LCA for regeneration of waste oil to base oil

Updating the study

Ecological and energetic assessment of re-refining waste oils to base oils - Substitution of primarily produced base oils including semi-synthetic and synthetic compounds

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Glossary

Glossary on terminology

This study follows the terminology determined by the Waste Directive (2008/98/EC), using the expressions:

- "Waste oil", covering "used oil": any mineral or synthetic lubrication or industrial oils which have become unfit for the use for which they were originally intended, such as waste combustion engine oils and gearbox oils, lubricating oils, oils for turbines and hydraulic oils.
- "Regeneration", covering "re-refining": any recycling operation whereby base oils can be produced by refining waste oils, in particular by removing the contaminants, the oxidation products and the additives contained in such oils.

The title of the cycle remain unchanged because it includes a citation.

Abbreviations

AGEB	Arbeitsgemeinschaft Energiebilanzen e.V. (Working Group on Energy Balances)
AP	Acidification potential
API	American Petroleum Institute
BREF	Best available technology reference document
CED	Cumulative energy demand
CH_4	Methane
CO_2	Carbon dioxide
CO_2eq.	Carbon dioxide equivalents
CRP	Carcinogenic risk potential
EU	European Union
GEIR	Groupement Européen de l'Industrie de la Régénération
GWP	Global Warming Potential
HFO	Heavy fuel oil
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Analysis

Glossary

LCI	Life Cycle Inventory
Mg	Megagram (= metric tonne)
MJ	Megajoule
MARPOL	International Convention for the Prevention of **Mar**ine **Pol**lution from Ships
N_2O	Nitrous oxide, laughing gas
NH_3	Ammonia
NO	Nitrogen monoxide
NO_2	Nitrogen dioxide
NO_x	Nitrogen oxides
PAH	Polycyclic Aromatic Hydrocarbons
PAO	Poly-alpha-Olefines
PCB	Polychlorinated Biphenyls
PCDD/F	Polychlorinated Dibenzodioxins /furanes
PEV	Person Equivalency Value
PM2.5	Particulate matter with an aerodynamic diameter of less than 2.5 µm
PM10	Particulate matter with an aerodynamic diameter of less than 10 µm
UBA	Umweltbundesamt, German Federal Environment Agency
UOP	Universal Oil Products (Company name)
VI	Viscosity index

1 Background and motivation

Legal basics

The European Waste Framework Directive (2008/98/EC) gives explicit instructions for the management of waste oils. Above all, it should be conducted in accordance with the priority order of the waste hierarchy. Moreover, preference should be given to options that deliver the best overall environmental outcome. Both principles require the separate collection of waste oils which remains crucial to their proper management and the prevention of damage to the environment from their improper disposal.

Need for an update

The identification of the option delivering the best overall environmental outcome has been scrutinized by means of a large number of life cycle assessments (LCA) since the late nineties of the last century and the beginning of the current one. One of these LCA studies was performed by ifeu on behalf of the GEIR (Fehrenbach 2005). Policymakers still refer to that study published over a decade ago. Even the recently published LCA studies on regeneration in the USA refer to the ifeu study from 2005 to describe the situation in Europe, although the situation has clearly changed (Geier et al. 2013, Grice et al. 2013).

Considering the current state of technology, the original set of data has to be regarded as outdated taking the actual state of technical practice into account. In 2005, some of the regeneration plants under assessment had been still in a pilot or testing phase of recently implemented new technologies. In addition, a significant change in the overall use of waste oil has taken place within the last decade. In 2005 waste oil has been most commonly energetically recovered as a substitute for coal in cement works. Today prevalence of this way of utilization has strongly decreased, whereas treatment to fuel oil in particular has emerged as the main competitor to re-refining. In order to respond to these key developments, there is need for a current assessment.

Objective of this study

It is the objective of this study to provide an update of the outdated reference 2005 considering the most recent process data as well as the change in terms of competition (reference). This study addresses European Policymakers and stakeholders. It shall provide a basis for an international discussion and a robust base of knowledge to assist decision making.

The herewith updated reference study (Fehrenbach 2005) can be downloaded from here: https://www.ifeu.de/wp-content/uploads/GEIR-final-report-LCA-21-04-05.pdf

2 Definition of goal and scope

In a very first step the authors have examined, whether and in what way, goal and scope defined by the study from 2005 would need to be revised. This has been discussed with GEIR at the beginning of the project. Apart from slight adaptations the core of the previous goal definition has been maintained.

However, there have been a number of significant developments within the last decade. Table 1 shows the main aspects of this development.

Aspect	Fehrenbach (2005)	this study (2017)
Participating Companies / number of techniques under study	5	4
Inventory - regeneration process - upstream data (currentness)	 - partly measured data from operation, partly projected - time frame late 2000	 - only measured data from operation in 2016[1] (annual mean) - time frame after 2010
Characterization factors - GWP 100 - Particulate matter	 - 2nd Assessment Report (IPCC 1996) - PM10	 - 5th Assessment Report (IPCC 2013) - PM2.5
Reference quantity for normalization: Waste oil to re-refining in the EU	600.000 Mg	935.000 Mg
Reference system	Cement works (energetic recovery and coal substitution)	Treatment to fuel oil

Table 1: Overview of the changes with respect to Fehrenbach (2005)

2.1 Goal of the study

Goal definition maintained

The goal of this study is to provide an updated and forward-looking view on the ecological and energetic aspects of regeneration of waste oil. The conclusions of the study by Fehrenbach (2005) representing more or less the situation of the last decade represent a starting position, as some major aspects have changed but methodical aspects remained constant for the most part. Similar to Fehrenbach (2005), information regarding the regeneration processes has been derived from common practice and process conditions of

[1] Process data was gathered in 2017 and refer to the annual mean in 2016.

four[1] leading companies operating in Europe. They comprise two thirds of European regeneration capacity in 2014. Key tasks of the study are:

- Outline the current situation in the field of waste oil management in Europe and the key developments within the last ten years.
- Modelling and comparing the four selected and advanced techniques of regeneration taking their environmental impact and benefits due to the substitution of primary products into account.
- Comparing the average result of the four advanced regeneration techniques considered with the reference case: the most significant alternative treatment of waste oil in Europe.
- Disclosing and discussing the most decisive parameters in a transparent way.

The study addresses policymakers and stakeholders in the field of waste management for waste oil.

2.2 Definition of scope

Considering the scope of the study, the following two items require particular attention:

- Revision of the definition of the reference system;
- How to deal with diverse technical qualities of the final base oil products.

2.2.1 Definition of the reference system

Waste oil management has changed in Europe

The study of 2005 considered alternatively waste oil combustion in a cement kiln as a substitution of standard fossil fuels. An analysis of the current situation of waste oil management in Europe shows that this type of recovery has lost its relevance. Today, only about 3% of the total collected waste oil is used in the cement industry. According to ascertainments by GEIR (2016), utilization of waste oil in Europe is dominated by regeneration to base oil: 42 % directly within the countries of collection and an additional 13 % after exporting for regeneration to some other European countries. In other words: more than half of the collected waste oil is subject to regeneration. The second most important pathway is treatment to fuel, which accounts for 31 % of the total collected waste oil. In other words: three quarters of the waste oil not regenerated to base oil are treated to produce fuel oil. Other treatment options, e.g. combustion in cement works in total account for about 15% (see Figure 1) and are thus negligible within this study.

Reference system updated

Hence, there is need to adapt the reference system to account for the major changes of waste oil management in Europe over the last decade. The decided reference system for this study is therefore: treatment to fuel as it is the only significant alternative to refining (further details see chapter 6).

[1] Fehrenbach (2005) investigated five companies. Evergreen, a company from the US, is not represented in this study.

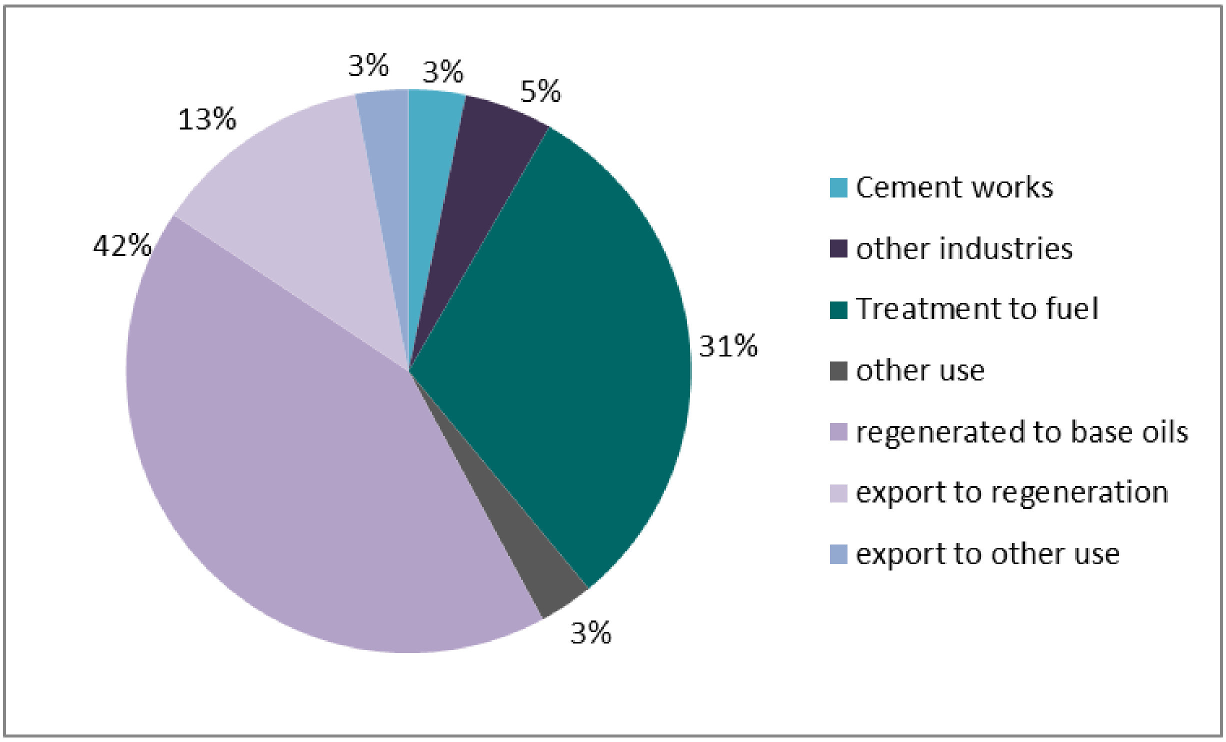


Figure 1: Waste oil utilization in Europe in 2014; total amount 1,739,500 tons; source: GEIR (2016)

2.2.2 How to deal with diverse technical qualities of the final base oil products

Approach by study 2005

The technical quality of the final base oil products has already been an important point of attention in former studies. The study from 2005 applied two levels of quality to compare regenerated base oil with virgin base oil of the same quality, assuming the two levels describe the range from a minimum to a presumed achievable optimum:

- Minimum: corresponding to group I base oil
- Presumed achievable optimum: corresponding to a mix of 70 % group I base oil and 30 % group IV base oil.

Today, the qualities of regenerated base oils are still ranging from group I quality to qualities approximating group III. It would be straightforward to mirror each regenerated base oil quality directly by the LCA data for the equivalent virgin base oil group. Unfortunately, the available data bases do not cover these groups by consistent LCA data. In particular, the most relevant groups II and III are not satisfactorily covered, while for group I and group IV (PAO) solid LCA data are still available.

Correlation model based on viscosity index

In order to bridge this gap, the authors have developed a correlation model based on the viscosity index (VI) as a proxy indicator to define the equivalent virgin base oil by interpolation of groups I (standard base) and IV (PAO). As shown in Figure 2 , the approach provides explicit data for any quality of base oil. The approach will be checked by a sensitivity analysis, since we cannot exclude the possibility of overestimating the environmental burden of virgin base oil production representing actually group II and III medium group qualities (see section 0).

For comparison of regenerated base oil with virgin base oil, we still refer to the two-level approach:

1. Standard quality (representing group I base oils with a viscosity index of 100),
2. Advanced quality (representing base oil quality group in between group II and group III with a viscosity index around 115, corresponding to a hypothetical blend of 70 % group I and 30 % group IV, as marked in Figure 2).

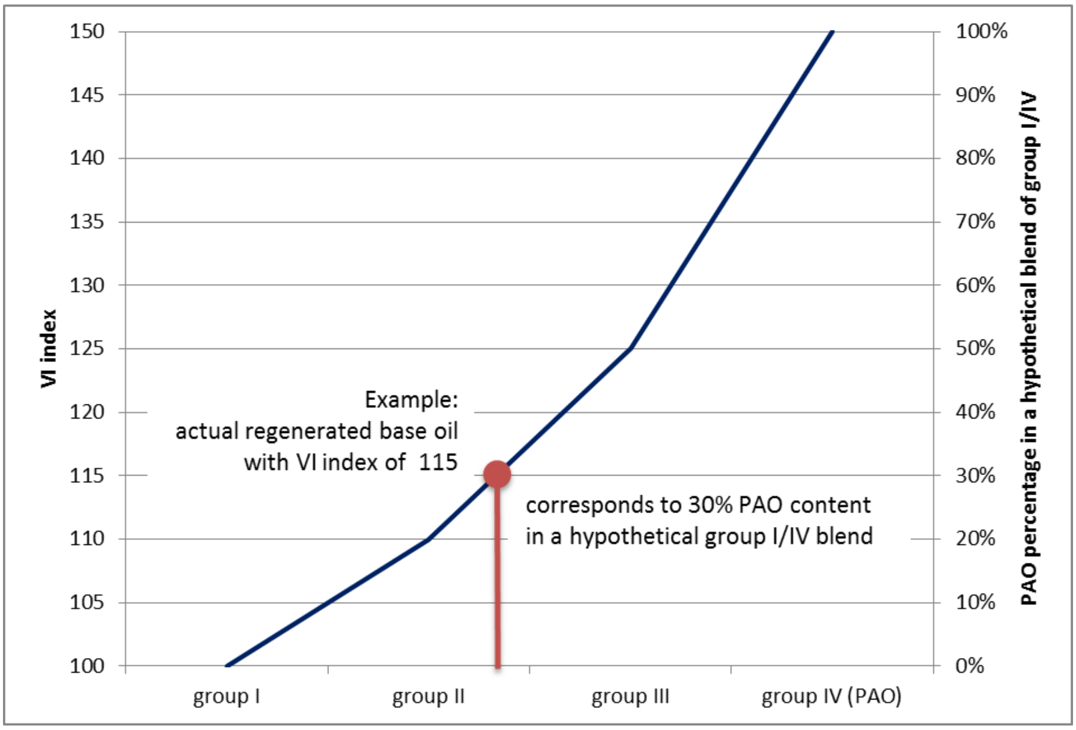


Figure 2: Correlation model based on viscosity index (VI) by actual recycled base oil as a numerical indication for the definition of replaced virgin base oil hypothetically blended from group I and group IV base oil.

2.2.3 Factors influencing the actual of the base oil product produced by regeneration

The final quality of recycled base oil produced by an advanced regeneration techniques is determined by a number of factors:

1. The quality of the collected waste oil (see also section 4);
   increasing quality of applied lubricants lead to waste oils containing these high quality components. Regeneration offers the possibility to preserve these components and incorporate them in the recycled base oil.
   However this factor is not under the control of the regeneration company, it is bound to the collecting area.
2. The applied level of technology (see also section 5);
   actually all techniques under study are qualified to produce high qualities. Three of them are based on hydrogenation technology, typically favoring an upgrade of the waste oil feedstock; one technique applies solvent extraction, typically preserving high quality components.
3. The base oil market the company is serving;
   even if a high quality would be feasible due to feedstock (a.) and technical conditions

(b.) a company might be prefer to serve the established market regardless of technical potentials.

The four techniques under assessment have to cope with these three major factors. It is outside the scope of this study to analyze the individual situation of each of these companies. However it can be stated that each of the techniques carry the potential to meet the criteria to produce the “advanced quality” of base oil as defined in section 2.2.2. Anyway we consider the application of the “standard quality” adequate to hedge the theoretical worst case (see also section 0).

2.2.4 Further basic settings

Reference volume and functional unit

The reference unit is the entire quantity of regenerated waste oil within the European Union. According to GEIR (2016), this is about **950,000 Mg per year** - apparently higher than the quantity of 600,000 Mg per year applied by the study in 2005.

The functional unit for the calculation of inventory and impacts will be focused again on the treatment of 1 Mg of collected and regenerated waste oil. For the purpose of normalization the results will be scaled up on the reference quantity of 950,000 Mg.

System boundary

Apart from the items discussed above, the system boundary still corresponds to the settings of the study in 2005, such as:

- Including transport from the waste producer to the regeneration plant.[1]
- Including all external processes due to regeneration (e.g. fuel production or electrical power supply, crude oil drilling and production, digging and mining). Also, downstream processes like waste disposal are included.
- The analysis of a regeneration option ends when a specified product enters the economic cycle. The quality specification has to be recognized because the production of an equivalent product has to be analysed under consideration of all elements in its primary production chain (defined as equivalencey system)
- By-products of the regeneration process – e.g. surplus of process energy – are considered. The benefit of these side-effects is also considered within the system of substituted primary products.
- The geographical boundary is sticking to Europe in terms of provenience of waste oil and technical standard. Imported materials – such as crude oil or coal from overseas – are likewise considered as far as they are consumed within the systems.
- In terms of the time scale, the study assesses techniques that are applied since a decade. The data concerning production and delivery of energy and raw materials are as up to date as available.
- Cut-off criteria are set to keep the system boundary in a well determined range. The general rule applied in this study is: The production of input materials that don’t exceed 1 % of mass of the reference flow (e.g. waste oil in the regeneration plant) is not

[1] Waste disposal in nearly all cases requires a form of transport. In order to correspond to Fehrenbach (2005), the same average distance of 100 km was applied. For an analysis of the sensitivity of transport aspects, we quote from Fehrenbach (2005) page 60: *“… with regard on the influence on the net results it is obvious that varying dis-tances is not a highly sensitive parameter. Nutrification is the only impact category taking more than 10 %. Doubling the distance from source to re-refining plant from 100 km to 200 km would decrease the environmental benefit concerning nutrification by 11 %.* .

considered. The sum of neglected materials within one process shall not exceed 5 % of the reference flow.

- Neither emissions due to construction of the plants nor due to other infrastructure are considered.
- Umberto (version 5.5) has been chosen as LCA modelling software[1]The definition of the system boundary as described in Figure 3 and Figure 4 is still valid.

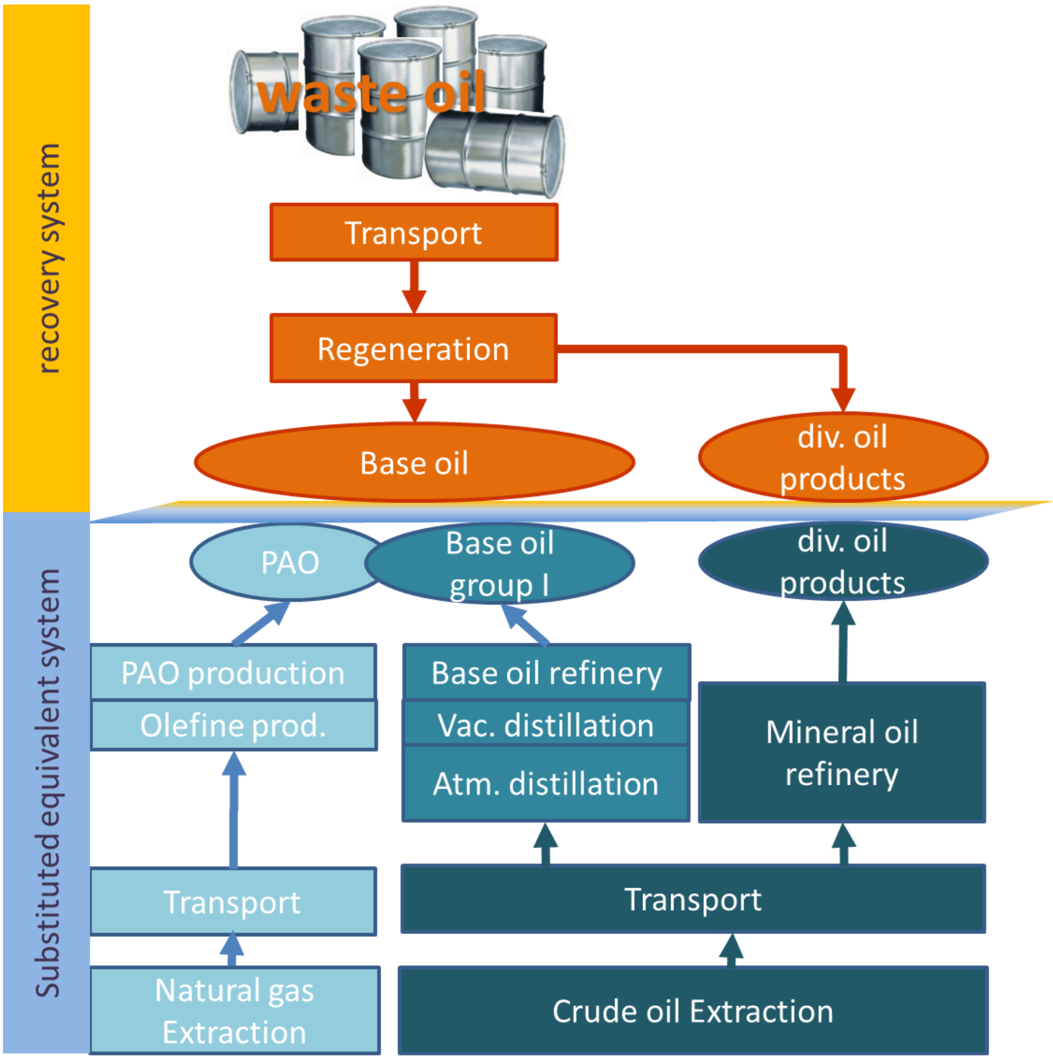


Figure 3: Simplified scheme of the system boundary for **regeneration** and its substituted equivalent system

[1] The former study, too, used Umberto as LCA software, albeit an older by now outdated version

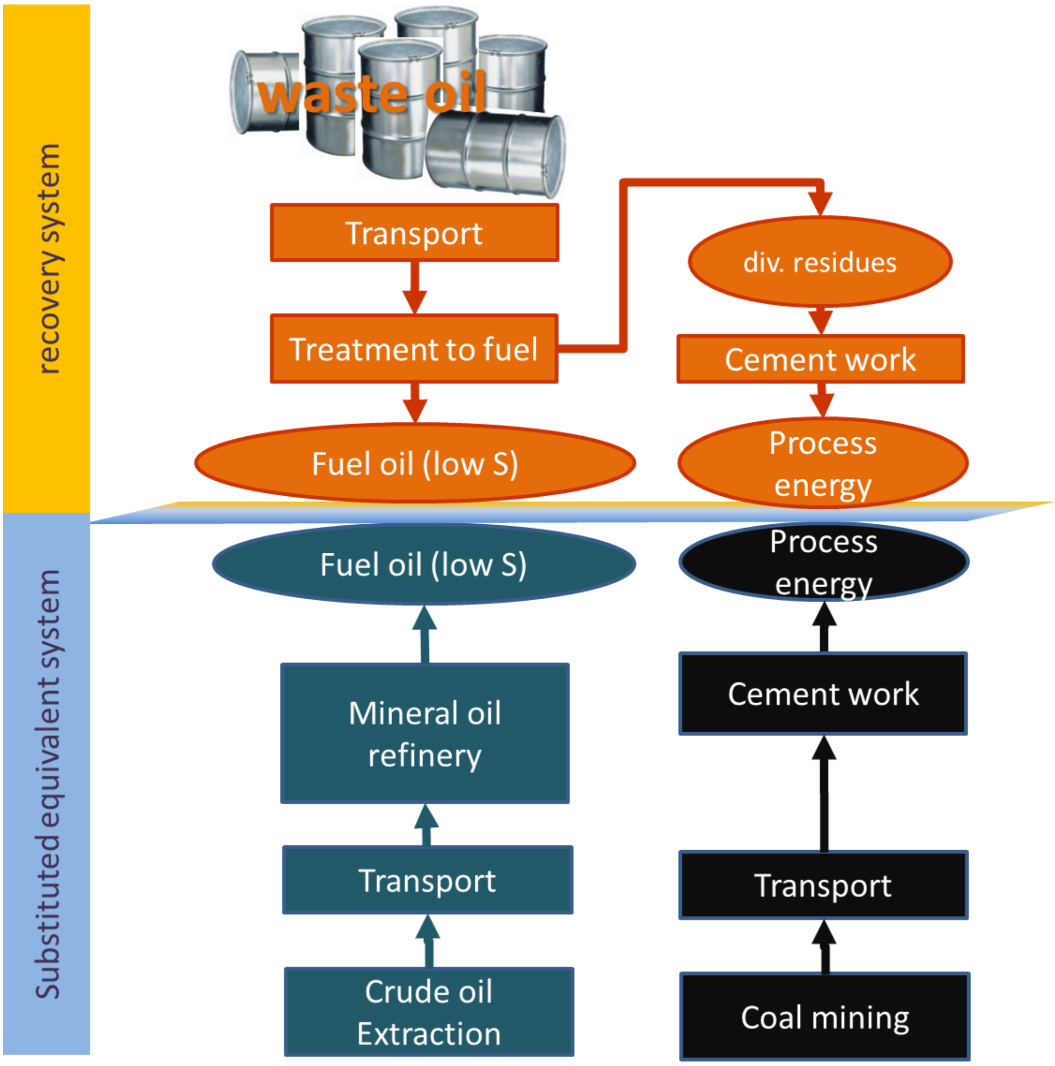


Figure 4: Simplified scheme of the system boundary for the **reference system** and its substituted equivalent system

3 Methodology and approach

3.1 Framework and working steps

Basics

The methodical principles and approaches applied by the study from 2005 are widely adopted by this study in order to facilitate comparability of the outcome. Nevertheless, some developments in LCA procedure are likewise followed. The basic rules given by ISO 14040:2006 and ISO 14044:2006 still apply.

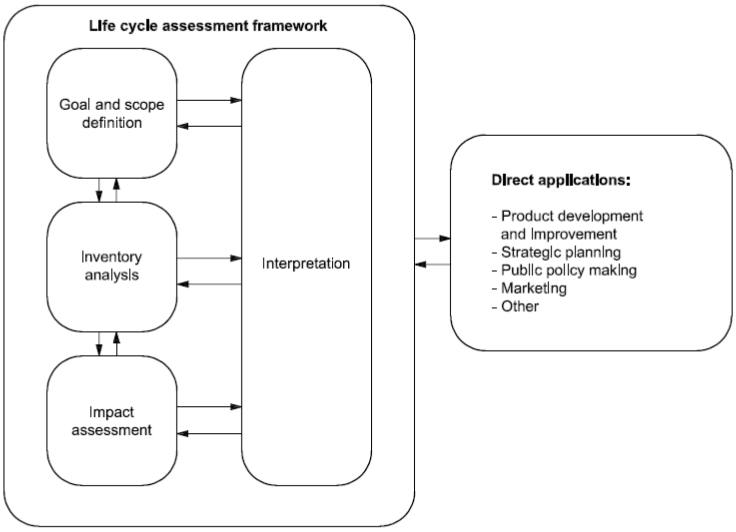


Figure 5: Phases of a life cycle assessment (LCA), according to ISO 14040:2006

Working steps

After the definition of the goal, the working steps are:

1. Collection of currently valid process data of the techniques under assessment
2. Modelling of the selected techniques based on
    a. most recent process data
    b. most recent background data (e.g. for electricity imported from general grid, fuels, transport, auxiliary material etc.)
3. Modelling a reference system describing alternative energetic use of waste oil
4. Calculating inventories and impact assessment
5. Discussion and interpretation of the results and comparison with the results obtained from the study 2005

3.2 Modelling of LC Inventories

LCAs of waste management activities have commonly shown that the main impacts of recycling or recovery rest on the relief of environmental stress by substituting primary production processes. This is not surprising since the primary logic of recovery is always conservation of resources. Fehrenbach (2005) has confirmed this finding.

Since 2005, the quality of applied lubricants has developed in line with the trend to higher shares of semi-synthetic and synthetic compounds. These compounds can be found in waste oil likewise, and will – with respect to the applied technology of the regeneration – be transferred into the regenerated base oil.

3.3 LC Impact assessment

A review of the applied impact categories has led the authors to maintain the set of categories with a few adjustments, such as:

- The indicator for resource depletion: The indicator "raw oil equivalents" applied in 2005 is rather uncommon and therefore has been replaced by the cumulative energy demand (CED), focusing on fossil primary energy sources.
- Particulate matter as an human toxicity indicator has been adjusted from PM10 to PM2.5, in order to address the more relevant indicator from a toxicological point of view.
- Updating the GWP100 characterization factors from IPCC (1996) to IPCC (2013).

Furthermore, in order to ensure a maximum in continuity to the previous study, the authors decided to investigate the same impact categories as Fehrenbach (2005). The original selection has been based on the most relevant areas, which are most likely to be affected by (petro-) chemical processes such as those that are subject to this study. Furthermore, the previous study has excluded impact categories of relevance but with significant shortcomings in terms of consistency and completeness.[1] Table 2 provides an overview of the applied impact categories including the covered data categories and characterization factors.

[1] Relevant but unconsidered impact categories are:
Summer smog, with wide ranges of volatile organic compounds, typically emitted by refineries
Aquatic toxicity, referring to water-borne emissions from refineries .
Due to incompleteness and inconsistencies, the authors decided not to investigate these impact categories.

Impact category	Data category	Characterization factors	Unit	Source
Resource depletion:	Mineral oil	42.62 a)	MJ / kg	UBA (1995)
cumulative energy	natural gas	37.78 a)	MJ / m^3	
demand, fossil (CED_{fossil})	coal	29.81 a)	MJ / kg	
	lignite	8.30 a)	MJ / kg	
Global warming:	$CO_{2\ (fossil)}$	1	kg CO_2-Eq. / kg	IPCC 2013
(GWP100)	$CH_{4\ (fossil)}$	30	kg CO_2-Eq. / kg	
	N_2O	265	kg CO_2-Eq. / kg	
Acidification:	SO_2	1	kg SO_2-Eq. / kg	CML 2013
	NO_X	0.7	kg SO_2-Eq. / kg	
	NH_3	1.88	kg SO_2-Eq. / kg	
	HCl	0.88	kg SO_2-Eq. / kg	
	HF	1.6	kg SO_2-Eq. / kg	
	H_2S	1.88	kg SO_2-Eq. / kg	
Nutrification,	NO_X	0.13	kg PO_4^{3+}-Eq. / kg	Heijungs et al.
terrestrial:	NH_3	0.346	kg PO_4^{3+}-Eq. / kg	(1992)
Human toxicity:				IRIS (2006)
Carcinogenic risk	As	1	kg As-Eq. / kg	
Potential:	Cd	0.42	kg As-Eq. / kg	
	Cr (10 % Cr-VI presumed)	0.279	kg As-Eq. / kg	
	Ni	0.056	kg As-Eq. / kg	
	Dioxine	3020	kg As-Eq. / kg	
	Benzo(a)pyren	20.9	kg As-Eq. / kg	
	PCB	0.279	kg As-Eq. / kg	
fine particulates	Primary particulates (PM2.5)	1	kg PM2.5-Eq. / kg	De Leeuw (2002)
(PM2.5):	Primary particulates (PM10)	0.5	kg PM2.5-Eq. / kg	
	SO_2	0.54	kg PM2.5-Eq. / kg	
	NO_X	0.88	kg PM2.5-Eq. / kg	
	NH_3	0.64	kg PM2.5-Eq. / kg	
	Hydrocarbons	0.012	kg PM2.5-Eq. / kg	

a) Lower heating values (LHV), not characterization factors in the actual sense, because yet defined as inventory category; in fact LHVs can vary within the same energy carrier

Table 2: Used impact categories and indicators, classified data categories and characterization factors

3.4 LC Interpretation

The approach applied for the identification of the significant issues is based on two procedures described in ISO 14044:2006 as optional elements of the impact assessment.

- Normalization : Calculation of the magnitude of the category indicator results relative to reference values (*specific contribution*). In this case, the total inventory of resource consumption and emissions in Germany was used as a reference.[1]
- Grouping: Ranking the impact categories in a given order of hierarchy, such as very high, high, medium and low priority.

The *specific contribution*, which is the calculated result of the balance process (normalization of impact assessment), is given here as an absolute value expressed in **Person Equivalency Values (PEV).** The Person Equivalency Value represents the average per-capita load of one inhabitant (e.g. 12 Mg CO_2-eq. per year). If the load caused by one recycling option or, respectively, the difference between two options is divided by this value, the result will be the number of inhabitants that corresponds to a particular option or the difference between two options respectively.

The interpretation step entails another procedure with a qualitative character to assess impact categories. The categories are defined independently from the LCA in general and, according to the UBA method, are divided each into five classes. Depending on their priority, the impact categories are assigned to these five classes (ranking of impact categories: Classes A "very high", B "high", C "medium", D "low", and E "very low" priority). Due to its global and immense impact combined with its supposed irreversibility, global warming, for example, is assigned a "very high ecological hazard potential". Until now, only slow progress has been made in reducing emissions on a global basis. Political goals are consequently unlikely to be met.

	Per-capita load German inhabitant PEV	Reference	Ecological Priority (b)
Fossil energy resources (CED $_{fossil}$)	134.296 MJ/a	(a)	"medium"
Global warming	11,776 kg CO_2-Eq./a	(a)	"very high"
Eutrophication, terrestrial	5.03 kg PO_4^{3-}-Eq./a	(a)	"high"
Acidification	31.5 kg SO_2 -Eq./a	(a)	"high"
Carcinogenic pollutants	8.63 g As Eq./a	(a)	"very high"
Fine particulates (PM2.5)	23,95 kg $PM_{2.5}$ Eq./a	(a)	"high"

References: a) aggregated data own calculation on the basis of data provided by UBA National trend tables for German reporting of airborne emissions, Statistisches Bundesamt (German Federal Statistical Office) and AGEB 2015
b) Ecological Priority based on the state of the art in application since UBA (1999)
Eq. = equivalents

Table 3: Total per-capita emission and consumption in the Federal Republic of Germany and valuation suggested by UBA regarding ecological hazard potential and distance to goal of protection

[1] The German data have been selected because the European data situation is incomplete. Note: the PEV shall give just an orientation in terms of the order of magnitude of LCIA results.

3.5 Collection of data

3.5.1 Regeneration processes

The data of the different regeneration processes were provided directly by the participating companies (see chapter 5). In order to gather all necessary information, the authors prepared an Excel-based questionnaire (see Annex I) concerning all relevant information for modelling the regeneration processes. These questionnaires have been thoroughly filled out by the companies throughout 2017, constituting the core data source of this study. The collected gate-to-gate data represent the twelve-month average of the year 2016 for each of the four regeneration processes under study. Each company has confirmed the suitability of these data for representing typical production conditions.

The authors haven't visited the operating plants for verifying the data provided. However all these data have been scrutinized in terms of technical plausibility and changes compared to the LCA from 2005. We are well-informed that one of the companies and regeneration sites under study has been going through an intensive verification process of all the data by the renowned certification company NSF International in 2015. That process has proofed the correctness of the data in detail.

3.5.2 Upstream and downstream processes

Data regarding auxiliary processes, e.g. provision of electricity, use of catalysts, transports, water supply, sewage treatment etc. were taken from the Umberto database. This data is regularly updated to account for ongoing developments.

In terms of the substituted primary processes, the ifeu refinery model provides the basis. This model is also interconnected to other (auxiliary) processes and databases (see Table 4).

Chemicals	**Data from**	**Settings/Assumptions**
sodium hydroxide	Plastics Europe	
potassium hydroxide	Ecoinvent 2.2	
sodium carbonate	Ecoinvent 2.2	
propane	Plastics Europe	
hydrogen	supplier-specific data	steam reforming
nitrogen	Ecoinvent 2.2	
sulphuric acid	Ecoinvent 2.2	
Fuller's Earth	Ecoinvent 2.2	
compressed air	Ecoinvent 2.2	
catalyst	Ecoinvent 2.2	
Energy		
electricity	ifeu grid model	EU average
natural gas	Ecoinvent 2.2	EU average mix
Transport	TREMOD	truck, 200 km
Sewage treatment	ifeu data base	European standards
mineral oil products	ifeu refinery model	European standard
base oil, naphtha, fuel oil, bitumen		

Table 4: Upstream and downstream data modules applied within the ife cycle inventory of this LCA

3.5.3 Reference system

Data referring to the reference system was derived from Kolshorn and Fehrenbach (2000). As mentioned above, the reference system was modelled anew.

3.5.4 Discussion of data quality

Table 5 gives a semi-quantitative pedigree matrix for the characterization of data quality (Weidema, Wesnæs 1996), taken as a guides for grading the quality of the applied data.

According to that, it can be stated that:

- The data for the regeneration processes correspond to the highest score in terms of all indicators: measured, complete and most recent.
- The quality of the majority of data sets regarding upstream and downstream processes (see Table 4) offers rather high reliability and completeness (score 2). Most data sets are taken from recognized data bases, such as ecoinvent.
- The data quality of the mineral oil refinery is based on long-term expertise in modelling particularly these processes.[1]

Indicator score	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumption	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representative unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal correlation	Less than 3 years difference to year of study	Less than 6 years difference to year of study	Less than 10 years difference to year of study	Less than 15 years difference to year of study	Age of data unknown or more than 15 years
Geographical correlation	Data from area under study	Average data from area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological correlation	Data from enterprises, processes, and materials under study	Data for processes and materials under study but from different enterprises	Data for processes and materials under study but from different technology	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Table 5: Matrix for the characterization of data quality according to Weidema, Wesnæs (1996)

Data quality of the reference system *treatment to fuel oil* meet the requirements for an indicator score 1 in terms of reliability, completeness, geographical correlation as well as technological correlation. Though it has to be stated that in terms of temporal correlation,

[1] The ifeu refinery model is on the way to constitute the origin of an update of mineral oil products for the ecoinvent database.

an indicator score of 5 has to be attibuted due to the fact that initial data collection has been carried out more than 15 years ago. However, a technical evaluation of the reference system in 2017 in consultation with a company operating in this field concluded that the process data applied in Kolshorn and Fehrenbach (2005) still represent the current state of the art for treatment to fuel oil. As a whole, data quality of the reference system is thus slightly worse, compared to the regeneration processes. On the other hand the reference is significantly less complex than the regeneration processes, and consumption levels are much lower. We assume the risk of false estimation to be very low.

4 Characterization of waste oil

The waste oil qualities for regeneration are based on separately collected used engine and other industrial waste oils suitable for regeneration to base oil. Qualities which don’t meet the specification for regeneration (e.g. oils contaminated with very high Chlorine or PCB, or so-called MARPOL oils) are not within the scope of this assessment.

The quality and composition of the waste oil were provided by the participating companies. On the basis of this data, an average waste oil composition was calculated and presumed to be the reflection of the typical European waste oil.

When compared to a typical waste oil in 2005, a clear trend towards advanced synthetic base oils with a corresponding higher PAO content can be observed (base oil type IV) (Phadke, M., Singh, A.K. 2017). This development is reflected by globally growing PAO production capacities, which grew some 20% in the time frame from 2012 to 2016 (Lubes’n’Greases 2017). Stricter emission standards for cars and thus higher requirements for lubricants as well as a rise of special applications such as wind turbines lead to higher demands in synthetic components (Chevron Philipps 2015).

Table 6 shows a comparison between a typical waste oil composition in 1997 and 2017, respectively. A clear trend toward lower amount of trace elements, ash content, sulphur content and lower, on average, viscosity at 40 ° C as well as a significantly lower range in viscosity can be observed. These results underline the development of base oils and consequently waste oils towards higher qualities and synthetic compounds.

	Unit	1997	2017
Flashpoint	° C	77 - 92	70 - 100
Lower heating value	MJ/kg	38.5 - 39.5	38.5 - 39.5
Density	kg/m^3	860 - 950	850 - 930
Viscosity @ 40 ° C	mm^2/s	30 - 120	49 - 60
Sulphur content	wt.%	0.59 - 1.03	0.3 - 0.8
Chlorine content	wt.%	0.018 - 0.12	0.01 - 0.11
Water content	wt.%	4 - 7	1 - 10
Ash content	wt.%	0.74 - 1.38	0.5 - 0.8
Sediment content	wt.%	0.75 - 1.21	0.5 - 1
PCB	mg/kg	< 0.5 - 1.8	< 0.5 - 1.5
PAH	mg/kg	300 - 400	300 - 400
Lead	mg/kg	62 - 86	5 - 16
Chromium	mg/kg	3.2 -16	1 - 5
Copper	mg/kg	25 - 117	15 - 30
Manganese	mg/kg	0 - 50	15 - 26
Vanadium	mg/kg	1 - 17	1 – 2
Tin	mg/kg	1.1 - 5.8	0.5 - 1.5
Zinc	mg/kg	615 - 753	500 - 700
Nickel	mg/kg	2.2. - 7.9	1 - 3
Cobalt	mg/kg	2.2 - 15	2.2 - 15
Cadmium	mg/kg	< 0.3 - 0.4	0.5 - 1

Table 6: Comparison between a typical waste oil composition in 1997 and 2017. Data provided by a participating company.

5 Description of the considered regeneration techniques

The considered four techniques cover the whole range of base oil quality as described in section 2.2.2. Together, the four mentioned companies comprise about 60 % of all available waste oil in the EU.

All below mentioned capacities refer to waste oil input.

5.1 Avista

For more than 60 years, AVISTA operates a constantly developing regeneration for recycling of waste oils in Dollbergen, Germany, with a today's input capacity of 125,000 Mg. The AVISTA Group also has regeneration plants in the USA and in Denmark, which together have a capacity of 175,000 Mg.

In all of them, base oils are produced from waste oil distillates by a modern solvent extraction technology (ESR). The whole process comprises several distillation steps for dewatering, gas oil separation and high vacuum thin film evaporation (WFD or Vaxon®) subsequently followed by solvent extraction. The base oils produced meet the highest quality requirements and are approved by many automobile manufacturers. The waste-free process of the Enhanced Selective Refining (ESR) efficiently separates all undesired constituents, e.g. polycyclic aromatic hydrocarbons (PAH) and organic heteroatom compounds from the distillate. The base oil produced in the European regeneration plants is to be classified as an API Group I++, it has a high viscosity index of about 120, a high degree of saturation, and a low evaporation loss.

5.2 LPC

LPC SA (formerly Cyclon Hellas SA) operates a regeneration plant based on hydro treatment technology in Aspropyrgo, Attica (Greece). It constitutes a modern unit which regenerates 38,000 Mg of mineral oils annually and provides a wide range of basic lubricants. At the same time, it is the only unit in Greece, which produces heavy mineral oils (Bright stock). The process comprises flash, vacuum and high vacuum distillation by thin film evaporator, propane deasphalting and catalytic hydrotreatment of recovered lube oil, followed by fractionation. LPC produces high quality API Group I, having relatively high VI and low sulphur.

5.3 Hylube process by PURAGLOBE

PURAGLOBE (formerly PURALUBE) operates a modern waste oil refinery in the Industriepark Zeitz (Saxony-Anhalt) Germany. It is the world-wide first facility which uses the HyLube™ technology developed by UOP. The specialty of this process is the hydrogenation of base oils which is executed in parallel to the catalytic treatment of the oil and also the high yield of more than 70 % base oil. The core parts of the facility are the special catalysts which are connected in line and the hydrogen which is circulated in the system and is used both as an auxiliary material and as an energy source. The refinery has a capacity of about 2 x 80,000 Mg waste oil per year and is operating since spring 2004/2008. The plant produces high quality base oils of API group II which are characterized by nearly water-clear color, low sulphur content and a high viscosity index.

5.4 Viscolube

The company is present in Italy with two production facilities – Ceccano (Frosinone) and Pieve Fissiraga (Lodi). We have analyzed the technology of the Pieve Fissiraga plant which treats about 120,000 Mg of waste oil every year, thus producing about 80,000 Mg of re-refined base oil.

Viscolube has developed, jointly with the French company Axens, an advanced technology enabling recovery of base oils from waste oils with properties similar to those of virgin base oils. This technology, named Revivoil, has already been successfully adopted in several countries. Today, the new hydrofinishing unit installed in Pieve Fissiraga refinery can produce, through a treatment with hydrogen at high pressure, base oils with API Group II characteristics, namely low sulphur and unsaturated content and very low aromatics content.

6 Description of the substituted and other inflicted processes

Overview of considered process (chains)

The processes substituted by regeneration of waste oil are:

- The complex primary production chain from crude mineral oil via waxy distillates to base oil group I (see also Figure 6) as well as for diverse co-products which arise during regeneration processes.
- The complex primary production chain from natural gas via i-decene synthesis to poly-alpha-olefins (PAO, base oil group IV)[1].

The reference system

The reference system for comparing regeneration with the alternativ use of waste oil is described by:

- A common technique to process waste oil to fuel oil quality meeting the quality of low sulphur fuel oil (≤ 0,5 % S). Quality requirements for "processed fuel oil" are definded e.g. by the environment Agency from UK (EA 2009).
- The processes substituted by the fuel oil production from waste oil.
- The primary production chains for diverse co-products which arise during treatment processes.

6.1 Mineral oil refinery

Process chains from study 2005 updated

All refinery products mentioned above had already been modelled by the study in 2005. Within the scope of this study the authors have applied an updated version of the underlying refinery model, taking into account the developments at European level according to the BREF (Barthe et al. 2015). The Umberto refinery model is shown in Figure 6. Data sets for following products are calculated based on this model:

- base oil group I
- naphtha
- light fuel oil
- heavy fuel oil
- bitumen

[1] Note: The regenerated base oils do not compare to advanced category IV base oils but rather to category I and II. However, since there is no LCA data for the category II and III base oils, a mixture of I and IV – based on the desired viscosity index and thus quality – are used to simulate groups II and III. This is due to the fact as there is data available for group I and IV and moreover, in principle, category II and III base oils can be seen as mainly a mixture of a certain amount of PAO (IV) and category I base oil.

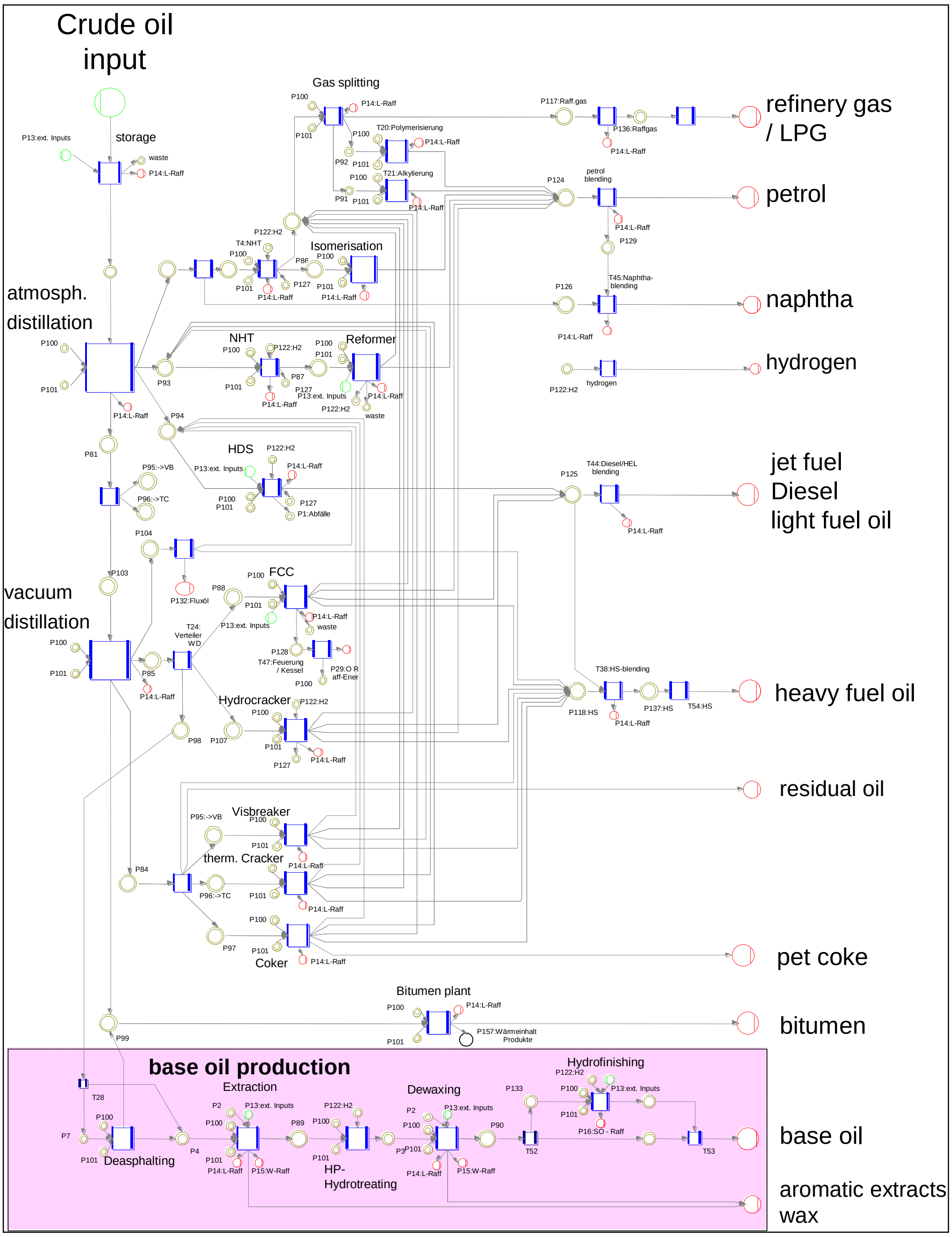


Figure 6: Network model for the calculation of mass and energy flow of a virtual mineral oil refinery

6.2 Treatment to fuel oil (reference system)

6.2.1 Three-stage treatment process

Unlike the other processes, the technique to process waste oil to fuel oil was modelled completely anew. The authors refer to a data set applied by Kolshorn et al.(2000). The treatment to fuel oil option follows a three-stage process. After collection and transport, the waste oil is heated and chemically treated. Water, sulphurous acid and precipitants are added in order to extract heavy metals. Subsequently, the mixture of phases is separated in a decanter. The solid phase which has a high calorific value (up to 31 MJ/kg) is put to use in cement works (energetic recovery), whereas the process water is largely re-used in a cycle[1].

As a second step, the remaining oil-rich phase is treated thermically in order to evaporate the highly volatile components. After the complete removal of the (undesirable) by-products, fuller's earth is added.

In a third step, the mixture is filtered in a filter press to separate the liquid phase (oil) and the remaining filter cake. The latter is recovered while the filtrate can be used as light fuel oil without further processing.

The yield ratio is 850 kg fuel oil per Mg waste oil. The input-output data are given in Table 7.

6.2.2 Substituted fuel oil

System substituted by the reference system

Section 6.1 describes the refinery model used for the calculation of data sets all types of mineral oil products. This includes the fuel oil replaced by recycled fuel oil from waste oil. In brief the overall process chain encompasses extraction and transport of the crude oil to the refinery, atmospheric and vacuum distillation, partly cracking processes and subsequent desulphurization to low sulphur fuel oil.

The selection of light fuel oil is justified by

a) low S-content,
b) corresponding heating value and viscosity and
c) the fact that such processed fuel oils are used to upgrade heavy fuels

Treatment to fuel oil leads also to diverse residues which, such as oil sludge and press cake (see also Table 7). These mass flows are combusted in a cement kiln, substituting coal as regular fuel.

Input			Output		
Item	**Quantity**	**Unit**	**Item**	**Quantity**	**Unit**
waste oil (reference flow)	1,000	kg	fuel oil (light fuel oil quality)	849.10	Kg
sulphuric acid	9	kg	gas oil	20.00	Kg
Fuller's earth	18	kg	gases	4.30	Kg
electricity	54,050	kJ	light ends	18.25	Kg
thermal energy	838,350	kJ	press cake (→ energy recovery)	22.60	Kg
			oil sludge (→ energy recovery)	18.75	kg
			waste water	100.00	kg

Table 7: Input (energy and auxiliary consumption) and output (yield and wastes) for treatment of waste oil to low sulphur fuel oil.

[1] About 30% of the added water has to be treated in a treatment plant.

7 Results and interpretation

In a first step, results are worked out for each of the four regeneration options assessed (section 7.1). The goal is to identify significant differences. In a second step, the average result of the four options will be compared to an alternative treatment and use as processed fuel oil (section 7.2). The average of the results of the four regeneration techniques represents the vast majority of regeneration capacities in Europe (see section 5). It allows a technology-neutral analysis of the impacts of regeneration, while techniques-related differences are discussed in section 7.1.

As a final step of interpretation, additional sensitive aspects and parameters concerning data, system boundary, allocation rules and valuation approach are discussed (section 7.3).

7.1 Comparison of the four regeneration options

Comparing regeneration with virgin base oil production

The study does not aim to deliver arguments for a marketing competition between the companies considered. Therefore the results are presented in an anonymous way. Table 8 provides the impact category results for every regeneration option and the corresponding (substituted) equivalency processes. To give an example:

1. Technique 1 leads to an emission of 365 kg of CO_2-equivalents per Mg waste oil, including combustion of by-products, natural gas for heat and steam, production of current, hydrogen and other auxiliaries.
2. The benefit of technique 1 (substitution of base oil and other by products) leads to a prevention of 827 kg of CO_2-equivalents per Mg waste oil, supposed the quality of the base oil substituted corresponds with group I in terms of VI. Supposed the quality equals the advanced case (VI ≙ group I/IV), the saved GHG emission extends to 1,072 kg CO_2-equivalents.
3. To get the “net impact” of the technique 1 of regeneration the omitted burden (827 or 1,072) is to be subtracted from the burden created (365). Hence, technique 1 releases the global warming in the range of 462 to 707 kg CO_2-equivalents per Mg waste oil.

	Regeneration Technique				
Reference: 1 Mg waste oil	**1**	**2**	**3**	**4**	**Average**
Resource depletion (GJ)					
Regeneration	5.36	9.12	2.52	5.56	5,64
Substituted processes					
base oil standard (VI ≙ group I)	47.9	48.1	46.7	47.6	47,6
base oil advanced (VI ≙ group I/IV)	51.7	52.0	50.1	51.8	50,5
Global warming (kg CO_2-Eq.)					
Regeneration	365	577	190	516	412
Substituted processes					
base oil standard (VI ≙ group I)	827	838	783	869	830
base oil advanced (VI ≙ group I/IV)	1 072	1 094	1 006	1 144	1 079
Acidification (kg SO_2-Eq.)					
Regeneration	1.02	1.36	0.41	0.75	0,88
Substituted processes					
base oil standard (VI ≙ group I)	4.43	4.49	4.18	4.69	4,45
base oil advanced (VI ≙ group I/IV)	4.52	4.59	4.26	4.79	4,52
Eutrophication (kg PO_4^{3-}-Eq.)					
Regeneration	0.089	0.138	0.029	0.089	0,086
Substituted processes					
base oil standard (VI ≙ group I)	0.181	0.181	0.174	0.182	0,18
base oil advanced (VI ≙ group I/IV)	0.252	0.256	0.239	0.262	0,24
Carcinogenic risk potential (mg As-Eq.)					
Regeneration	4.1	11	2.5	14	7,82
Substituted processes					
base oil standard (VI ≙ group I)	242	239	233	246	240
base oil advanced (VI ≙ group I/IV)	242	239	233	246	240
Fine particulates (kg $PM_{2.5}$-Eq.)					
Regeneration	0.93	1.33	0.31	0.74	0,83
Substituted processes					
base oil standard (VI ≙ group I)	3.13	3.17	2.97	3.28	3,14
base oil advanced (VI ≙ group I/IV)	3.48	3.53	3.29	3.67	3,41

Table 8: Results of impact assessment for the 4 technical options according to burdens by regeneration system and equivalency system

Figure 7 up to Figure 12 illustrate the impact assessment results given in Table 8. Category by category the diagrams are designed as follows:

- Left bar: the impact by the regeneration system; corresponds to the upper part of the system flow chart given in Figure 3.
- The two bars in the middle: the impact of the substituted primary production of base oil; corresponds to the lower part of the system flow chart given in Figure 3
- The two right bars: the net balance between impact by the regeneration system minus the impact of the substituted primary production.

Each bar is subdivided to show the lowest, the highest and the average value each.

Fossil resource depletion

Figure 7 shows the result for resource depletion represented by the cumulated fossil energy demand. The advantage of regeneration against the substituted equivalent system (including primary base oil production) is prevalent reflecting the benefit of safeguarding the fossil feedstock of base oil by recycling. Of low significance is the range between minimum and maximum within the four assessed techniques.

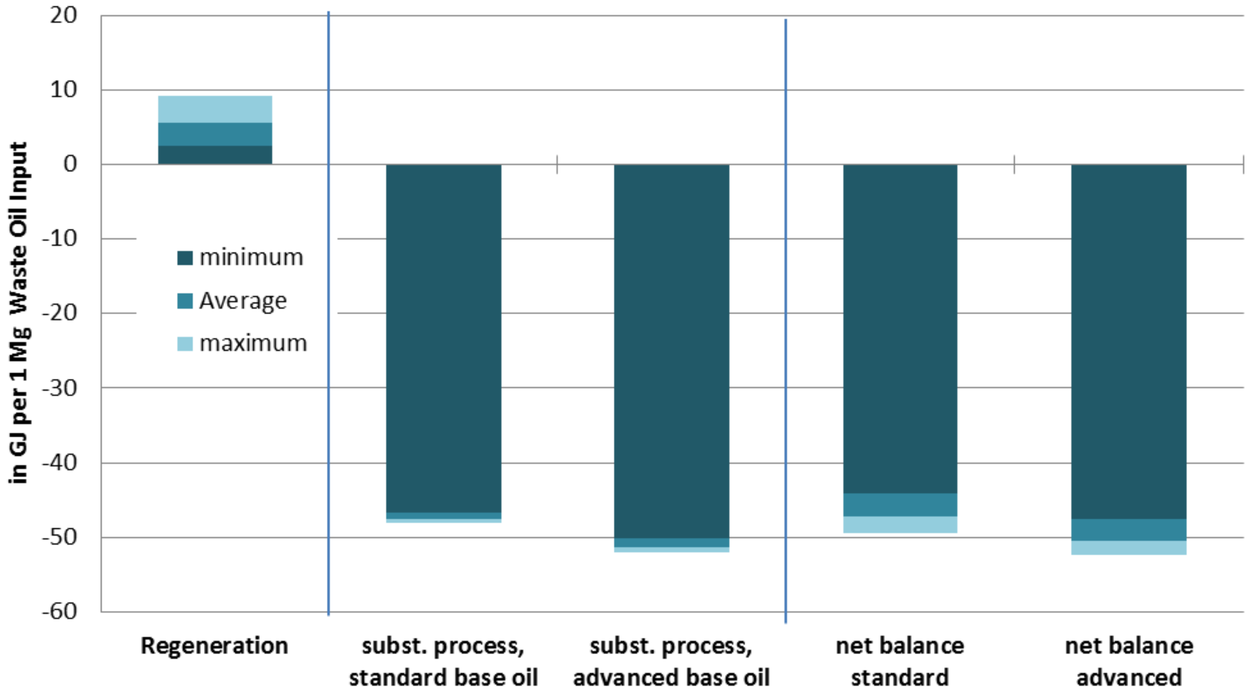


Figure 7: Impact assessment results for resource depletion; showing the average result (arithmetic mean) of the four techniques as well as the individual minimum and maximum.

Global Warming Potential

Figure 8 shows the global warming balance. Unlike the resource category this item is determined only by the GHG emission due to processes along the respective production chains. At its maximum the impact of regeneration can be around half of the average impact of the substituted equivalency processes. The range between the techniques is more significant here, but even the minimum case still shows a clear advantage against the equivalency processes.

This impact category shows distinct advantages of producing advanced base oil quality instead of standard quality, whereas the substitution of standard quality still leads to clearly better results regarding the net balances.

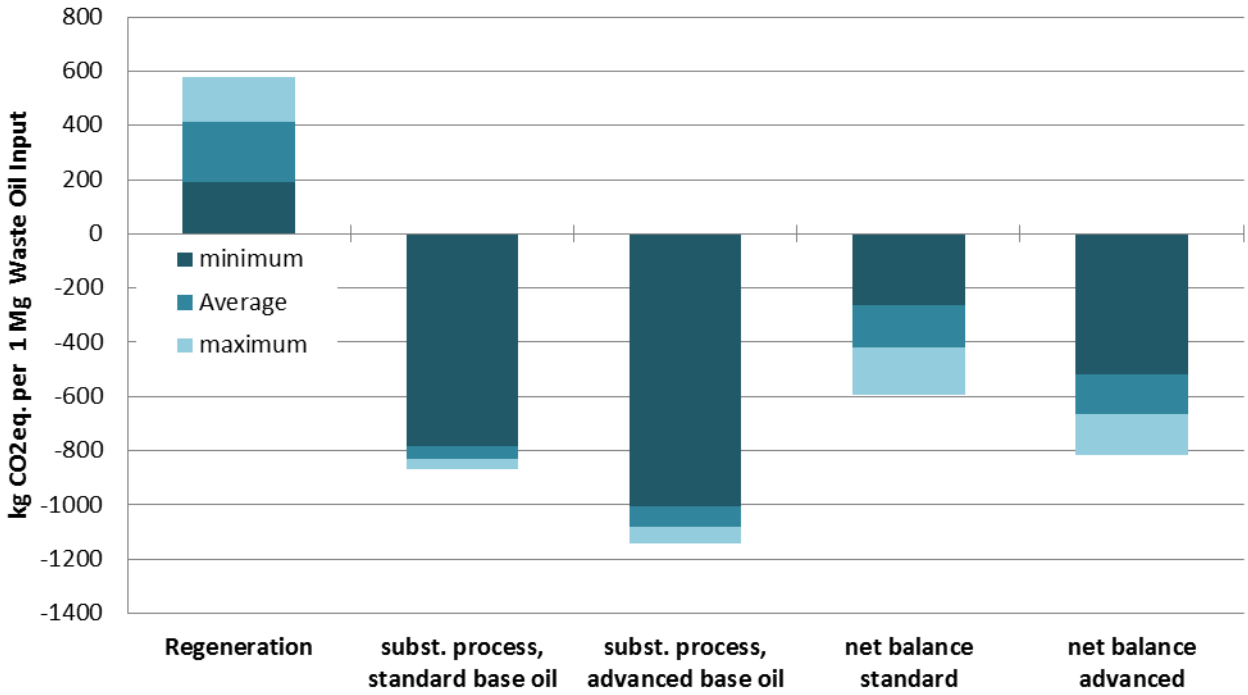


Figure 8: Impact assessment results for global warming; showing the average result (arithmetic mean) of the four techniques as well as the individual minimum and maximum

Acidification

The results for acidification (see Figure 9) are even more significant than for GWP. The impact of the regeneration system is much smaller than the equivalency system which can be traced on the rather high sulfur dioxide emissions connected with primary mineral oil refining. The range between the techniques as such is comparably high, while this range does not appear to be relevant when focus is on the net balance.

Terrestrial eutrophication

Terrestrial eutrophication (see Figure 10) gives a picture similar to GWP: results are even more significant than for GWP: At its maximum the impact of regeneration can be around half of the average impact of the substituted equivalency processes. The range between the techniques is also more significant here, but again the minimum case still shows a clear advantage, compared to the equivalency processes.

This impact category shows distinct advantages of producing advanced base oil quality instead of standard quality, whereas the substitution of standard quality still leads to clearly better results regarding the net balances.

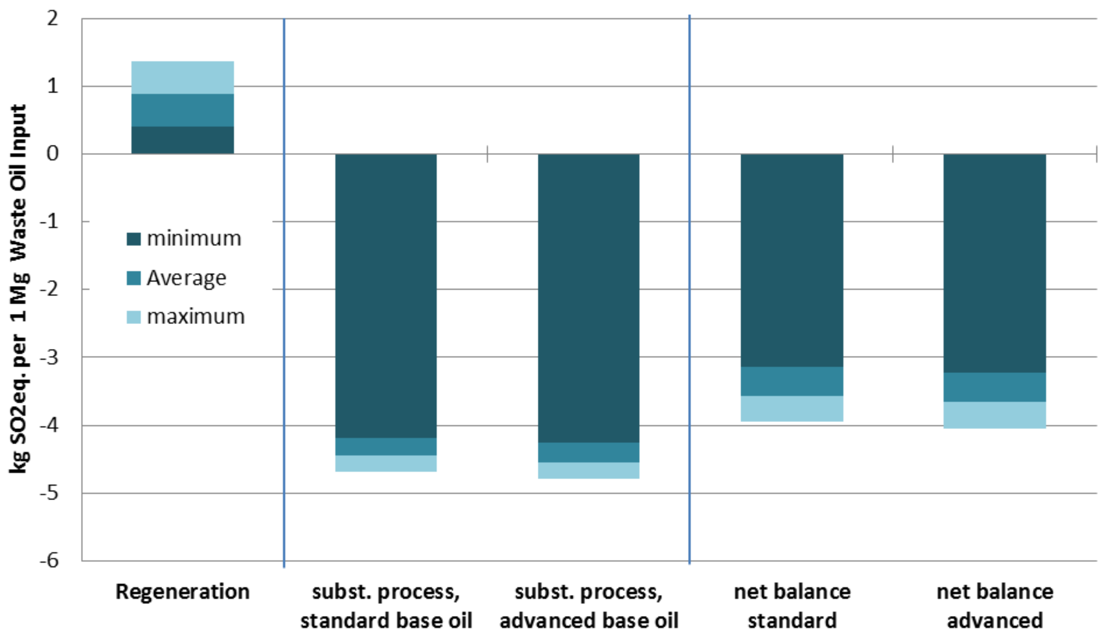


Figure 9: Impact assessment results for acidification; showing the average result (arithmetic mean) of the four techniques as well as the individual minimum and maximum

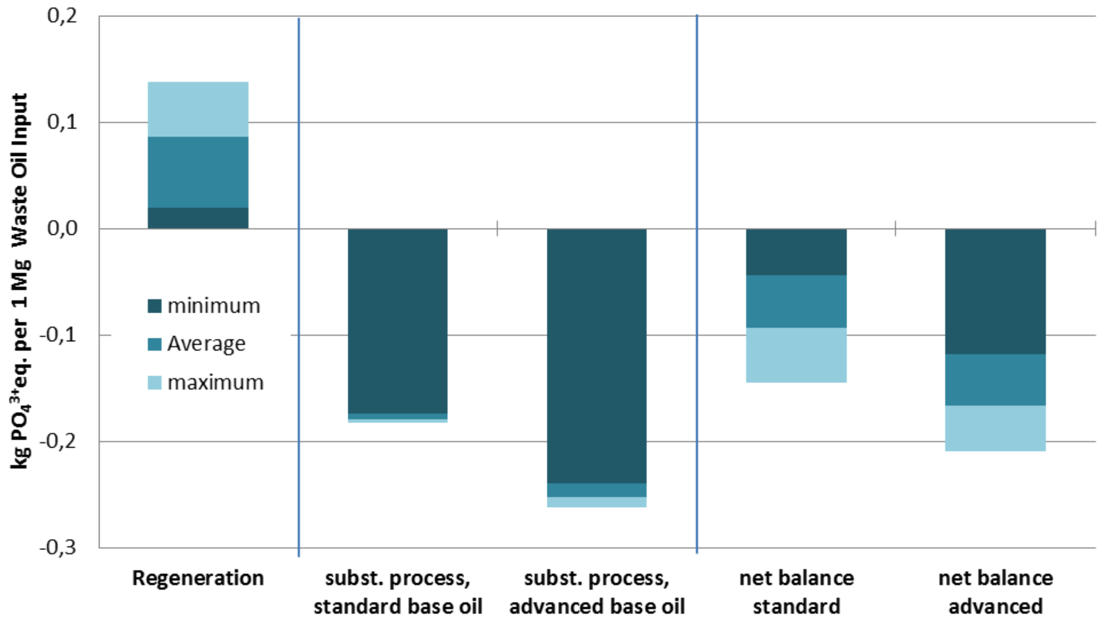


Figure 10: Impact assessment results for eutrophication; showing the average result (arithmetic mean) of the four techniques as well as the individual minimum and maximum

Human toxicity

This study covers the impact category human toxicity by the indicators carcinogenic risk potential (arsenic equivalents) (see Figure 11) and fine particulates (PM2.5, see Figure 12) showing rather different pictures.

Carcinogenic risk potential: the regeneration system shows quite low impacts. Lower emission levels are on the one hand due to the fact that plants are mostly more recently installed and therefore equipped with abatement measures. On the other hand the applied fuels (natural gas or co-processed gases) are more or less free from heavy metals etc. On the contrary the primary equivalency processes are affected by heavy fuel oil application, emitting significant amounts of nickel.

This indicator shows no significant difference between the substitution of advanced base oil quality and standard quality because the primary production of virgin group I base oil already shows high specific emissions.

Fine particulates: gives a picture similar to terrestrial eutrophication. This is due to the NO_x, which contributes relevantly to the impact in both categories.

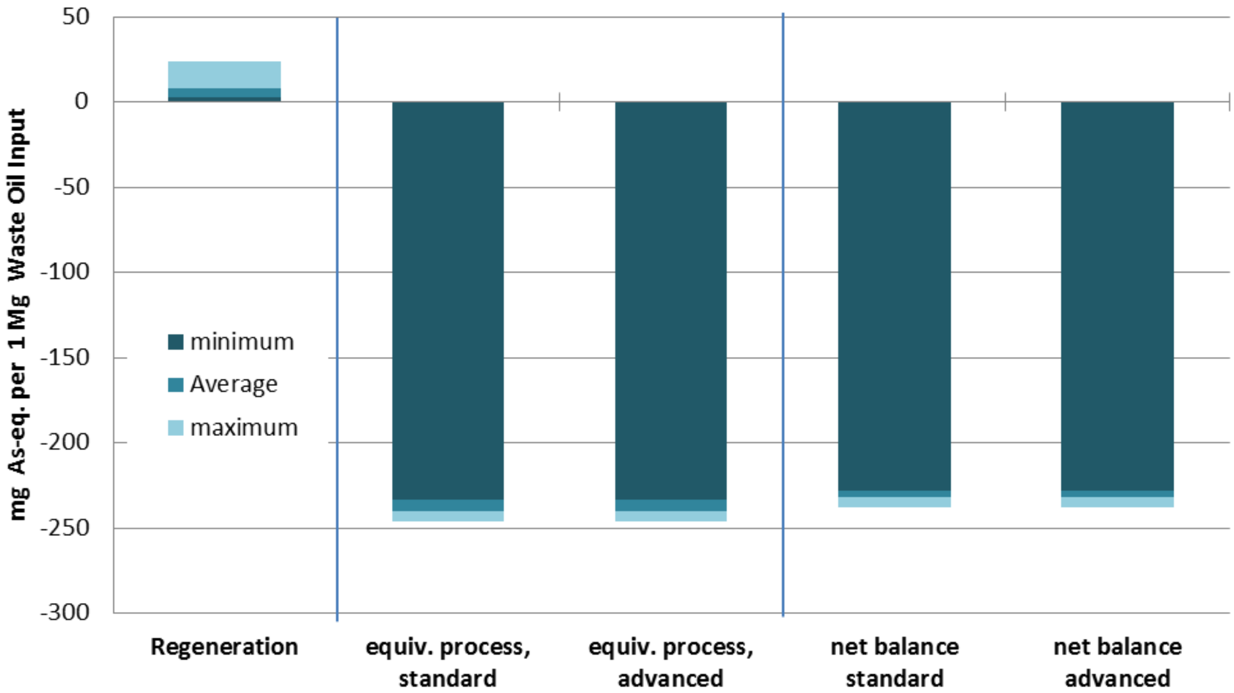


Figure 11: Impact assessment results for human toxicity represented by carcinogenic risk potential; showing the average result (arithmetic mean) of the four techniques as well as the individual minimum and maximum

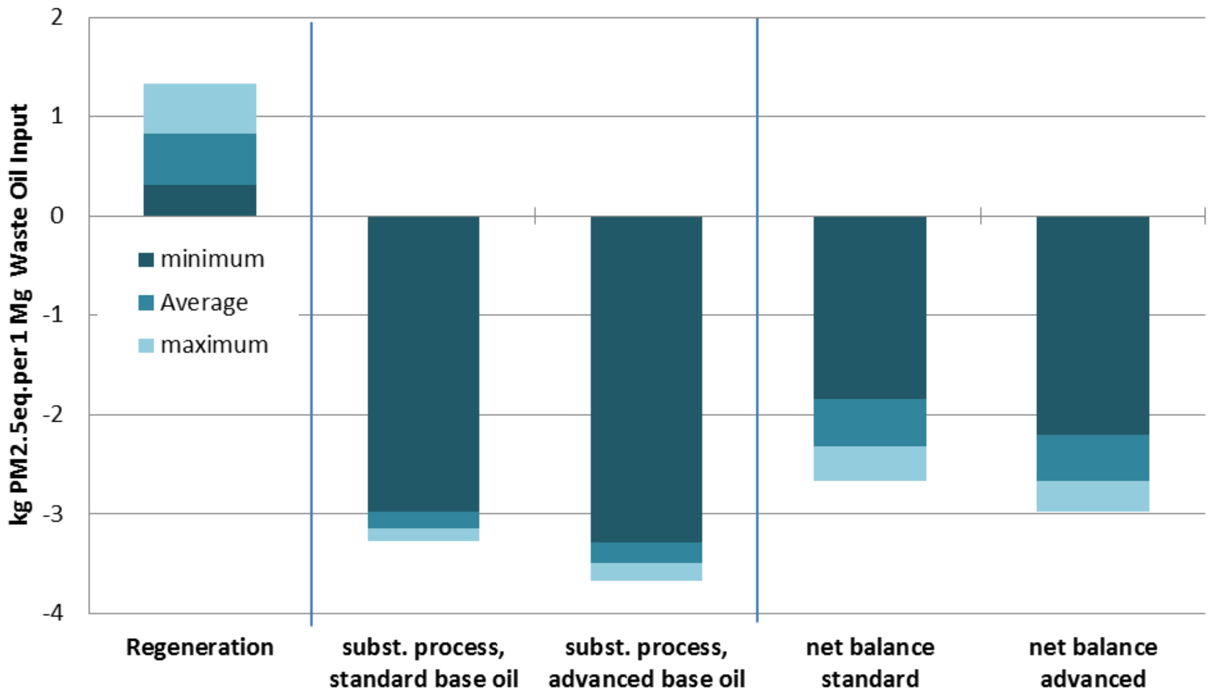


Figure 12: Impact assessment results for human toxicity represented by fine particulates (PM2.5 showing the average result (arithmetic mean) of the four techniques as well as the individual minimum and maximum.

Synopsis of impact categories

Figure 13 gives a synopsis on all the impact category results listed in Table 8 and described within the text and diagrams above. The numbers are scaled on the particular result of “regeneration” (= 1) to enable combining the different categories with different units each within one graph. The bars representing the substituted primary processes show the factor relative to regeneration. The main bars stand for the average result of the four techniques. The deviation bars show the range of the four techniques in detail. In fact, Figure 13 gathers all the information shown in Figure 7 through Figure 12 into one picture.

One motivation to highlight this synopsis within this report is to allow a direct comparison with Fehrenbach (2005): Table 8 and Figure 13 correspond to Table 7-2 and Figure 7-1 enclosed by the study 2005.

Example: GWP100 (values in kg CO_2-Eq.) taken from Table 8:		
-regeneration (average):	412	→ 1
- subst. base oil standard (average):	830	→ 2,01 (= 830/412)

Some differences appear to be obvious with focus on fossil resources and carcinogenic risk potential. These changes are due to the following reasons:

- In general, the percentaged scaling is prone to display large bar lenghths even for small impacts. If the index-1-basis is actually small at absolute scale, doubling of the value may be of low significance in reality.

- This is true e.g. for *resource depletion*: In 2005, the substituted primary system has shown a 35-fold higher demand than the regeneration system. The point is: The energy demand of the regeneration system is higher according to the updated data. However, this increase is still very low in absolute figures. Therefore, the high value of saved resources is *reduced* to ten timesthe demand of the regeneration system, being still a high saving rate in absolute figures
- It is the other way around with *carcinogenic risk potential*, where we now state a 30-fold better result in relation to saved emissions. This is due to a decrease of the on-site emissions of the regeneration plants from low level in 2005 to an even lower level today.

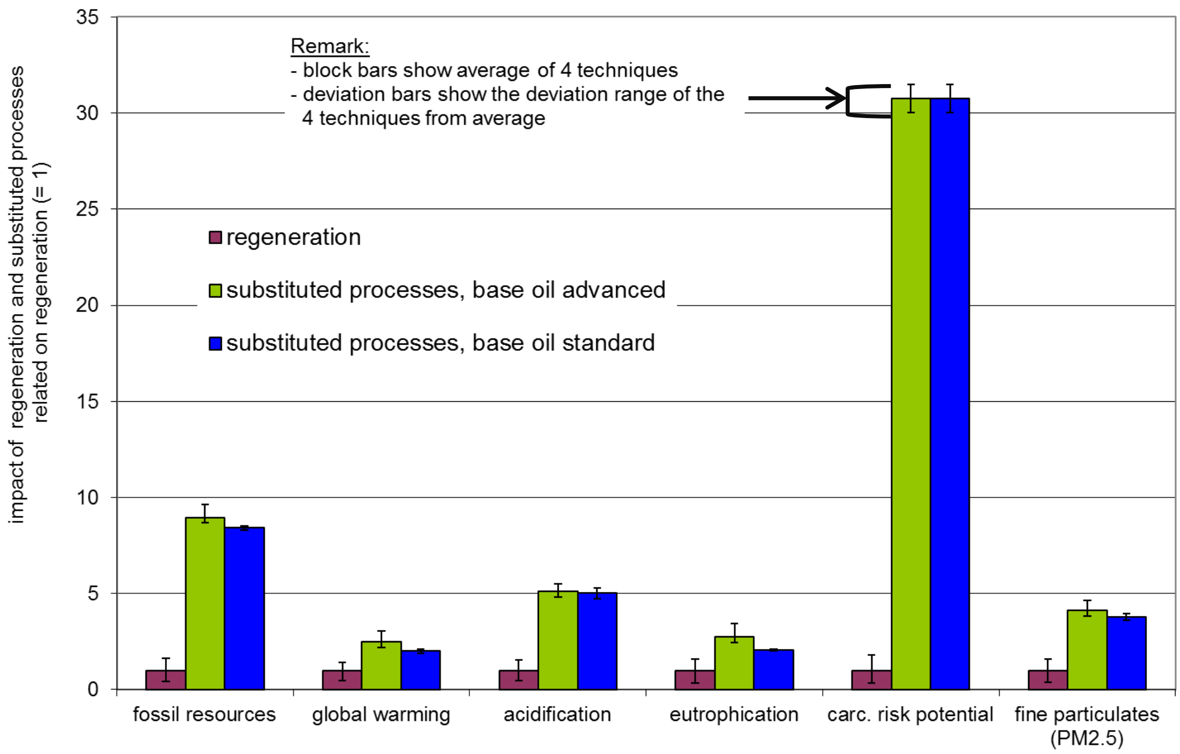


Figure 13: Total view on the impact assessment results; all figures related to the particular result of “regeneration”, main bars: average result (arithmetic mean) of the four techniques, deviation bars: range of the four techniques

7.2 Comparison of regeneration to base oil with processing to fuel oil

7.2.1 Impact assessment results

In Table 9 the impact assessment results for:

- Regeneration; This comprises the arithmetic mean of the aformentioned four processes (see Chapter 5), substituting either base oil standard (Viskosity Index (VI) equivalent to a group I type base oil) or base oil advanced (VI equivalent to a 70:30 mixture of group I/IV type base oils) and
- The treatment to fuel oil, substituting light fuel oil quality

are shown in comparison. Within the middle column this table therefore repeats the average data from Table 8.

	Regeneration		treatment to fuel oil	
Fossil resources (GJ)	burden of …		burden of …	
	…regeneration	5,64	…treatment	0,27
	subst. base oil standard	47,6	…subst. light fuel oil	40,5
	subst. base oil advanced	50,5		
Global warming	burden of …		burden of …	
(kg CO_2-Eq.)	…regeneration	412	…treatment	234
	subst. base oil standard	830	…subst. light fuel oil	426
	subst. base oil advanced	1079		
Acidification	burden of …		burden of …	
(kg SO_2-Eq.)	…regeneration	0,88	…treatment	1,21
	subst. base oil standard	4,45	…subst. light fuel oil	1,89
	subst. base oil advanced	4,52		
Eutrophication	burden of …		burden of …	
(kg PO_4^{3+}-Eq.)	…regeneration	0,086	…treatment	0,019
	subst. base oil standard	0,18	…subst. light fuel oil	0,084
	subst. base oil advanced	0,236		
Carcinogenic risk potential	burden of …		burden of …	
(g As-Eq.)	…regeneration	7,82	…treatment	24
	subst. base oil standard	240	…subst. light fuel oil	129
	subst. base oil advanced	240		
Fine particulates	burden of …		burden of …	
(kg PM_{10}-Eq.)	…regeneration	0,83	…treatment	0,66
	subst. base oil standard	3,14	…subst. light fuel oil	1,36
	subst. base oil advanced	3,41		
Explanations: "regeneration" stands for the average results of the four techniques (see Table 4)				

Table 9: Line-up of impact results for regeneration (average of four) and treatment to fuel oil; all results based of 1 Mg of recovered waste oil

Figure 7 until Figure 12 display the basic impact assessment results from Table 9. Within this section this net balancing is also done for the reference system – treatment to fuel oil, based on the results given in Table 9 (right column).

Figure 14 explains the stepwise combination of the single results to the final result: the difference between regeneration and treatment to fuel oil. The example refers to the GWP data which can be found in Table 9. It shows an advantage of 474 kg CO_2eq. per Mg waste oil in favor of regeneration to advanced base oil.

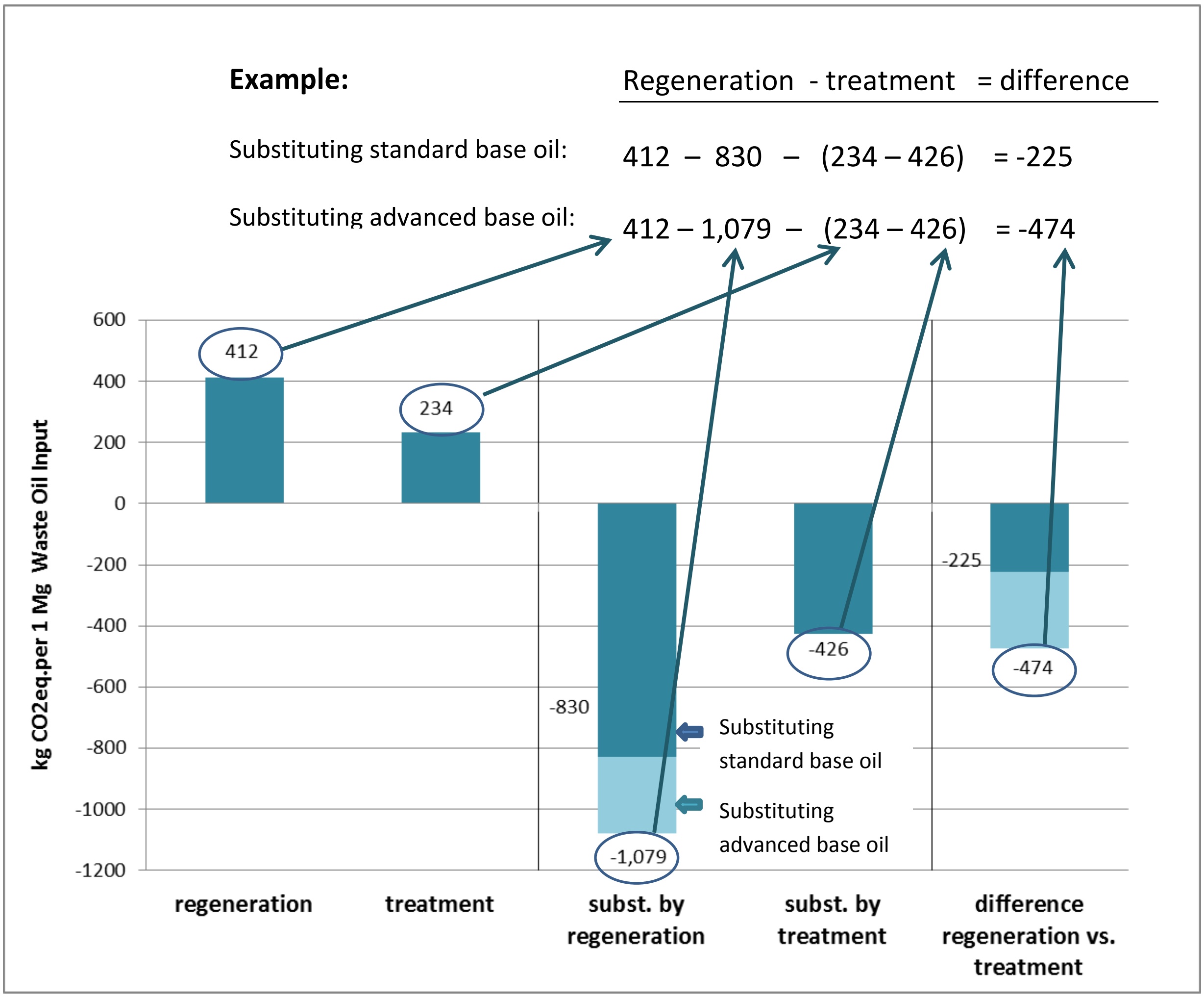


Figure 14: Illustrative example for the final combination of the impact assessment result to analyze the difference between regeneration and treatment to fuel oil.

For a synopsis of all impact categories we refer once again to diagram layout used by Fehrenbach (2005) in order to allow a direct comparison with the previous study. To that end Figure 14 corresponds to Figure 7-2 enclosed by the study 2005, where the “net impacts” of all categories for

- regeneration and substitution of standard base oil,
- regeneration and substitution of advanced base oil,
- treatment to fuel oil and substitution of low sulphur fuel oil

are shown. Again in order to allow combining the different categories with different units each within one graph, the value for regeneration (substituting standard base oi) is set to be 1 and the other values are scaled correspondingly. In fact all options considered contribute to environmental relief in all categories.

Example: GWP100 (values in kg CO_2-Eq.):			
- burden: of regeneration:	412	burden of treatment:	234
- subst. base oil standard:	830	subst. light fuel oil:	426
net balance:	- 418	net balance:	-192
advantage of regeneration: 226 (= 418 – 192)			
relation: -418 / -192 = 2,2			

The diagram shows that:

- Regeneration to standard base oil offers advantages throughout all analysed impact categories compared with treatment to fuel oil; in case of global warming, acidification, carcinogenic risk and fine particulates, the relative advantage is higher than a factor 2.
- The advantage of regeneration to base oil of advanced quality is even more significant.

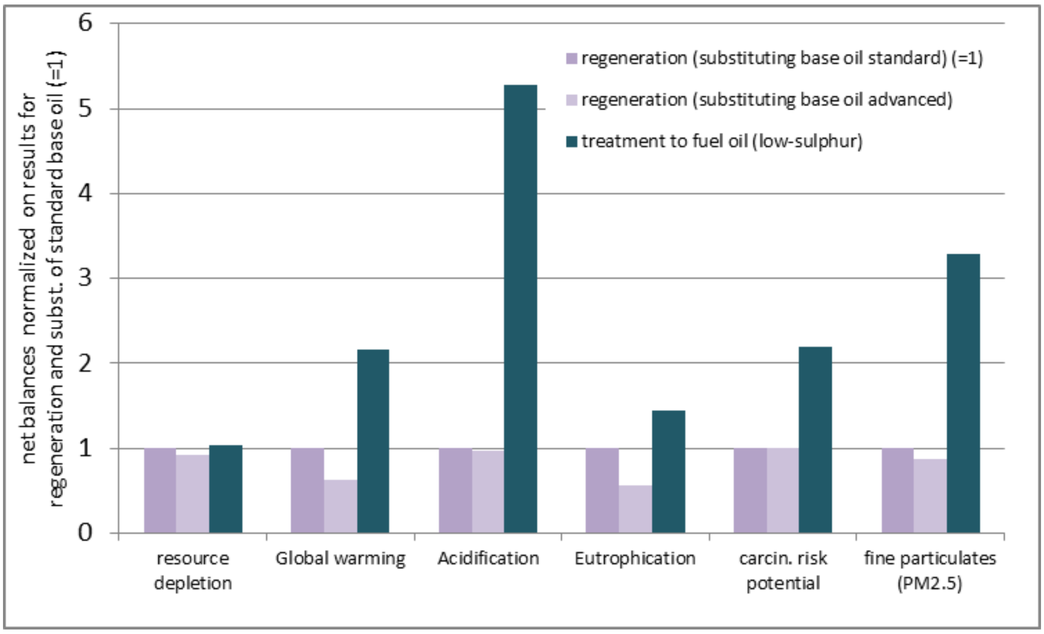


Figure 15: Synopsis on the comparable impact assessment results – regeneration (average) vs. treatment to fuel; values <1 describe better performance than regeneration and substitution of standard base oil and vice versa.

7.2.2 Normalization of impact assessment results and grouping

In the same way as in the section above, the differences among the options in the impact assessment results are calculated and normalized using Person Equivalency Values (PEV).

These illustrations again show the distinct advantages of regeneration against treatment to fuel in all impact categories and the advantages of the substitution of base oil advanced (VI ≙ group I/IV) against base oil standard (VI ≙ group I). The advantages range between 90,000 PEV (acidification) and at least around 5,000 PEV (eutrophication). In terms of Global warming the advantage of the advanced case is 34,000 PE, that is to say: were regeneration in Europe stopped and waste oil treated to fuel oil the greenhouse gas emissions would increase equivalent to the emission accounted for 34,000 average German inhabitants in 2015.

Example: GWP100:
- advantage of regeneration to base oil of advanced quality vs. treatment to fuel oil: = 419 kg CO_2-Eq./Mg waste oil
- multiplied with 950,000 Mg waste oil per year = 400,000 Mg CO_2-Eq. per year
- divided by the PEV = 34,000 PEVs (11.8 Mg CO_2-Eq. per year and person)

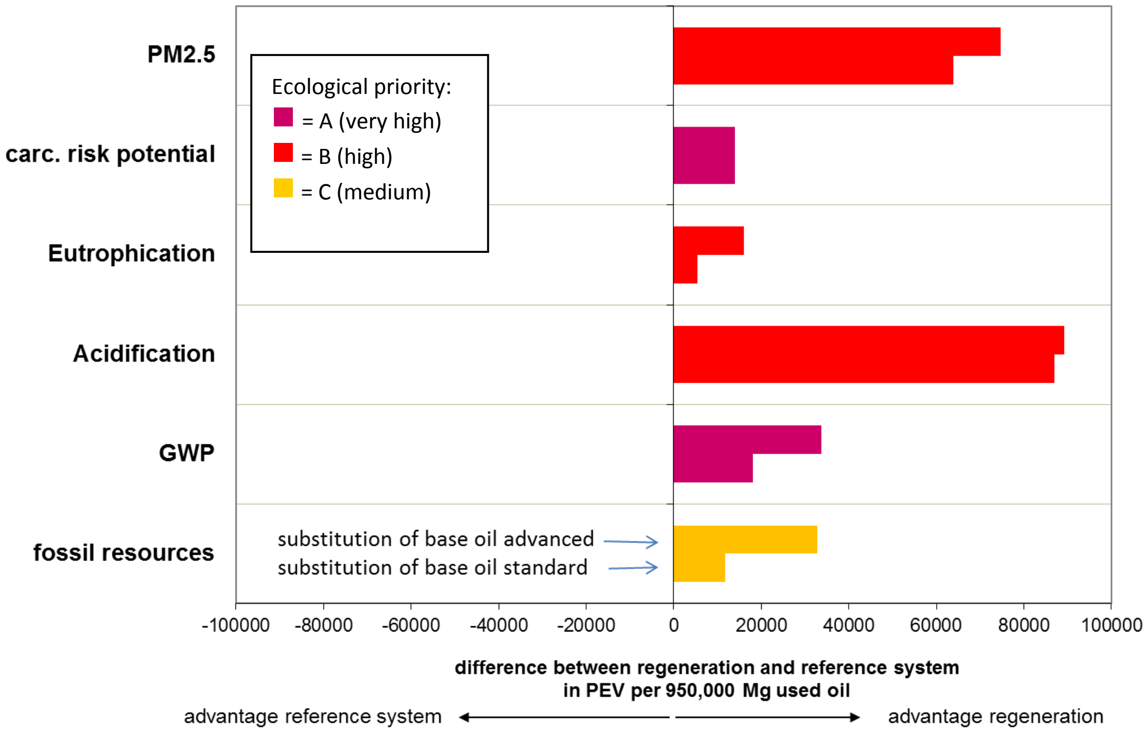
Table 10 gives an overview of the different investigated treatment options, standardized to PEV relative to the most beneficial treatment option in each investigated impact category. The figures correspond to the results presented in Table 9 multiplied by the total amount of available waste oil in Europe per year (950,000 Mg) and divided by the specific PEV for each impact category (for reference, see example above). For example, if one would consider treating the total amount of available waste oil to fuel oil, this would lead to a plus in GHG emissions equivalent to the average amount of GHG emissions of 34,000 average German citizens per year, compared to regeneration to base oil with advanced quality.

Figure 16 presents another overview of these results. The x-axis represents the amount of PEV relative to the other treatment options, with both regeneration systems to the right and the reference system to the left. All results refer to the average of the four investigated techniques.

	Regeneration (standard quality)	**Regeneration** (advanced quality)	**Reference case** (fuel oil)
Fossil resources	21,000	①	33,000
Global warming	16,000	①	34,000
Acidification	2,000	①	89,000
Eutrophication	11,000	①	16,000
carc. risk potential	①	①	14,000
Fine particulates	11,000	①	75,000
Fossil resources	■■■■	①	■■■■■■■
Global warming	■■■	①	■■■■■■■
Acidification	●	①	■■■■■■■■■■ ■■■■■■■■
Eutrophication	■■	①	■■■
Carc. risk potential	①	①	■■■
Fine particulates	■■	①	■■■■■■■■■■ ■■■■■

Scaled by specific contribution in PEV related to 950,000 Mg of waste oil; the figures resp. the number of squares shows the deviation from the most beneficial option in each case, which is marked by ①;
1 square corresponds to 5,000 PEV (rounded); differences below 2,500 PEV are marked by •, meaning, the more circles / squares, the worse the option compared to the most beneficial option.
Ecological priority: ■ = A (very high), ■ = B (high), ■ = C (medium), based on the state of the art in application since UBA (1999)

Table 10: Overview of impact-related and normalized differences between regeneration to base oil and processing to fuel oil; in PEV 2015.



Ecological Priority based on the state of the art in application since UBA (1999)

Figure 16: Overview of impact-related and normalized differences between average regeneration and treatment to fuel oil

Another option to illustrate these numbers might be a comparison with transport efforts: 400,000 Mg of CO_2-Eq. correspond to the GHG emissions caused by:

- one person traveling 3,7 billion km in a car[1], which would equal: during 400,000 times from Lisboa to Moscow back and forth.
- one waste oil truck driving 200 million km.
- or transporting 950,000 Mg of waste oil by truck over 4,200 km.

[1] On the basis of TREMOD (Transport Emission Model), we assume an average fuel consumption of 7.8 litres / 100 km.

7.3 Sensitivity analysis

Fehrenbach (2005) analyzed that the following items contain assumptions of more or less relevant influence on the results:

- Allocation method
- Fuel substitution
- Distribution distances

Aspect 1 and 3 don't need any further examination. Their influence has been sufficiently evaluated within the former study.

Apart from those aspects, the authors would like to highlight following points of attention:

- We still deem "fuel substitution" worth consideration
- How strongly does the selection of regeneration technique affect the result – in other words: how robust is the average result?
- Is there a bias concering data quality of primarily collected data from regeneration and possibly outdated information about the refence system?
- How strongly does the base oil quality supposed to be achieved by the regeneration techniques affect the result?

7.3.1 Fuel substitution

The authors still deem "fuel substitution" worth consideration. There are two aspects to be pointed out:

- Exactly which fuel is substituted by treated fuel oil (reference system)?
- How about emissions from fuel oil use?

The authors determined that type of fuel substituted by treated fuel oil to a fuel oil of light to medium density and low sulphur content. We substantiate this by the practice using treated fuel oil for upgrading heavy fuel, which is normally done by admixing low sulphur fuel oil.

Given that heavy fuel oil would be substituted by the treated waste oil, hypothetically, the results would slightly change in favor of regeneration within nearly all of the impact categories because the effort to produce heavy fuel is lower than for light heating oil. Figure 17 repeats the results in Figure 15 and adds results based on substitution of heavy fuel oil (HFO) by the reference system.

Consequential life cycle thinking however would clearly argue against assuming heavy fuel oil to be substituted, because in general, refineries do the utmost to reduce the share of heavy fuel oil in their product portfolios. Thus, it is unlikely that offering an alternative (recycling) fuel would lead to reduced production of heavy fuel oil.

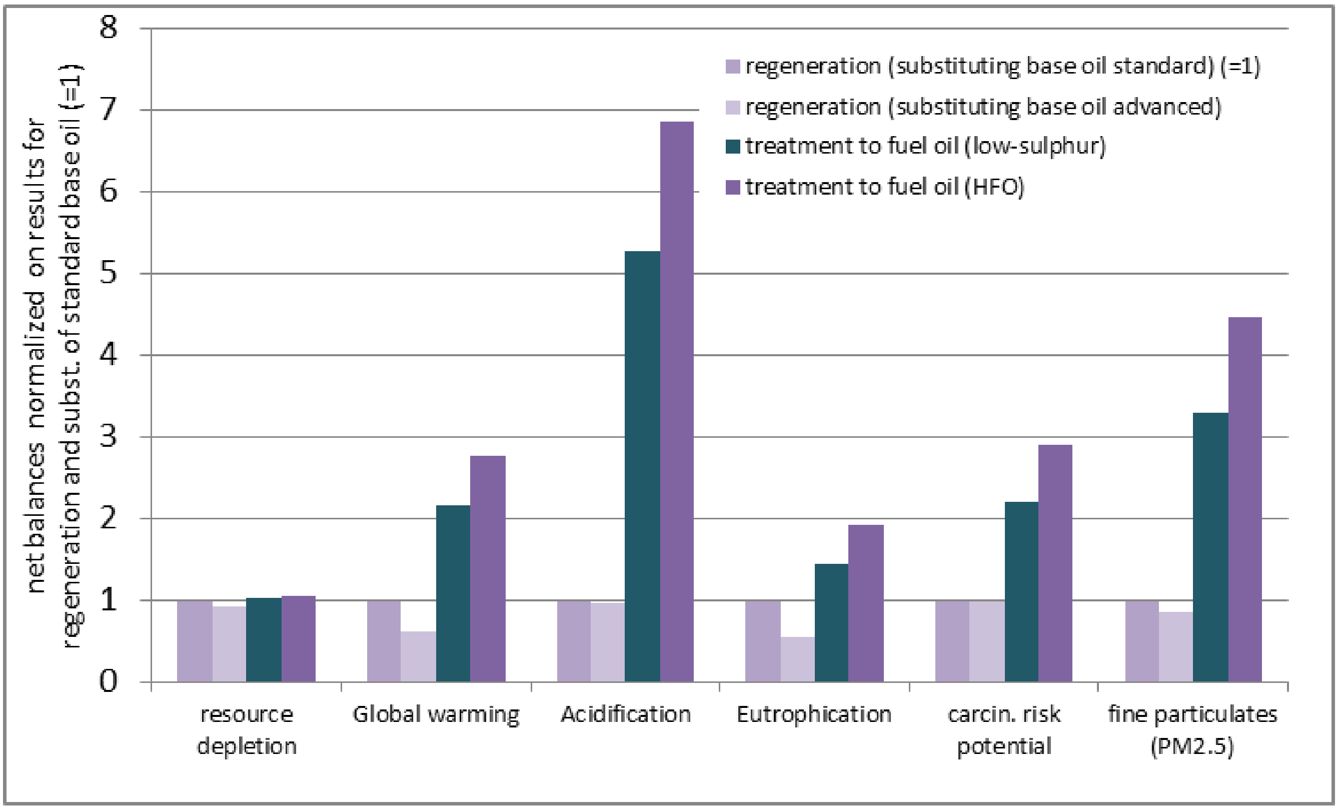


Figure 17: Total view on the comparable impact assessment results – regeneration (average) vs. treatment to fuel – **sensitivity of the choice of fuel oil type** - ; values <1 describe better performance than regeneration (base oil group I) and vice versa.

With regard to the second aspect, the use phase of the treated fuel oil has been left out of the system boundary. This setting was founded on the assumption that the secondary fuel oil from waste oil treatment should equal the substituted light heating oil regarding their compositions. In fact, no sufficient data is available to consolidate this assumption. While the authors suppose the composition of standard light fuel oil and the treated fuel oil to be identical, in reality there might be differences which might lead to slight modifications in results. Assuming that the treated fuel oil would have lower contents of heavy metals (e.g. Nickel) than the standard oil, the result might change within the category of carcinogenic risk potential.

7.3.2 Does the average of four regeneration techniques properly represent the single techniques?

The analysis and interpretation given in section 7.1 should give sufficient answer to that question. In fact there are large ranges between the four techniques as for the impacts of the regeneration system.

For resource depletion there is more than a factor 3 between the technique with lowest energy demand and the one with the highest demand. However the avoided impact due to substitution of virgin base oil is as factor 5 higher than the upper end of the range between the techniques.

For GWP these relations are much closer: again the range between the techniques spans by a factor 3 and in this case the substituted impacts are not that distanced (just a factor

1.3) from the most GHG intensive technique. However also in this case there is still a net saving rate, even if only standard base oil is substituted. For Eutrophication the situation is even a little more close, but even here the “worst case” selection is saving net emissions. Acidification and the toxicity indicators are rather distinct in that point, similarly to resource depletion.

It can be summarized that the average result gives a solid picture of the overall performance of the assessed regeneration techniques, taking into account that some perform better than others and vice versa.

7.3.3 Temporal bias concerning the reference system?

While we state that the data collected directly from the operators of the four regeneration techniques is very current (→ 12 month average in 2016), we have applied 15 year old data to model the reference system (treatment to fuel). This might lead to presume a temporal bias within the data applied.

The following argument should invalidate this presumption: the impact of the treatment process is in most cases significantly lower that from regeneration. This might be clear taking the much higher effort into account for regeneration to high quality products as base oils. As shown in Figure 18 this is not true for acidification and carcinogenic risk potential. However just these two categories are very strongly dominated by the equivalency processes while the waste oil processing system is not determining the result.

Figure 19 illustrates this referring to acidification: Even if the emissions from treatment to fuel oil (basically 1.21 kg SO_2eq/Mg waste oil) would be zero, the difference between regeneration and treatment (basically 2.89 kg SO_2eq/Mg waste oil) would still be clearly in favor of regeneration.

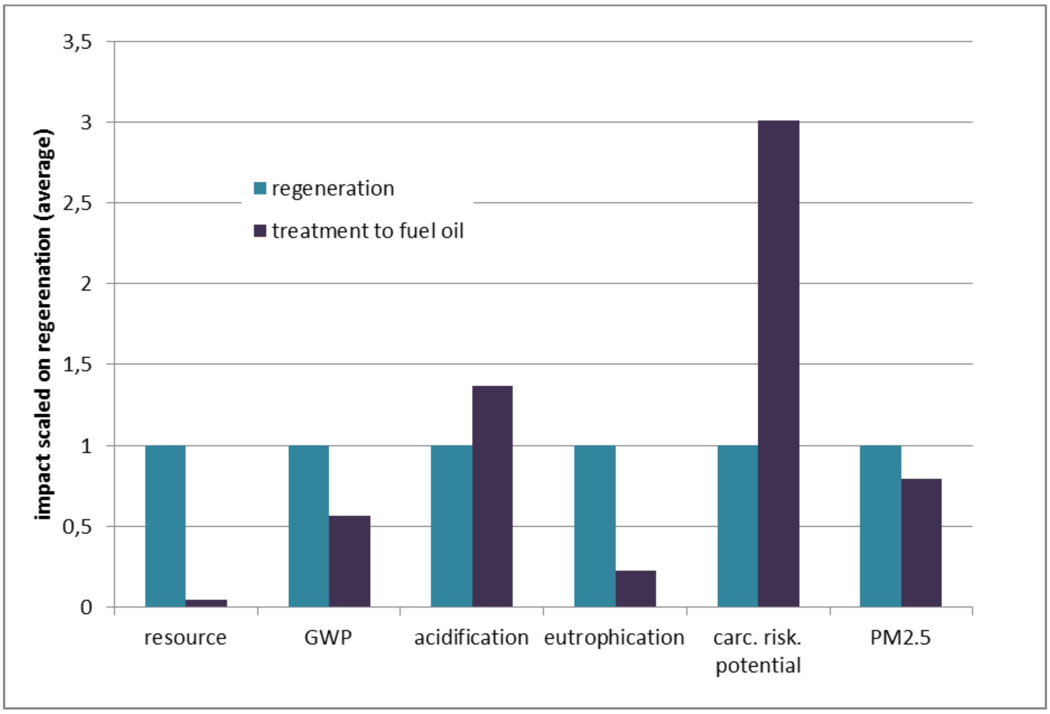


Figure 18: Comparison of regeneration (average) and treatment processes (no substituted equivalency system considered) scaled on regeneration for each impact category.

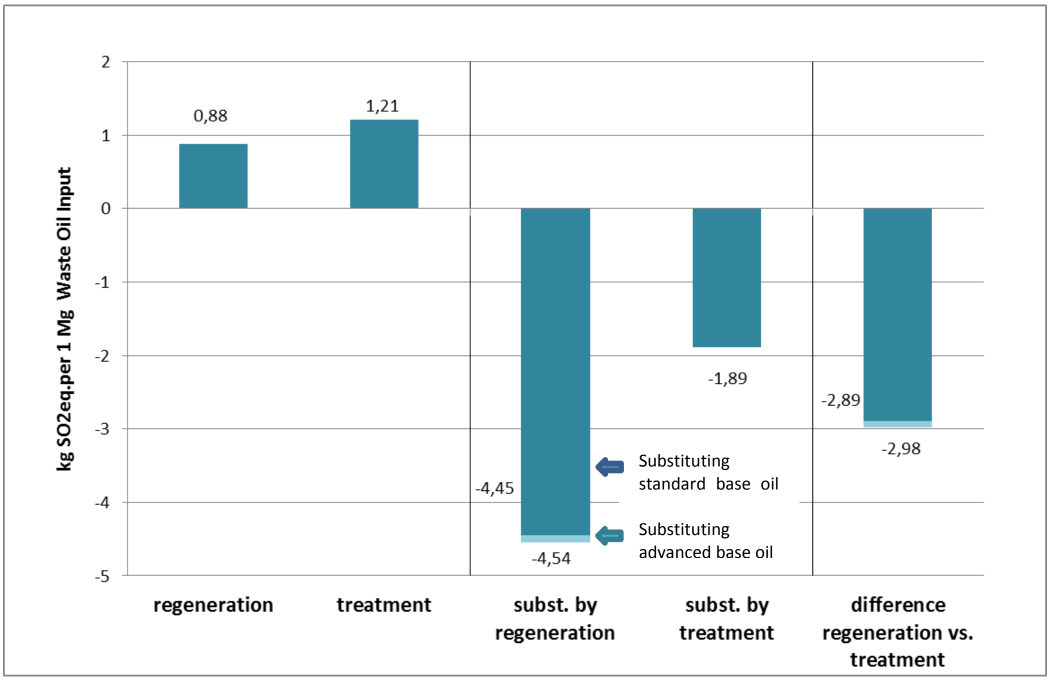


Figure 19: Acidification for regeneration, treatment and its equivalency systems and final combination of these components for the comparison of both opions.

Given the current performance of facilities processing waste oil to fuel oil would be much better; there would not be an effect on the LCA result.

7.3.4 How does the base oil quality affect the results?

Section 2.2.2 describes the applied correlation model based on the viscosity index (VI). This has been developed to bridge a gap within the continuous transition of base oil quality as described by the AP groups from I to IV. This gap refers mainly to the groups II and III, which are typical for high quality recycling base oils. The applied model does an interpolation between group I (conventional base oil) and group IV (PAO), presuming that a continuously increasing technical quality should correlated with deployed effort – in other words: caused environmental impacts. Of course this presumption means uncertainty. We cannot exclude the possibility that a group II/III primary base oil could be produced with lower environmental burden than group I virgin base oil.

As long as the environmental burden from producing high quality virgin base oil (up to group III) still exceeds the LCA performance of group I base oil, the conclusions of this study will be still valid. Given the environmental burden of such a high quality base oil should be lower than that for the production of group I, there is still a wide gap to fill before we could claim equivalency between regeneration and treatment to fuel oil.

The results for GWP given in Figure 20 (as a replication of Figure 14) show, that the gap is approx. 220 kg CO_2eq/Mg waste oil. That would allow a reduction of GWP emission from virgin base oil production from 830 kg CO_2eq (if group I, standard) down to 610 kg CO_2eq before the advantage of regeneration would be levelled out.

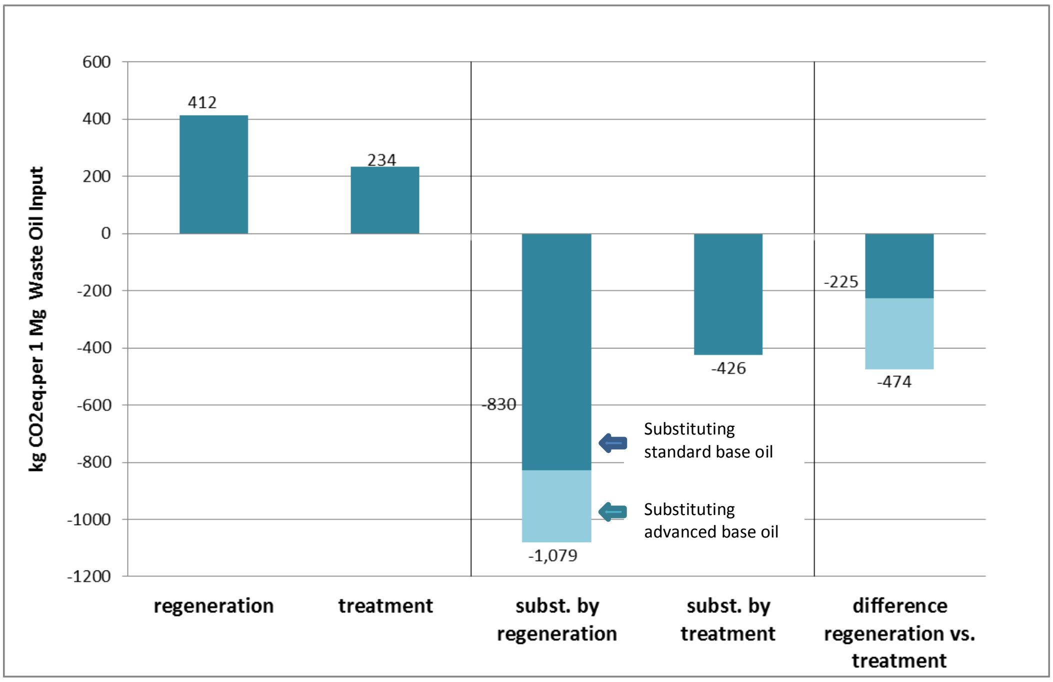


Figure 20: GWP for regeneration, treatment and its equivalency systems and final combination of these components for the comparison of both opions.

7.3.5 Summary

Considering the number of analyzed sensitive aspect, the authors deem the result and subsequent conclusions robust in the light of the goal and scope as defined in this study.

8 Conclusion

Comparing these results with the results of the study in 2005 we draw the following conclusions:

- Most importantly, the environmental advantages of regeneration of waste oil to base oil were apparent in all applied impact categories. This holds true even in the case that just base oil group I ("standard") quality is substituted. This is of particular importance since regeneration in Fehrenbach (2005) was disadvantageous in terms of the impact category global warming when compared with the reference system.
- Substitution of higher base oil groups ("advanced" e.g. group II+) leads to even better results for all applied impact categories.[1]

The most relevant reason for this difference from the study of 2005 is the change concerning alternative treatment: In the early years of last decade, a relevant share of used oil was used as fuel in cement works – and cement works predominantly use diverse types of coal as standard fuel. Substituting any type of coal consequently leads to extraordinary high credits – credits in favor of the cement work option. Therefore, earlier LCAs for used oil regeneration were always captivated by the issue of how cement works deal with fuel. A central conclusion transmitted from the former study might be formulated as follows: as long as the competing reference system is able to claim it desists from a highly climate-crucial practice like coal burning, any regeneration system – even the most efficient and most advanced – will merely excel the coal-substitution credit.

Today the cement work option is just of marginal relevance regarding the European practice of waste oil treatment. Logically the reference system has been adapted to the actually relevant one, which is treatment to fuel oil.

However there are other points of attention, in particular those referring to the update of data:

- The update of data by the regeneration companies leads to improved results with regard to some aspects, but not to others: in fact we applied data from real practice within this study and eliminated uncertainties from former assumptions based on few experiences.
  Nevertheless, the results for regeneration are positive in all respects.
- The update of refinery data also included some improvements within the system producing the substituted base oils and other mineral oil products;
  these improvements lower the positive net results for the regeneration but do not lead to real significant changes regarding the overall result.

[1] As described in section 2.2.3 the quality produced by a regeneration company is determined by a number of factors, such as: a.) the quality of the collected waste oil; b.) the applied level of technology (all techniques under study are qualified to produce high qualities; c.) the base oil market the company is serving.

In summary, the regeneration of waste oil for the recovery of base oils leads to significant resource preservation and relief from environmental burdens.

This study underlines the results of 2005 and enhances the previous conclusions, stating that an advanced regeneration technology shall be the favored way to keep waste oil as long as possible as high-graded material within the circular economy. In brief: this LCA supports the higher ranking of regeneration[1] versus treatment to fuel oil[2] according to the waste hierarchy required by EU policies.

[1] corresponding to recycling in sense of the waste directive 2008/98/EC
[2] explicitly excluded from recycling according to the waste directive 2008/98/EC, Article 3, point 17

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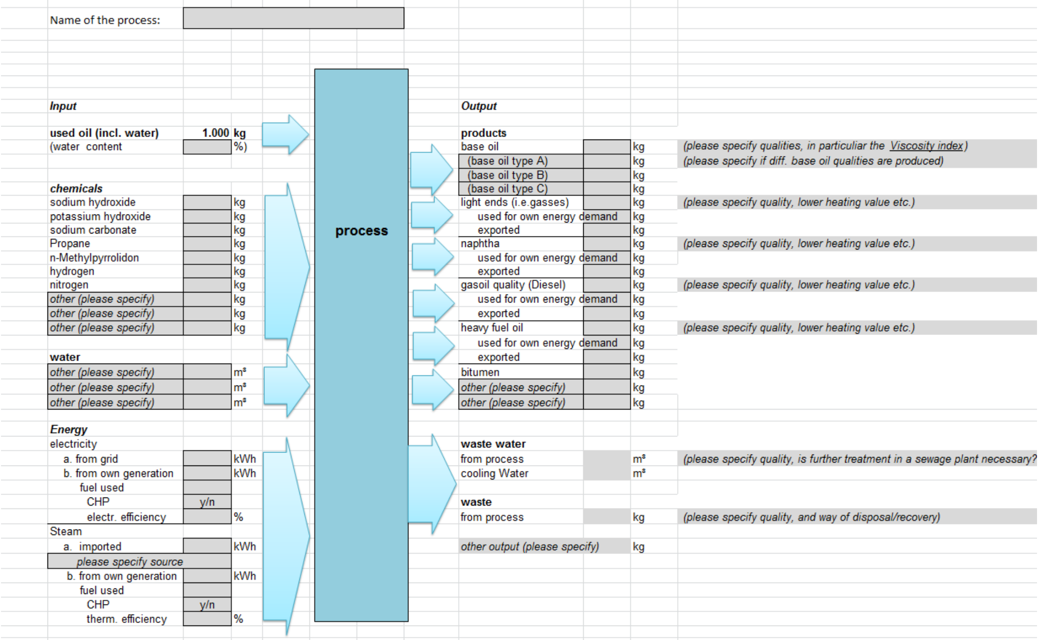
Annex I Process information spread sheet

The following figure shows the aforementioned questionnaire that the participating companies filled out. This information provided the basis for the modelling in UMBERTO.



Name of the process:

process

Input

used oil (incl. water) 1.000 kg
(water content %)

chemicals
sodium hydroxide kg
potassium hydroxide kg
sodium carbonate kg
Propane kg
n-Methylpyrrolidon kg
hydrogen kg
nitrogen kg
other (please specify) kg
other (please specify) kg
other (please specify) kg

water
other (please specify) m³
other (please specify) m³
other (please specify) m³

Energy
electricity
a. from grid kWh
b. from own generation kWh
fuel used
CHP y/n
electr. efficiency %
Steam
a. imported kWh
please specify source
b. from own generation kWh
fuel used
CHP y/n
therm. efficiency %

Output

products
base oil kg *(please specify qualities, in particular the Viscosity index)*
(base oil type A) kg *(please specify if diff. base oil qualities are produced)*
(base oil type B) kg
(base oil type C) kg
light ends (i.e.gasses) kg *(please specify quality, lower heating value etc.)*
used for own energy demand kg
exported kg
naphtha kg *(please specify quality, lower heating value etc.)*
used for own energy demand kg
exported kg
gasoil quality (Diesel) kg *(please specify quality, lower heating value etc.)*
used for own energy demand kg
exported kg
heavy fuel oil kg *(please specify quality, lower heating value etc.)*
used for own energy demand kg
exported kg
bitumen kg
other (please specify) kg
other (please specify) kg

waste water
from process m³ *(please specify quality, is further treatment in a sewage plant necessary?*
cooling Water m³

waste
from process kg *(please specify quality, and way of disposal/recovery)*

other output (please specify) kg

Figure 21 Questionnaire for the participating companies