oil (wax distillate) and vacuum residue. A part of the atmospheric residue is fed into the visbreaker (mild thermal cracking).

Small amounts are introduced directly into the heating oil blending system and the asphalt-blowing process. The light gas oil, as a product of the vacuum distillation, goes to the hydrofiner, is desulphurised, and employed to the middle distillate blender. Some of the vacuum distillate, which has been taken from the middle trays of the vacuum distillation, is introduced to the base oil production of lubricants and waxes. Most of it is fed either to a catalytic cracker (first desulphurised) or a hydrocracker, where the feeds are converted into shorter chains by molecule restructuring. The products are gases, gasoline, middle distillates and heavy cycle gas oils (components of the heavy fuel oil). The gases of the catalytic cracking are treated in an alkylation and polymerisation unit to manufacture additional valuable gasoline components. These processes are used to combine small petroleum molecules into larger ones. Butylene of the catalytic cracker is further used to produce MTBE, a product used as octane booster. Sometimes, external purchased bio-ethanol is used instead. The naphtha of the FCC has to be treated in a special desulphurisation process to reduce the high sulfur content. The vacuum residues go into the coking process, which produces gases, gasoline, middle distillates and heating oil. A further product is petroleum coke, which is then purified. The vacuum residue, like some of the atmospheric residue, is also used as feed for the visbreaking, which also produces gases, naphtha, middle distillates and heating oil. The extracted hydrogen sulphides of all desulphurisation processes are fed to a sulfur recovery unit (claus plant) to recover elemental sulfur. The energy generation (heat, steam and electricity) requires a large amount of fuels. The fuels burned in refineries power plants and incinerators may be refinery gas, heating oil (residual oil), petrol coke and sometimes middle distillates and LPG. Beside these purchased natural gas and electricity are employed.

All important material and energy flows (input- output) are shown in the following figure of the system boundaries of the refinery model.

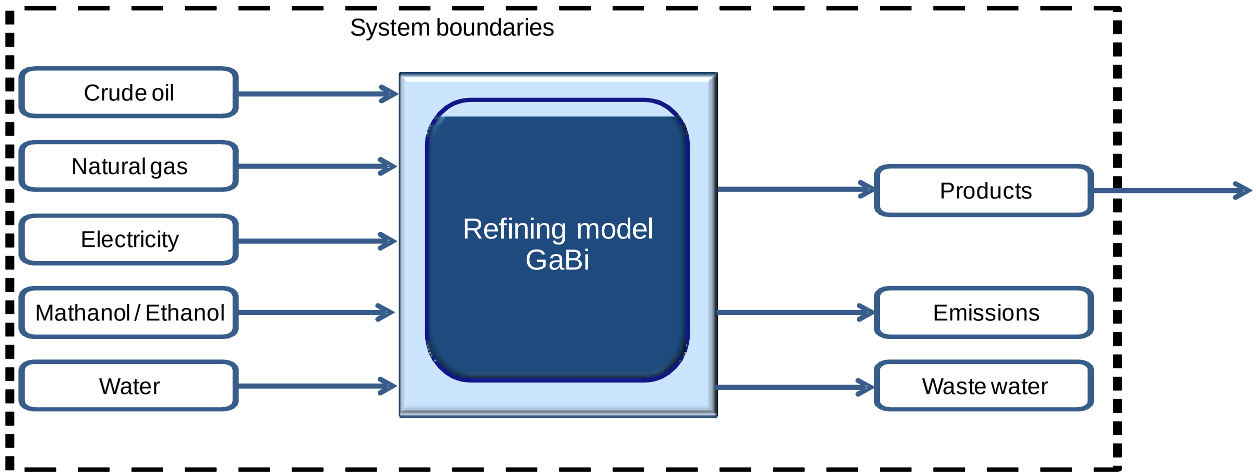


Figure 3-1: System boundaries of PE INTERNATIONAL's refining model[34]

Furthermore a simplified flow chart is shown below. The arrangement of these processes varies among refineries, and few, if any, employ all of these processes.

[34] Background data sources used for the set up of the LCA refinery model are listed in Annex 6

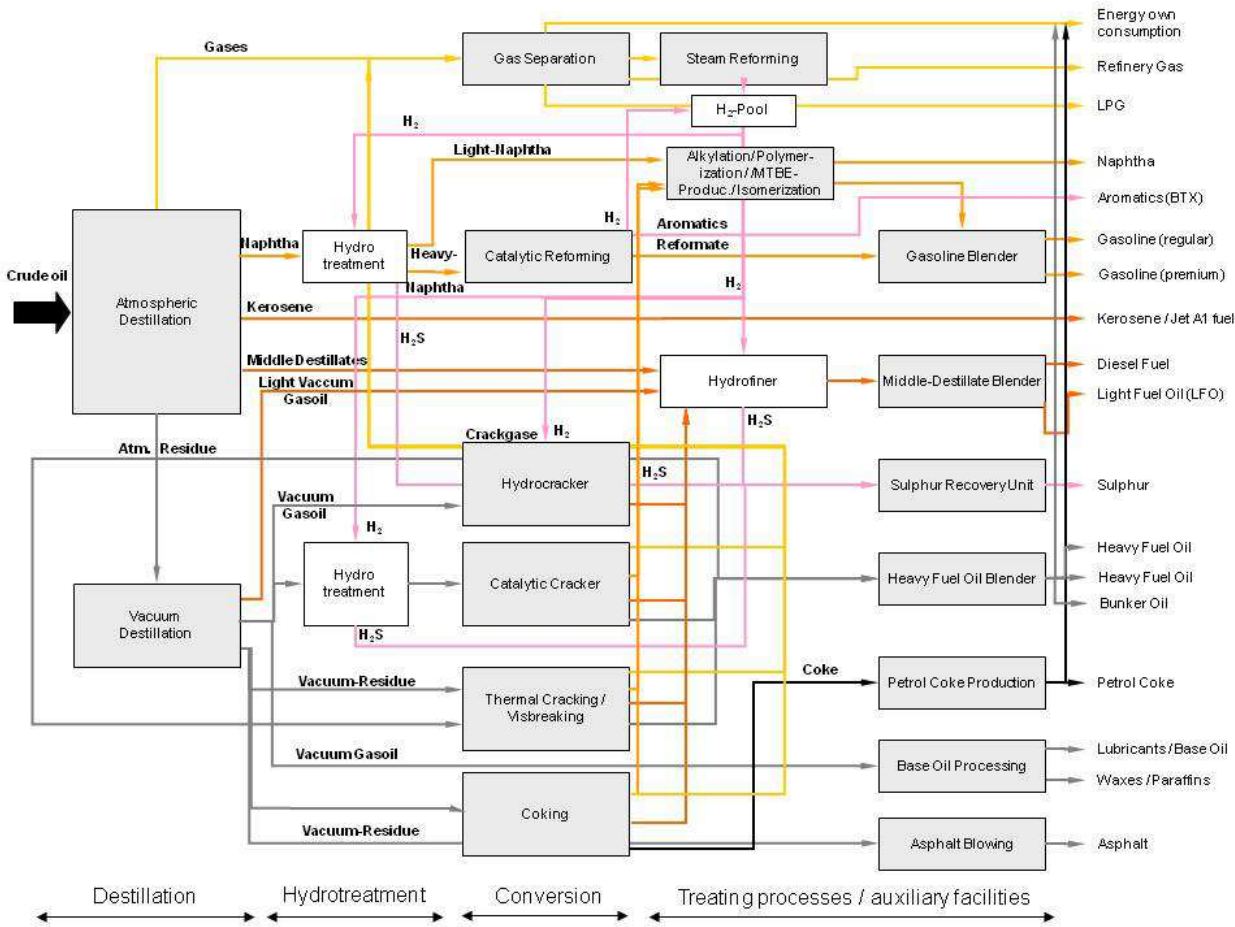


Figure 3-2: Flow chart of a refinery

Diesel fuel, gasoline, technical gases, fuel oils, lubricants and residues such as bitumen are modeled with a parameterized country-specific refinery model. The refinery model represents the current US resp. Californian standard in refining techniques (e.g. emission level, internal energy consumption, etc.) as well as the individual country-specific / region-specific product output spectrum, which can be quite different from country to country. The refinery model describes a mass-weighted average refinery for the respective country / region.

Again, the supply of crude oil is modeled according to the country-specific situation with the respective properties of the resources

3.3 Allocation in PE International's LCA refinery model

Almost all refinery operations are multifunctional processes. Multifunctional processes create two or more simultaneous products (co-products).

Following ISO allocation should be avoided wherever possible by:

1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
2) expanding the product system to include the additional functions related to the co-products,

Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them

The challenge is to allocate the individual loads of the material and energetic input as well as the emissions released by the process to each product. ISO standards 14040 and 14044 define allocation as "partitioning the input or output flows of a process or a product system between the product system

The inputs of nearly each of the refinery unit processes are thermal energy, steam (both from now on called simply "energy"), electricity and crude oil (crude oil only fed in the atmospheric distillation, the other refinery processes only has a corresponding crude oil consumption). The environmental burdens associated with the provision of these energy and material inputs, e.g. emissions from the steam generation or the upstream emissions of the crude oil supply, must be allocated according to the relationship of the different products. This association is done using a distribution tool called allocation factors.

Furthermore, it is assumed that all emissions caused within the refinery (from thermal energy, steam, and electricity production as well as single processes and losses) arise in the "refinery power plant", and are allocated to the refinery products with the help of the amount of energy input of each unit process. This assumption is validated by the fact that nearly all emissions (>95%) are released by the energy supply and in particular by the power plant.

Therefore, the environmental burdens of the following "processes" listed below must be allocated to the refinery products. These include:

- The emissions of the "refinery power plant" (incl. the power plant itself, converting plants, - decentralized boilers, storage, losses) -
- The impact of the crude oil supply (crude oil mix)
- The impacts of the electricity supply (electricity which is purchased in addition to the one - produced in the power plant; electricity mix) -
- The impacts of the natural gas supply (if natural gas is used; natural gas mix)
- The impacts of the methanol/ ethanol supply (if MTBE/ETBE is produced)
- The impacts of the hydrogen supply (if hydrogen from external sources is used).

An appropriate allocation factor must be chosen and its suitability must be justified.

The emissions caused by refining are allocated similarly to the impacts of the upstream chains external electricity and natural gas following a mass allocation. The impacts related to the crude oil supply are allocated by energy content to the products. Impacts from methanol/ethanol and hydrogen supply[35] are assigned directly to the applicable products, e.g. the methanol and ethanol emissions to the produced gasoline.

In the next paragraph, the choice of the allocation method is described theoretically and in the following further explained by applying to an example.

In general, the allocation condition must be fulfilled, i.e. the inputs and outputs which have been allocated in a unit process must add up to the inputs and outputs before the allocation were performed.

3.3.1 CRUDE OIL DEMAND ALLOCATION

Crude oil demand is how much crude oil is received into the refinery. This crude oil is processed to refinery products like diesel, gasoline, etc. Processing crude oil determines emissions in the crude oil supply (crude oil production and crude oil transport), which then must be attributed to each product of the refinery.

Crude oil demand in mass, $CO_{i,Process}$, needed for the production of product i, with mass, m_i, and net calorific value, NCV_i, of a given value is calculated proportionately to mass, m_i, and average net calorific value, NCV_{avg}, of all that leave the value of the products. The mass, m_i, is calculated with the percentage, m_{pi}, of the total mass of products leaving that value and the crude oil input of the process.

$$CO_{i,Process} = \frac{m_{pi}}{100\%} \cdot m_{Crude\quad i} \cdot \frac{C\quad i}{C} \qquad (1)$$

with:

$$C \qquad = \sum^{i}\ {}_{1} \frac{m_{pi}}{100\%} \cdot \quad C\ \ i \qquad (2)$$

The crude oil demand (or better, the burden of crude oil supply) is allocated to the refinery product according to the quantity produced in the unit process and its energy content. Hence, crude oil consumption of product i, is allocated according to its net calorific value.

[35] Neither methanol/ ethanol nor external hydrogen supply are relevant for base oil production of US and Californian refining operations.

3.3.2 THERMAL ENERGY DEMAND ALLOCATION

The thermal energy demand, $TE_{i,Process}$, needed for the production of product i, with mass, m_i, of the manufacturing process is calculated with the total energy demand, $TE_{tot,Process}$:

$$_{i,Process} = \quad _{o\ ,Process} \cdot \frac{m_i}{\sum^{i} \quad m_i} = \quad _{o\ ,Process} \cdot \frac{m_{pi}}{100\%} \qquad (3)$$

The energy demand required for the production of a product corresponds to a value that is relative to its weight percent of the total mass.

The thermal energy demand is also allocated by mass.

3.3.3 ELECTRICITY DEMAND ALLOCATION

The electricity demand, $E_{i,Process}$, required for the production of product i, with mass, m_i, of the manufacturing process is calculated in the same way as the thermal energy demand with the total demand of electricity, $E_{tot,Process}$:

$$\mathrm{E_{i,Process}} = \mathrm{E_{tot,Process}} \cdot \frac{\mathrm{m_i}}{\sum_{\mathrm{n}}^{\mathrm{i}} \quad \mathrm{m_i}} = \mathrm{E_{tot,Process}} \cdot \frac{\mathrm{m_{pi}}}{100\%} \qquad (4)$$

Hence, the electricity demand is also allocated by mass.

3.3.4 ALLOCATION EXAMPLE AND ALLOCATION METHOD CHOICE EXPLANATIONS

Figure 3-3 shows the allocation of the atmospheric distillation (example).

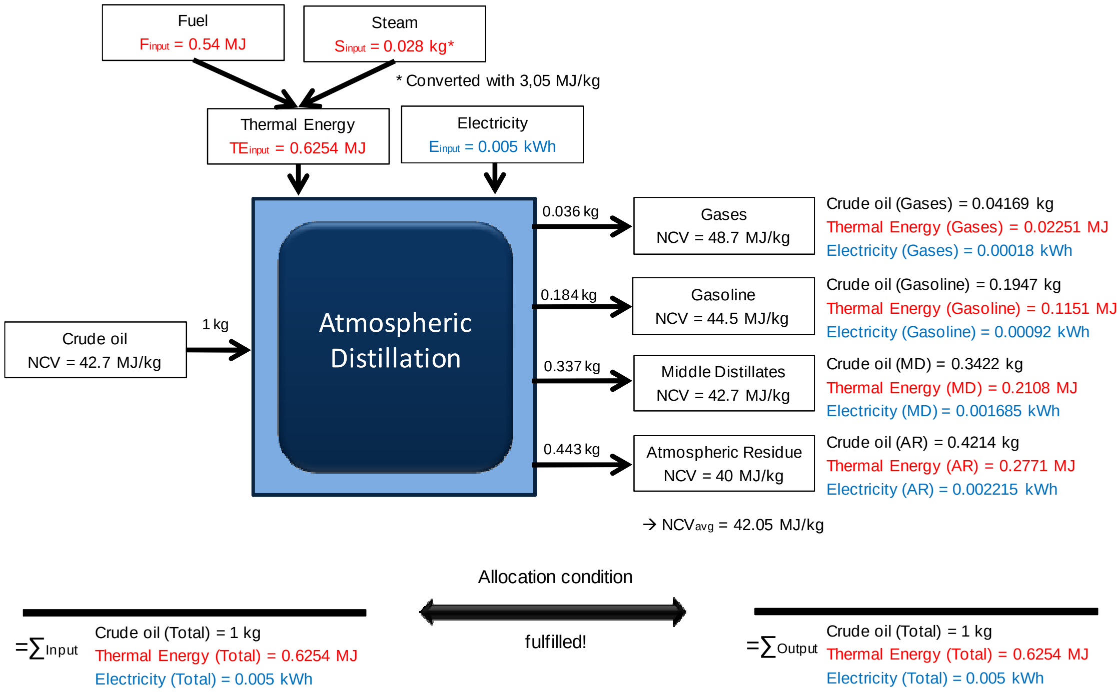


Figure 3-3: Allocation example of the atmospheric distillation

3.3.4.1 CRUDE OIL DEMAND

Figure 3-3 demonstrates that products with higher net calorific values (gases, naphtha, middle distillates, weighted in mass such as in equation (1) than the average, result in a higher amount of crude oil consumption compared with products with a lower net calorific value (atmospheric residue). For example, from 1 kg of crude oil input, 0.036 kg gases arise. To produce a specific amount of product (in this case 0.036 kg), a corresponding amount of 0.036 kg of crude oil is necessary. Through allocation, the gases are attributed 0.04169 kg of the crude oil demand.

The atmospheric residue works contrary to those with high net calorific value. The material consumption (corresponding crude oil demand) is 0.443 kg but the allocation attributes only 0.4214 kg due to its low net calorific value. Therefore, products with higher net calorific value are attributed higher input amounts, and therefore higher environmental impacts (generated by the crude oil supply), than products with a lower net calorific value. This form of allocation of a greater share for inputs with a higher net calorific value is logical, because lighter fractions are the preferred refinery products (with higher market value), and a lot of effort is undertaken to produce them. For instance a lot of additional manufacturing steps are involved in converting heavy fractions to lighter fractions, ultimately to a higher calorific value, due to the higher market demand and market price. As previously mentioned, all products are considered to be the main product (outputs) and are taken into account in allocation, but there are also main products with a higher complexity than others, resulting from the lighter fractions and require more exertion in production to obtain the required amount of refinery products in the end. The allocation by net calorific value of the crude oil input could also be explained from physical point of view, because the energy content is a representative value relating to the crude oil consumption of the refinery products. Background is the predominant energetic applications of the refinery products, on which representative oil consumption should be based.

This method is therefore within appropriate limits, providing a cause-oriented assignment of environmental impacts. The physical factor "net calorific value" as opposed to "market price" is preferred for allocation, because a semi-finished product assessment with "market price" is not possible and not a preferred allocation method following ISO 14044. Because there is a correlation (not linear and within limits) between market price and heating value, the conclusion of both allocation methods should anyway be similar.

3.3.4.2 THERMAL ENERGY/ STEAM DEMAND

The first step to find an adequate method for the allocation is to clarify the scope of the parameters (in this case thermal energy and steam) used in the processes and then a fair assessment must be developed according to the input involved. The preheating phase to heat the different refinery process input materials to process temperature is the primary energy consumer in the most of the refinery processes.

Equation (5) shows that heat, Q, which is the affiliated energy of a medium, depends on the specific heat capacity, c. The mass is m, and the heating temperature of the medium is ΔT.

$$Q = m \cdot c \cdot \Delta \qquad (5)$$

Based on the aforementioned information the following conclusion can be made: An allocation based on crude oil demand, similar to that based on "net calorific value," would increase the environmental impact associated with the provision of thermal energy, associated with producing heavier fractions. Since the heavier fractions have a higher specific heat capacity c compared to the lighter products, a higher amount of energy is needed to heat them to the same temperature, resulting in a higher ΔT. For example, for the separation via distillation (higher boiling point) an allocation by mass was chosen for the energy demand. As a result a "preferential treatment" toward the heavier products is avoided (compared to the allocation with net calorific value).

3.3.4.3 ELECTRICITY DEMAND

The allocation by mass can also be used for the electricity demand. The mass of the product is used for the allocation, not because of higher specific heat capacity c, but rather the higher density of heavier products. The electricity is primarily used to run the equipment, which includes pumps and mixers. The pump performance increases with the density of the medium, so allocation by mass is sufficiently efficient to demonstrate the higher impact of heavy fractions.

Figure 3-3 shows a fulfilled allocation constraint. The sum of allocated inputs and outputs to a process are equal to the sum of inputs and outputs before allocation. This point can be observed at the bottom of Figure 3-3, where a comparison of the sums of the inputs and outputs are made.

3.3.5 The Backpack Principle

To quantify and assess the energy and material (crude oil) demand essential to produce refinery-finished products, the consideration of the atmospheric distillation process alone is not sufficient. Since most of the products pass through a great number of processes within the refinery, all refinery processes must be considered and allocated to the final products. More complex products (which undergo many more manufacturing process), such as fuel, require a higher electricity and energy demand (and therefore higher environmental loads) compared to products which undergo fewer refinery processes, such as vacuum residue which can be used directly as bitumen.

This requirement is achieved through the "Backpack Principle". Each output of the refinery unit processes is assigned a "backpack" of allocated crude oil, energy and electricity demand. Thereby the backpack (crude oil, energy and electricity demand) of the feedstock plus the energy and electricity demand of the subsequent processes are allocated to the products and hence the backpack continues to accumulate during subsequent travel through the refinery.

The formula for the distribution of the feedstock backpack's content is the same as for the crude oil, energy and electricity demands of the atmospheric distillation process. In their respective backpacks the products carry a proportionate amount of the feedstock, as well as a proportionate amount that has been redefined in each process stage.

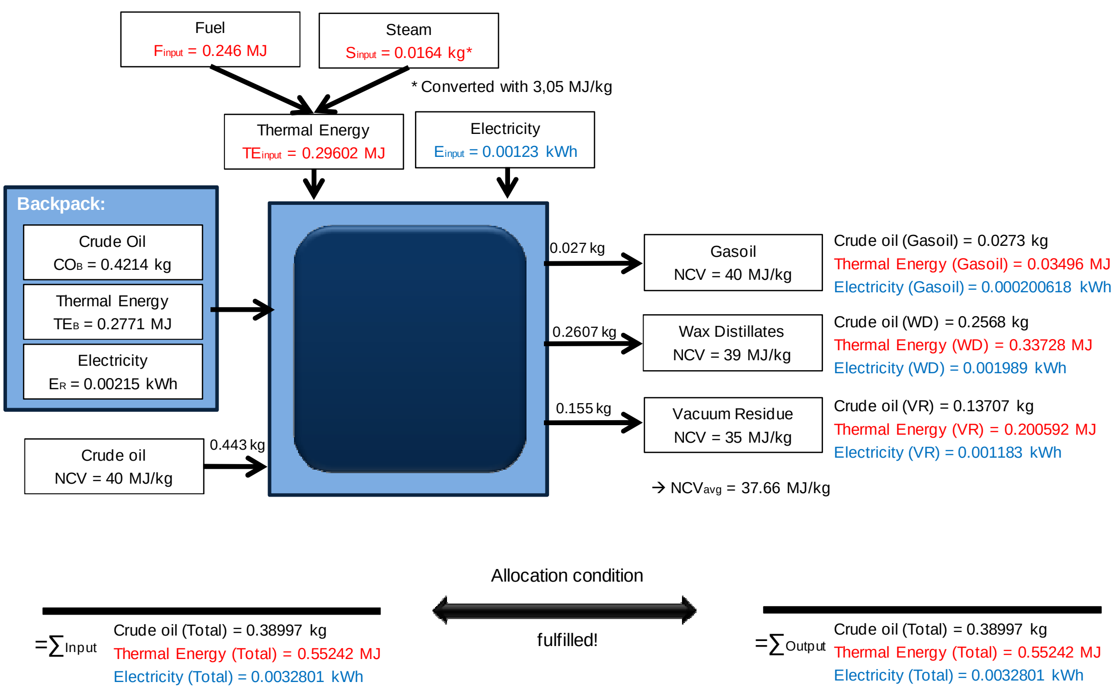


Figure 3-4: Allocation example of the vacuum distillation

To the three products of the vacuum distillation unit (gas oil, wax distillates and vacuum residue) a share - of the crude oil (backpack of raw material), electricity (backpack of electricity and electricity demand of -

process) and energy demand (backpack of energy and energy demand of process) is allocated. The allocated crude oil demand of subsequent process inputs in the “downstream processes” is redistributed to the products (“subsequent processes are not allocated crude oil input”), during which the shares of energy and electricity in the backpack increase according to the energy required at the current process stage.

For processes with two or more hydrocarbon inputs, the respective input fractions of the backpacks are added together.

All subsequent processes of the atmospheric distillation consist of five corresponding inputs. Crude oil, energy and electricity of the input backpack, as well as energy and electricity at each specific step in the refinery process (in rare cases there are zero inputs, which means no consumption occurs, or even negative inputs, which means that energy or electricity is produced).

There are significant differences in the energy and electricity demands of each unit process. There are also differences in the number of processes a finished product undergoes over the course of its production route. But the backpack principle guarantees that each finished product is assigned the environmental impact of all processes over the course of its production pathway.

Gasoline derived from atmospheric distillation, which only undergoes gasoline desulfurization and passes through the catalytic reformer, has a smaller backpack than gasoline produced via atmospheric distillation followed by vacuum distillation, vacuum distillate desulfurization, and FCC because more processes are involved. Vacuum residue which can be sold directly as bitumen has a smaller backpack than the finished diesel fuel product.

The GaBi model is set up to reflect the input as 1 kg of crude oil. However, in the end all products are obtained relative to 1 kg of product.

3.4 Life Cycle Inventory Analysis Results

ISO 14044 defines the Life Cycle Inventory Analysis Result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, the inventory can be seen in the GaBi LCI data set. The data sets are delivered as partly aggregated data sets allowing the LCA practitioner to connect country /region specific upstream processes, like crude oil mixes, the natural gas mixes, and electricity.

4 - Interpretation

4.1 Identification of Relevant Findings

- Crude oil emission inventory of California better than US average due to different mix (origin of crude oils)
- Electricity emission inventory of US West better than US average due to different mix (energy carriers converted to electricity)

- Energy consumption in Californian refineries higher than US
- Refinery energy consumption higher and thus global warming potential (GWP) worse in California compared to US average (caused by higher energy demand, but better flue gas cleaning systems). This is reflected that most emission factors of Californian refineries are lower than US average.

4.2 DATA QUALITY ASSESSMENT

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied on a study serving as a data source) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data (taken from statistics) in combination with consistent background LCA information from the GaBi LCI database were used. The LCI data sets from the GaBi LCI database are widely distributed and used with the GaBi 5 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

1.1.11 Precision and completeness

- ✓ **Precision:** As the relevant foreground data are based on primary information sources of statistics, no better precision is reachable to set up an average dataset. Seasonal variations or variations across different manufacturers were balanced out by using yearly averages. All background data is GaBi data with the documented precision**.**

- ✓ **Completeness:** Each unit process was checked for mass balance and completeness of the emission inventory in accordance to the defined cut-off criteria (see Chapter 2.5).

1.1.12 Consistency and reproducibility

- ✓ **Consistency:** To ensure consistency, all foreground data were complied with the same level of detail, while all background data were sourced from the GaBi databases. Allocation and other methodological choices were made consistently throughout the model.

- ✓ **Reproducibility:** Reproducibility is given as much as possible by documentation of all key of input-output data, dataset choices, and modeling approaches in this report. Since

1.1.13 Representativeness

- ✓ **Temporal:** All foreground data were collected for the year 2010. All background data comes from the GaBi 5 2011 databases and are representative of the years 2006-2010. As the broader context of the study intended to compare the product systems for the reference year 2010, temporal representativeness is warranted.

- ✓ **Geographical:** All foreground data were collected specific to US and California. All background data are also country / region specific. Where country / region specific data were unavailable, proxy data were used (see Chapter 2.8). Geographical representativeness is considered to be high.

- ✓ **Technological:** All foreground and background data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used (see Chapter 2.8). Technological representativeness is considered to be high.

5 References

All references used for the project are citied at the corresponding next phrases of this document.

6 APPENDIX

Mapping of PE's refinery model and the EIA data nomenclature.

PE Refinery model	EIA
Refinery gas	Still gas
LPG	Liquefied refinery gases
Naphtha	Petrochemical feedstock
Naphtha	Special naphtha
Gasoline	Finished motor gasoline
Kerosene /Jet A1	Finished aviation gasoline
Kerosene /Jet A1	Kerosene-type jet fuel
Kerosene /Jet A1	Kerosene
Diesel fuel	Distillate fuel oil - 15ppm S or less
LFO & marine diesel	Distillate fuel oil - 15-500ppm S
LFO & marine diesel	Distillate fuel oil - over 500ppm S
HFO (inland)	Residual fuel oil - 0.31% S or less
HFO (marine, SECA)	Residual fuel oil - 0.31-1.00 % S
HFO (marine, global)	Residual fuel oil - over 1.00 % S
Lubricants	Lubricant
Waxes/Paraffins	Waxes
Asphalt	Asphalt and road oil
Petrol Coke	Petroleum coke
Other	Misc. products

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