INSTITUT FÜR ENERGIE- UND UMWELTFORSCHUNG HEIDELBERG

Updated LCA for regeneration of waste oil to base oil – Final Report

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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.
- “Standard base oil”, “category I base oil”, “conventional base oil” or “base stock” refer to base oil qualities of group I according to the API classification. They represent a mineral-oil based lubricant without any synthetic compounds and thus have a lower level of saturates (< 90 %), a higher sulfur content and a lower viscosity index (100), compared to base oil categories II - IV (for reference, see API base oil classification: https://olezol.com/api-base-oil-classifications)
- “Advanced base oil”, “base oil advanced”, “category II+ base oil” etc. refer to base oil qualities of group II+ within this study. This group consists of 70 % conventional base oil and 30 % synthetics. The latter is assumed to be polyalphaolefin (PAO). The advanced base oil of category II+ in this study is assumed to have a viscosity index of 115 (for reference, see: https://olezol.com/api-base-oil-classifications)
- Averaging within this study does not consider production capacity of the six different plants under investigation. The average of the results for the regeneration product system(s) thus does not represent a weighted average, but the arithmetic mean of all six plants.
- Representativenes: The six plants under investigation within this study comprise a total capacity of about 570.000 tons per year or about 50 % of total waste oil treated by regeneration in Europe (1,100,000 tons per year).

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
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 basis

The European Waste Framework Directive (2008/98/EC), amended by the Directive (EU) 2018/851, 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

In order to reflect on ongoing technological advances on the one hand as well as to incorporate the most current data regarding the background datasets, this study constitutes an update to the last assessment, carried out by the authors in 2018 [Abdalla & Fehrenbach (2018)]. In addition, the scope of the assessment in this study was expanded to involve a larger sample size of rerefining technologies / plants by the participating GEIR companies. Hence, this study comprises six different companies operating six distinct re-refining plants, covering a larger proportion of the European waste oil market.

In consistency with the latest version of the authors assessment, the choice of a reference scenario for the treatment of waste oil was determined considering available market data, resulting in the choice of the treatment to fuel oil as most relevant alternative case. Here, too, recent process developments were taken into account and modelled, accordingly.

Objective of this study

It is the objective of this study to provide an update of the outdated reference 2018 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 a discussion on European level and a robust base of knowledge to assist decision making.

The herewith updated reference studies (Fehrenbach 2005, Abdalla & Fehrenbach 2018) can be downloaded from here:

https://www.ifeu.de/wp-content/uploads/GEIR-final-report-LCA-21-04-05.pdf

https://www.ifeu.de/fileadmin/uploads/GEIR-final-report-LCA-21-04-05.pdf

https://www.ifeu.de/fileadmin/uploads/ifeu-GEIR-LCA-regeneration-waste-oil_final-version-2018corr.pdf

https://www.ifeu.de/projekt/oekobilanz-zur-zweitraffination-von-altoelen-zu-basisoelen/?sword_list%5B0%5D=GEIR

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 studies from 2005 and 2018 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 years. Table 1 shows the main aspects of this development.

Aspect	Fehrenbach (2005)	Abdalla & Fehrenbach (2018)	This study (2021)
Participating Companies / number of techniques under study	5	4	6
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	 - exclusively primary data collected from plant operators was utilized; data refer to the period of 2018 and 2019[2], representing a two-year average - upstream data was expanded to include the latest developments concerning crude oil / natural gas production
Characterization factors - GWP 100 - Particulate matter	 - 2nd Assessment Report (IPCC 1996) - PM10	 - 5th Assessment Report (IPCC 2013) - PM2.5	 - 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	1,100,000 Mg
Reference system	Cement works (energetic recovery and coal substitution)	Treatment to fuel oil	Treatment to fuel oil

[1] Process data was gathered in 2017 and refer to the annual mean in 2016.
[2] One plant was not operational in this time frame and thus collected data for the time frame of 2021 and 2022

Table 1: Overview of the changes with respect to Fehrenbach (2005) and Abdalla & Fehrenbach (2018)

2.1 Goal of the study

Goal definition maintained

The goal of this study is to provide an updated view on the ecological and energetic aspects of the different treatment options of waste oil in an anonymous manner, with a focus on the rerefining of waste oil to base oil of various qualities as well as the treatment of waste oil to processed fuel oil (PFO). The conclusions of the studies by Fehrenbach (2005) and Abdalla & Fehrenbach (2018) represent more or less the situation of the last decades and constitute a starting position, as some major aspects have changed. However, methodical aspects remain constant for the most part. Similar to Fehrenbach (2005) and Abdalla & Fehrenbach (2018), information regarding the regeneration processes has been derived from common practice and process conditions of six leading companies operating in Europe. Thus, the scope has been expanded, compared to previous studies by the authors. The six companies comprise about 50 % of the waste oil actually treated by regeneration in Europe in 2019 and represent mainly the modern state of the art plants.

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 years.
- Modelling and comparing the represented techniques of regeneration taking their environmental impact and benefits due to the substitution of primary products into account.
- Comparing the average result of the regeneration techniques considered with the reference case: the most significant alternative treatment of waste oil in Europe.
- Transparent disclosure and discussion of key parameters.

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:

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

Definition of the reference system

Waste oil management has changed in Europe

The previous studies carried out by the authors considered – in principle – two alternatives to the rerefining of waste oil to base oil: a) waste oil combustion in a cement kiln as a substitution of standard fossil fuels and b) the treatment of waste oil to (processed) fuel oil. An analysis of the current situation of waste oil management in Europe shows that the first type of recovery has lost its relevance. In 2018, only about 4 % of the total collected waste oil is used in the cement industry in Europe (GEIR (2021)). This confirms the rather subordinate role of this option as outlined in Abdalla & Fehrenbach (2018). According to ascertainments by GEIR (2021), utilization of waste oil in Europe is dominated by regeneration to base oil: roughly 50 % directly within the countries of collection and an additional 12 % after exporting for regeneration to some other European countries. In other words: more than half of the collected waste oil is subject to regeneration. In total, this amounts to about 1,100,000 Mg per year (GEIR (2022)). The second most important pathway is treatment to fuel, which accounted for 24 % of the total collected waste oil. In other words: two-thirds 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 neglected within this study.

Reference system updated

Following the above, treatment to fuel oil remains the most significant alternative to rerefining waste oil. Accordingly, this option represents the chosen reference system for the evaluation within this study (further details see chapter 6).

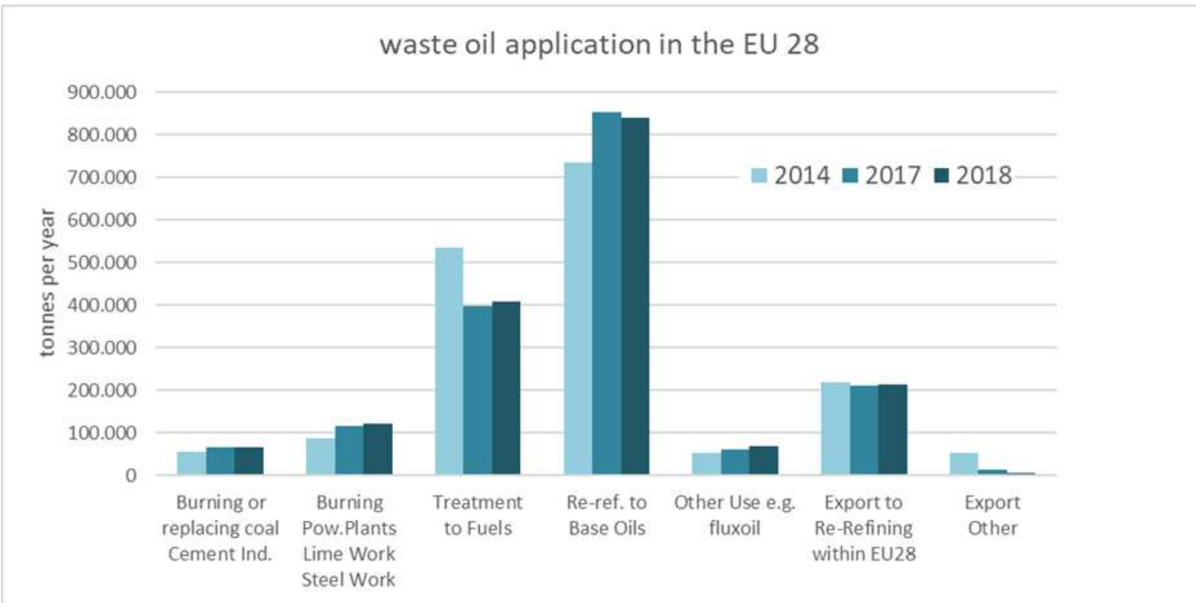

Figure 1: Share of different waste oil treatment options in the EU28. Development over time (Source: GEIR 2021)

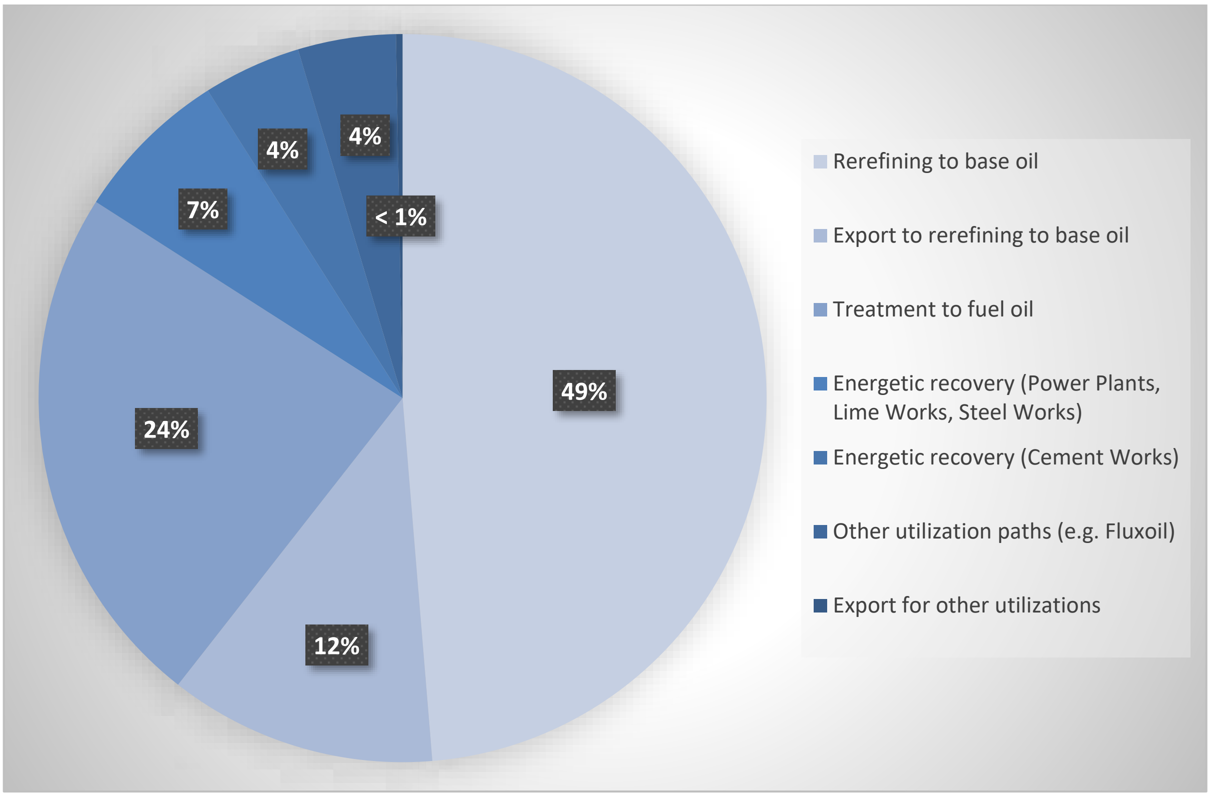

Figure 2: Relative market shares of waste oil treatment in the EU28, 2018 (GEIR (2021))

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

Approach by previous studies

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. Ideally, one would mirror each regenerated base oil quality directly by the LCA data for the equivalent virgin base oil group. Unfortunately, the available databases do not cover these groups with 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 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 for the base oil quality to define the equivalent virgin base oil by interpolation of groups I (standard base) and IV (PAO, fully synthetic). As shown in Figure 3 , the approach provides explicit data for any quality of base oil. 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, the approach was verified by a sensitivity analysis in the previous studies and will be discussed in chapter 7.3.

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

1. Standard quality / “base oil standard” (representing group I base oils with a viscosity index of 100),
2. Advanced quality / “base oil advanced” (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 3).

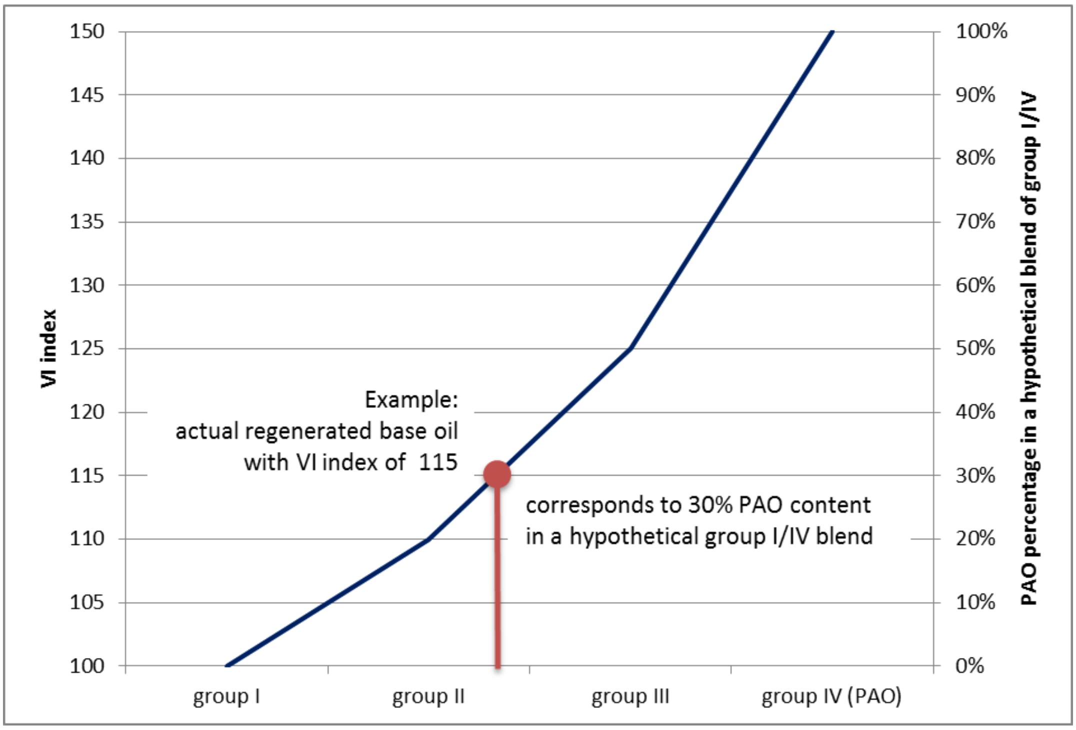

Figure 3: Correlation model based on viscosity index (VI) by actual recycled base oil as a numerical indication for the definition of replaced virgin base oil hypothetically blended from group I and group IV base oil.

Additional factors influencing the actual quality of the base oil product produced by regeneration

The final quality of recycled base oil produced by an advanced regeneration technique 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 influenced by the regeneration company, it is bound to available qualities within the collecting area.
2. The applied level of technology (see also section 5);
   all techniques under study are qualified to produce high qualities. Four of them are based

on hydrogenation technology, typically favoring an upgrade of the waste oil feedstock; two techniques apply 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 prefer to serve the established market regardless of technical potentials.

The six techniques under assessment have to operate under 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 carries the potential to meet the criteria to produce the "advanced quality" of base oil as defined above. In any case, we consider the application of the "standard quality" adequate to hedge the theoretical worst case.

Further basic settings

Reference volume and functional unit

According to GEIR (2022) the total amount waste oil treated by regeneration was about **1,100,000 Mg per year**[1] - slightly higher than the quantity of 950,000 Mg per year applied by the study in 2018. The six plants under investigation in this study comprise a total treatment capacity of about 570.000 Mg per year. Results of both systems, the average of the six regeneration plants, depicting a typical regeneration operation, on the one hand and the reference system on the other, will be scaled to the total amount available for regeneration (e.g. the 1,100,000 Mg) in chapter 7.2.2 in order to map, what the consequences of treating the total amount would be.

In consistency with the previous studies, the treatment of 1 Mg of collected waste oil was chosen as the functional unit for the calculation of inventory and impacts. This constitutes the reference flow of this study, meaning that all results are expressed per Mg of collected waste oil. For the purpose of normalization, the results will be scaled to the total available quantity treated by regeneration of 1,100,000 Mg, as outlined above.

System boundary

Apart from the items discussed above, the system boundary still corresponds to the settings of the previous studies, such as:

- Including transport from the waste producer to the regeneration plant.[2]
- Including all external processes due to waste oil treatment (e.g. fuel production or electrical power supply, crude oil drilling and production, digging and mining, provision of process materials including upstream processes,..). Also, downstream processes like waste disposal are included.
- The analysis of a regeneration / treatment option ends when a specified product enters the economic cycle. The quality specification – in this case, the quality (expressed in terms of VI) of the regenerated base oil (see Figure 3) – has to be recognized because the

[1] According to GEIR (2022), the total installed capacity of regeneration plants amounts to 1.5 Mio. Mg per year.

[2] Waste disposal in nearly all cases requires a form of transport. In order to correspond to Fehrenbach (2005) and Abdalla & Fehrenbach (2018), 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 distances is not a highly sensitive parameter. Eutrophication 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 eutrophication by 11 %."*.

production of an equivalent product has to be analysed under consideration of all elements in its primary production chain (defined as equivalence system).

- By-products of the regeneration process – e.g. gasoil, bitumen or other products – are considered. The benefit of these by-products is also considered within the system of substituted primary products as well as within the reference system.
- The geographical boundary is limited to Europe in terms of provenance 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 in the years 2018 and 2019. The data concerning production and delivery of energy and raw materials are as up to date as available. This includes especially the revised crude oil and natural gas production upstream processes, where venting and flaring are adequately covered.
- 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 do not exceed 1 % of mass of the reference flow (e.g. waste oil in the regeneration plant) is not 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 5.6) has been chosen as LCA modelling software[1]
- The definition of the system boundary as described in Figure 4 and Figure 5 is still valid.

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

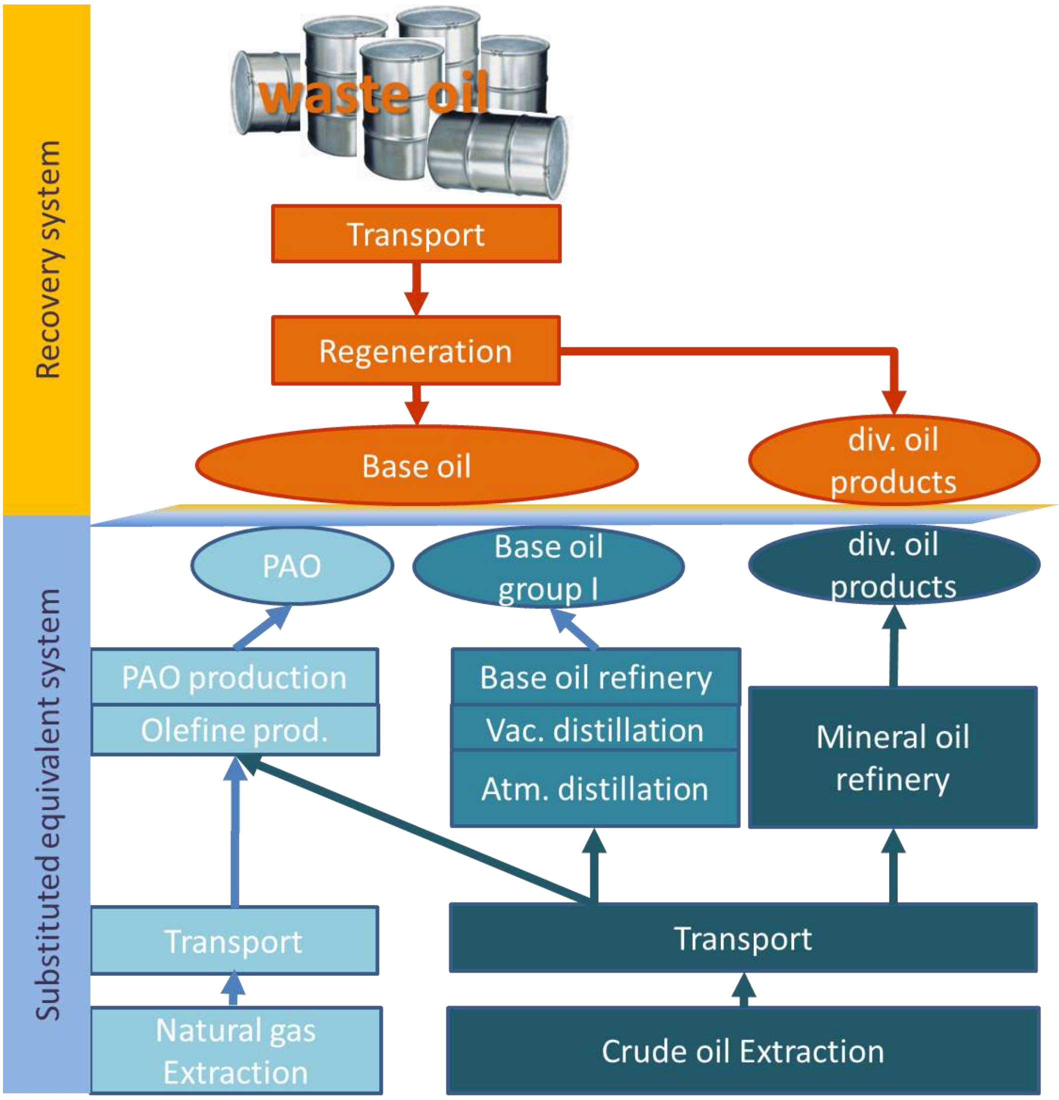

Figure 4: Simplified scheme of the system boundary for **regeneration** and its substituted equivalence system

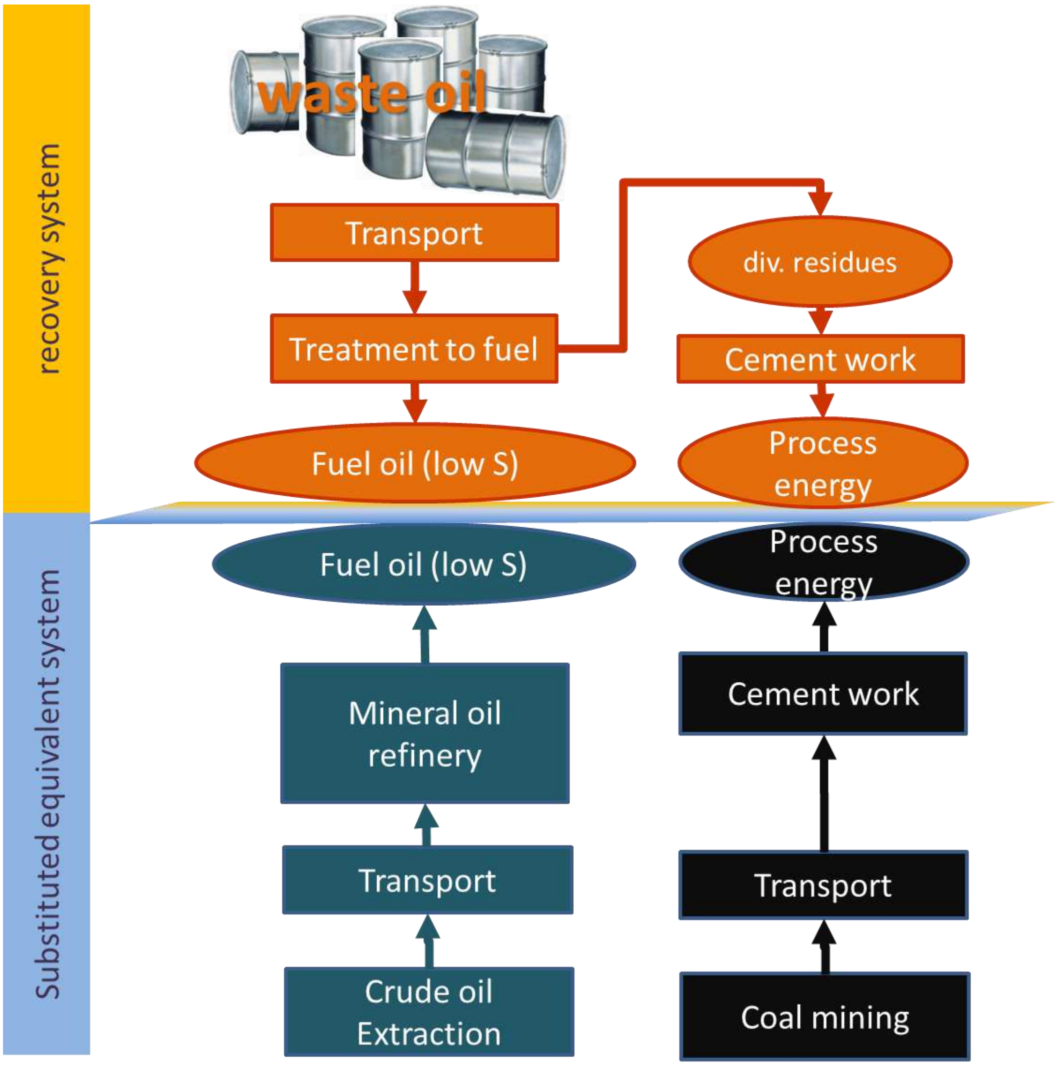

Figure 5: Simplified scheme of the system boundary for the **reference system** and its substituted equivalence system

3 Methodology and approach

3.1 Framework and working steps

Basics

The methodical principles and approaches applied by the former studies 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.

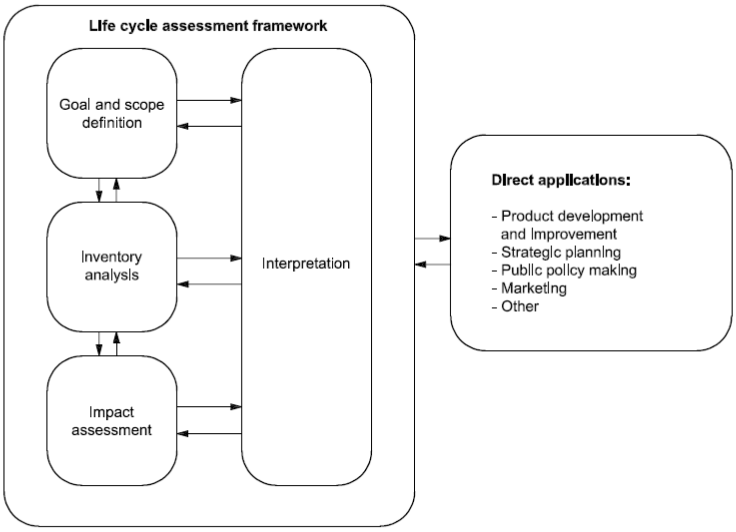

Figure 6: Phases of a life cycle assessment (LCA), according to ISO 14040:2006

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 treatment of waste oil to fuel oil
4. Calculating inventories and impact assessment
5. Discussion and interpretation of the results and comparison with the results obtained from the study 2018

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) and Abdalla & Fehrenbach (2018) have confirmed this finding with respect to the treatment of waste oil, in particular.

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. Compared to the latest study (Abdalla & Fehrenbach (2018)), no significant changes in the lubricant market are assumed.

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:

- In order to reflect on the changes in our energy sector from a fossil-based to a renewable future, the indicator for the consumption of energy / energy demand has been adapted: Whereas Abdalla & Fehrenbach (2018) focused on fossil primary energy sources, expressed as the *cumulative energy demand, fossil* (CED_{fossil}), the general cumulative energy demand without any restriction to fossil energy only was chosen.
- Carcinogenic risk potential: Against the background of a) particulate matter formation as a more robust indicator for human toxicity and b) the relative high uncertainties / inconsistencies in datasets related to the impact category carcinogenic risk potential, the authors decided to not consider this impact category within this study. The potential risks to human health are depicted with particulate matter formation.

To ensure a maximum in continuity to the previous study, the authors decided to investigate otherwise the same impact categories as Abdalla & Fehrenbach (2018). 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 (CED)	Coal	29.81 [a)]	MJ / kg	
	Lignite	8.30 [a)]	MJ / kg	
	Renewables	1 [b)]	MJ / MJ	
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	
Eutrophication,	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)
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

b) CED of renewables is set to 1 MJ/MJ per definition. This is due to the fact that compared to other energy carriers, there is no primary energy factor to attribute to

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 PEV represents the average per-capita load of one inhabitant (e.g. 12 Mg CO_2-eq. per year). If the burden of one recycling option or the difference between two options, respectively, 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.

While normalization will be conducted within this study, the authors refrain from the option of grouping.

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

a) AGEB AG Energiebilanzen e.V.: Energieverbrauch in Deutschland im Jahr 2008; http://www.ag-energiebilanzen.de/viewpage.php?idpage=118
b) Umweltbundesamt - Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen (THG) 1990-2007 (Endstand 12.11.2008). Dessau, November 2008
c) Umweltbundesamt - Nationale Trendtabellen für die deutsche Berichterstattung atmosphärischer Emissionen 1990-2007 (Endstand 20.02.2009). Dessau, Februar 2009

Table 3: Total per-capita emission and consumption in the Federal Republic of Germany

[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

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 2021, constituting the core data source of this study. The collected gate-to-gate data represent the twenty-four-month average of the years 2018 and 2019 for each of the six regeneration processes under study, except for one plant, which was not operational in this time frame. Here, data collection comprised the time frame 2021/2022. 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 previous studies. We are well-aware of the fact 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 proven the correctness of the data in detail.

Upstream and downstream processes

Data regarding auxiliary processes, e.g. provision of electricity, use of catalysts, transports, water supply, sewage treatment etc. were either taken from the ecoinvent database (ecoinvent 2020), or were generated by ifeu. 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	ecoinvent 3.7.1 (ecoinvent 2020)	
potassium hydroxide	ecoinvent 3.7.1 (ecoinvent 2020)	
sodium carbonate	ecoinvent 3.7.1 (ecoinvent 2020)	
propane	ecoinvent 3.7.1 (ecoinvent 2020)	
hydrogen	ecoinvent 3.7.1 (ecoinvent 2020)	
nitrogen	ecoinvent 3.7.1 (ecoinvent 2020)	
sulphuric acid	ecoinvent 3.7.1 (ecoinvent 2020)	
Fuller's Earth[1]	ecoinvent 3.7.1 (ecoinvent 2020)	
compressed air	ecoinvent 3.7.1 (ecoinvent 2020)	
catalyst	ecoinvent 3.7.1 (ecoinvent 2020)	
Energy		
electricity	ifeu grid model, ecoinvent 3.7.1 (ecoinvent 2020)	country-specific average
natural gas	ecoinvent 3.7.1 (ecoinvent 2020), ESU data (Meili et al. 2021)	EU average mix
Transport	TREMOD (Knörr et al.)	Truck, 200 km
Sewage treatment	ifeu database	European standards
mineral oil products base oil, naphtha, fuel oil, bitumen	ifeu refinery model, ESU data (Meili et al. 2021)	European standards

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

Reference system

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

Discussion of data quality

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

Accordingly, 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 databases, such as ecoinvent.
- The data quality of the mineral oil refinery is based on long-term expertise in modelling particiliarly these processes.[2]

[1] Fuller's Earth: A clay-like substance that's mostly composed aluminum magnesium silicate.
[2] The ifeu refinery model constitutes the basis of mineral oil products represented in the ecoinvent database (as of version 3.7).

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, an indicator score of 5 has to be attributed due to the fact that initial data collection has been carried out more than 20 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 (2000) 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 do not 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.

Whereas Abdalla & Fehrenbach (2018) found significant changes compared to the previous iteration of this study (Fehrenbach 2005), there have not been significant changes as regards to neither the waste oil collection schemes, nor the virgin base oil composition. Therefore, this study assumes the same waste oil characteristics as outlined in Abdalla & Fehrenbach (2018). These were calculated based on data 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.

Table 6 presents a comparison of a typical waste oil composition in 1997 and 2017, respectively. Following a trend towards a higher share of synthetic compounds, lower amounts 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 as a function of a higher share of 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/m³	860 - 950	850 - 930
Viscosity @ 40 ° C	mm²/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 participating companies in 2017.

5 Description of the considered regeneration techniques

The considered six techniques cover the whole range of base oil quality as described in section 2. Together, the six mentioned plants treat about 50 x % of all regenerated waste oil in the EU.

All below mentioned capacities refer to waste oil input.

5.1 Avista

Nameplate (input) capacity: 135.000 t/a

AVISTA started rerefining in Dollbergen in 1951. The technology applied is based majorly on own knowledge and partly patented (Vaxon distillation, solvent extraction). In addition, AVISTA operates a nationwide collection to secure feedstock supply and feedstock quality control. The same technology is installed at AVISTA plants in Denmark (Kalundborg) and USA (Peachtree City, GA). The process as such can be summarized as follows:

- Quality control of incoming used oil. Stepwise rerefining technology which includes:
- Pre-filtration
- Atmospheric distillation – separation of water and light ends
- Vacuum distillation – separation of gas oil fraction
- Thin film evaporation under vacuum (2-5 mbar) using wiped film or Vaxon technology – separation of wide cut base oil fraction
- Refining of the base oil fraction by solvent extraction (Enhanced Solvent Extraction technology)

The solvent extraction (patented) was developed especially for the application on wide cut base oil fractions from used oil. Main goals were efficient separation of aromatic (polyaromatic) and heteroatomic compounds by simultaneously retaining all synthetic (Group II/IV) base oil material present in the used oils. This results in comparatively high VI, high oxidation stability, low aromatics (polyaromatics) and low evaporation loss of the base oils produced. Depending on the market and therefore the used oil composition Group I, II and III base oils are achievable.

5.2 LPC

Nameplate (input) capacity: 43,000 t/a

In the re-refinery of LPC SA (formerly CYCLON HELLAS SA), located close to Athens Greece, 43,000 t/year of waste lube oil are re-refined to produce high-quality base lube oils of API Group I, having relatively high viscosity index and low sulphur content. The applied re-refining technology is the KTI (Kinetic Technology International) process combined with the IFP (Institut Francais du Petrole) propane extraction process.

Re-refining process includes flash dewatering, gas oil stripping, vacuum distillation with thin film evaporator and selective propane extraction. The yield of lube oil recovery contained in waste oil is about 73%. The core of Base Oil production is the catalytic hydro-treatment at 50 barg and 300-320°C on $Ni/Mo/Al_2O_3$ catalyst. The purpose of catalytic hydro-treatment is

1. desulphurisation (average 500 ppm),
2. denitrification,
3. demetallization,
4. dechlorination,
5. removal of other heteroatoms,
6. reduction of unsaturated fraction (reduction of carcinogenic poly-aromatic compounds below 1%),
7. improvement of oxidation stability,
8. improvement of VI (average 115).

5.3 Hylube process by PURAGLOBE

Nameplate (input) capacity: 150,000 t/a

Puraglobe operations in in Elsteraue/Zeitz started in 2004.

Significant characteristics & process steps

HyLube® process differs from typical process steps used by conventional re-refining processes, as its process operates continuously (no batch-wise production) HyLube® and HyLubeSAT® processes generate high performance API Group II+ to III base oils suitable for application in e.g., industrial, metal working, coating, motor oil. Both, the base oils and the by-products (e.g. naphtha and diesel) are desulfurized. The following process steps can be distinguished:

- Mixer Unit Intimate mixing of hot hydrogen gas with the feed at 370°C and 70 bar pressure.
- Feed Flash Separator: Hydrocarbons (approx. up to C40) including high value lubricating oil molecules are transformed into gaseous state and separated from heavy asphaltic components (bottom). The gaseous hydrocarbon material is routed to the catalyst section.
- Catalyst section: Catalytical hydrotreating & selective hydrogenation: A special developed composition of different types of catalysts are used to maintain qualities / mostly regarding saturation and desulphurization of all base oil fractions and the light by-products. The purified liquid lube boiling range fractions are passed through different further process steps and are routed to the 45 meters high vacuum column. Here, the purified hydrocarbon mixture is separated into naphtha, diesel and various grades of straight cut base oils of API Group III quality (HyLubeSAT®).

5.4 Itelyum

Nameplate (input) capacity: 120,000 t/a

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

The applied process consists of 3 phases:

1. Pretreatment: preflash, sedimentation and centrifugation in order to separate solids, biocompounds, water and light hydrocarbons;
2. 2) Vacuum distillation (thermodeasphaltation) in oprder to fractionating dehydtared used oil in gasoil, base lube cuts, bitumen;
3. 3) Hydrofinishing through heterogeneous catalytic reaction at high pressure hydrogen achieving high performance base lube Group II+ and Group III.

5.5 Tecoil STR

Nameplate (input) capacity: 70,000 t/a

Tecoil (STR Tecoil Oy) is an oil re-refining company located in Hamina, Finland. Tecoil transforms used lubricant oils with refining and hydroprocessing technologies into API Group II/II+ base oils. Annually, 70,000 tons of used lubricants can be processed into 50,000 tons of base oils using the plant's hydro-treating technology. As by-products, the refinery produces low and high sulphur gas oils and bitumen flux utilized in the bitumen/asphalt, marine oil and power generation industries.
The company utilizes the CEP (Chemical Engineering Partners) process, which comprises the following steps:

1. Pretreatment;
2. Extraction of water and light fraction;
3. Extraction of the fuel oil fraction;
4. Separation of the lubricant by distillation;
5. Conversion of the lubricant distillate into base oil by hydrotreatment;

5.6 Tayraş

Nameplate (input) capacity: 60,000 t/a

Tayras headquarter is based in Istanbul and the refinery is located in Osmaneli, Turkey. . In addition to plant operation of the used lubricating oil refinery, collection activities and analysis of samples in an accredited laboratory comprise the company's activities. The processing capacity is 60,000 tons of used lubricating oil per year, from which Tayras produces 45,000 tons of Group II+ base oil. The process comprises a 4-Stage evaporator distillation:

1 Dehydration
2 Low vacuum evaporation section
3 High vacuum evaporation
4 Oil- water separation, followed by hydro-treatment with up to 125 bar and by fractionation to produce the base oils of API Group II+.

6 Description of the substituted and other processes involved

The processes substituted by regeneration of waste oil are:

Overview of considered process (chains)

- The complex primary production chain from crude mineral oil via waxy distillates to base oil group I (see also Figure 7) 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 alternative 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 defined 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 2018 updated

All refinery products mentioned above had already been modelled by the studies in 2005 and 2018. Within the scope of this study, the authors have incorporated an updated version of the underlying refinery model, taking into account the developments at European and global level according to the BREF (Barthe et al. 2015). Moreover, recent developments in crude oil and natural gas extraction, production and transport with emphasis on emissions related to venting and flaring were considered (Meili ((2021)). This data constitutes the basis

[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.

for further refining processes within the ifeu refinery model. The Umberto refinery model is shown in Figure 7. Data sets for following products are calculated based on this model:

- base oil group I
- naphtha
- light fuel oil
- heavy fuel oil
- bitumen
- low-sulphur diesel
- refinery gas / light ends
- vacuum gas oil

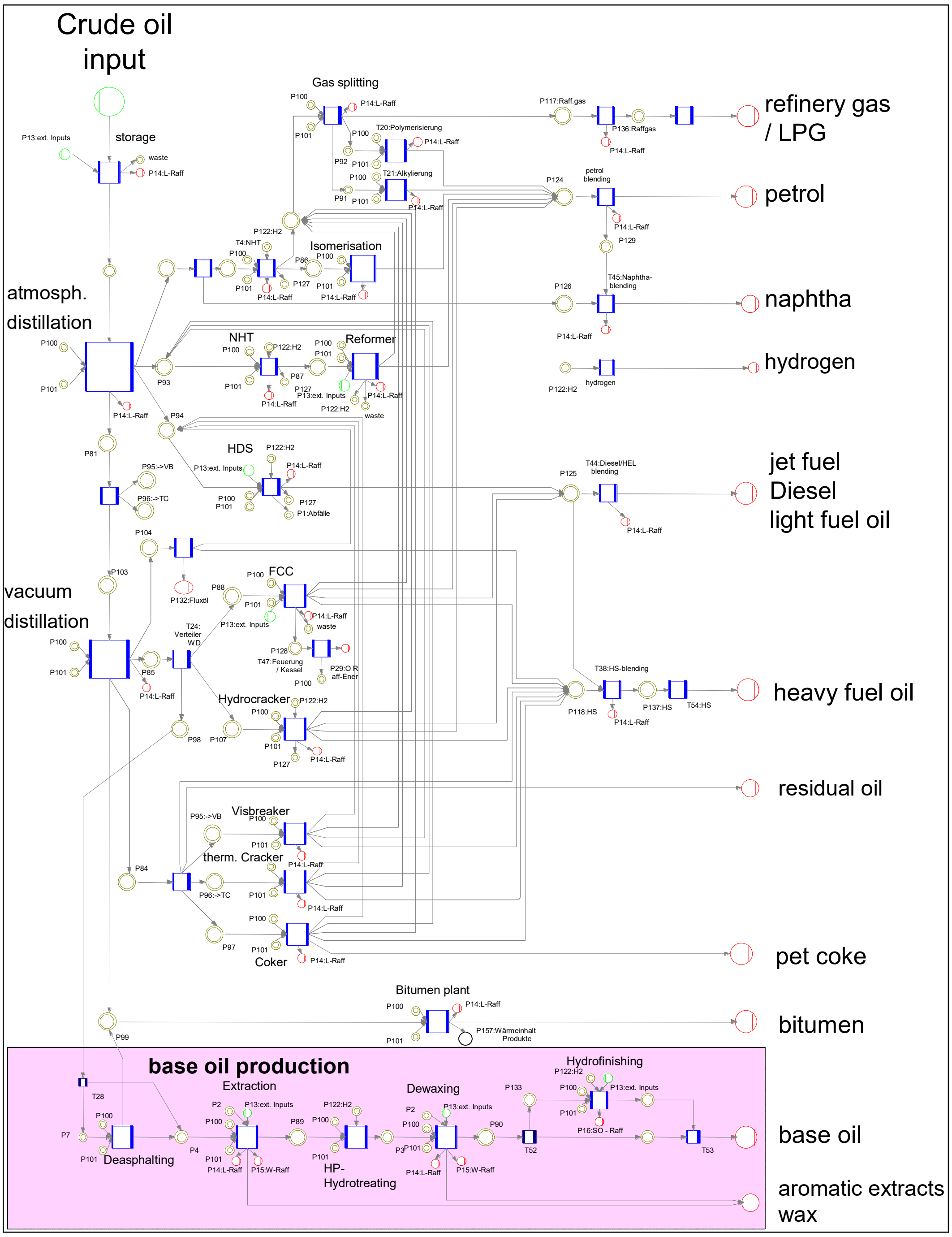

Figure 7: Network model for the calculation of mass and energy flow of a virtual mineral oil refinery

6.2 Treatment to fuel oil (reference system)

Three-stage treatment process

Waste oil to fuel oil

Unlike the other processes, the technique to process waste oil to fuel oil was modelled completely anew within Abdalla & Fehrenbach (2018). The authors refer to a data set applied by Kolshorn et al. (2000) as a basis. This data was reviewed by the authors and supplemented by separately collected data, depicting a more up-to-date status-quo. However, the process remains – in principle – the same: The treatment to fuel oil option follows a three-stage process. After collection and transport, the waste oil is heated and chemically treated. Water, process chemicals (an 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 thermally 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 approx. 870 kg of various products per Mg waste oil.

Substituted fuel oil

System substituted by the reference system

Section 6.1 describes the refinery model used for the calculation of data sets for all types of mineral oil products. This includes the products replaced by recycled fuel oil products 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 as well as other finishing / treatment steps.

The selection of gas oil as a reference product 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, such as oil sludge and press cake (These mass flows are energetically recovered in a cement kiln, substituting coal as regular fuel).

[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 six regeneration plants assessed (section 7.1). The goal is to identify differences. In a second step, the average result of the six options will be compared to an alternative treatment to processed fuel oil (section 7.2). The average of the results of the six 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 technology-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 six 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 7 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 454 kg of CO_2-equivalents per Mg waste oil treated, including combustion of by-products, natural gas for heat and steam, production of electricity, hydrogen and other auxiliaries.
2. The benefit of technique 1 (substitution of primary produced base oil and other by products) leads to a prevention of 1,274 kg of CO_2-equivalents per Mg waste oil, assumed, the quality of the base oil substituted corresponds with group I in terms of VI (Viscosity Index). In assumption of the quality equals the advanced case (VI ≙ group I/IV), the saved GHG emission extends to 1,568 kg CO_2-equivalents.
3. To get the “net impact (net balance)” of the technique 1 of regeneration, the omitted burden (1,274 or 1,568 kg CO_2-equivalents) is to be subtracted from the burden created (454 kg CO_2-equivalents) via rerefining. Hence, technique 1 leads to an avoided burden (in terms of global warming) in the range of 820 to 1,114 kg CO_2-equivalents per Mg waste oil.

Reference: 1 Mg used oil	Regeneration Technique 1	2	3	4	5	6	Average
Resource depletion (GJ)							
Regeneration	7,69	3,46	11,06	8,97	8,54	4,91	7,44
Substituted processes							
base oil standard (VI ≙ group I)	52	53	44	55	52	54	52
base oil advanced (VI ≙ group I/IV)	56	57	49	60	57	59	56
Global warming (kg CO_2-Eq.)							
Regeneration	454	216	779	599	421	304	462
Substituted processes							
base oil standard (VI ≙ group I)	1274	1281	1162	1399	1296	1383	1299
base oil advanced (VI ≙ group I/IV)	1568	1562	1480	1742	1608	1729	1614
Acidification (kg SO_2-Eq.)							
Regeneration	1,06	0,39	1,52	1,36	1,03	0,76	1,02
Substituted processes							
base oil standard (VI ≙ group I)	10,1	10,1	9,2	11,1	10,3	11,0	10,3
base oil advanced (VI ≙ group I/IV)	10,0	10,0	9,1	10,9	10,2	10,8	10,2
Eutrophication, terr. (kg PO_4^{3-}-Eq.)							
Regeneration	0,07	0,03	0,10	0,07	0,07	0,05	0,07
Substituted processes							
base oil standard (VI ≙ group I)	0,29	0,29	0,26	0,32	0,29	0,31	0,29
base oil advanced (VI ≙ group I/IV)	0,32	0,32	0,29	0,35	0,33	0,35	0,33
Fine particulates (kg PM2.5-Eq.)							
Regeneration	0,82	0,33	1,14	1,11	0,85	0,90	0,86
Substituted processes							
base oil standard (VI ≙ group I)	6,83	6,85	6,21	7,47	6,96	7,40	6,95
base oil advanced (VI ≙ group I/IV)	6,84	6,86	6,22	7,48	6,97	7,42	6,97

Table 7: Results of impact assessment for the six technical options according to burdens by regeneration system and equivalency system

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

- The left bar: the impact by the regeneration system (min, max, average); corresponds to the upper part of the system flow chart given in Figure 4.
- 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 4.
- 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.

Resource depletion

Figure 8 shows the result for resource depletion represented by the cumulated 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.

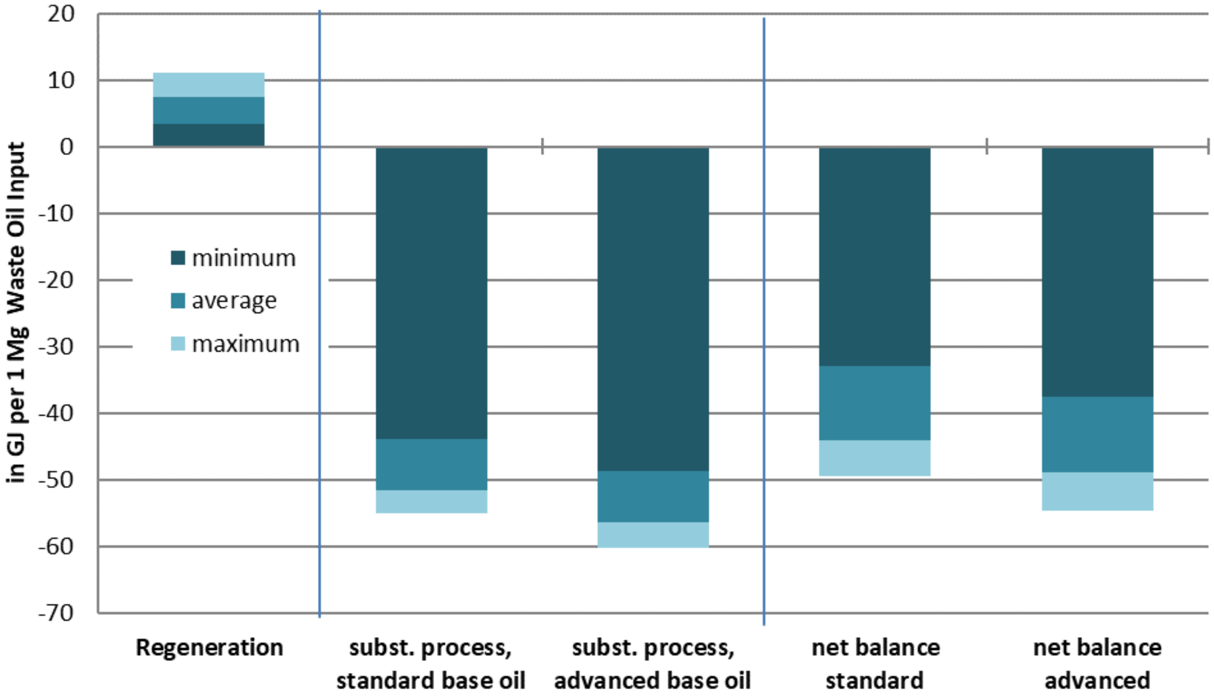

Figure 8: Impact assessment results for resource depletion; showing the average result of the six techniques as well as the individual minimum and maximum.

Global Warming Potential

Figure 9 shows the global warming balance. 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 two-thirds of the average impact of the substituted equivalency processes. However, the range between the techniques is substantial here, but even the minimum case still shows a clear advantage against the equivalency processes. Compared to previous studies, the effects of updated upstream crude oil and natural gas production are reflected in the results.

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.

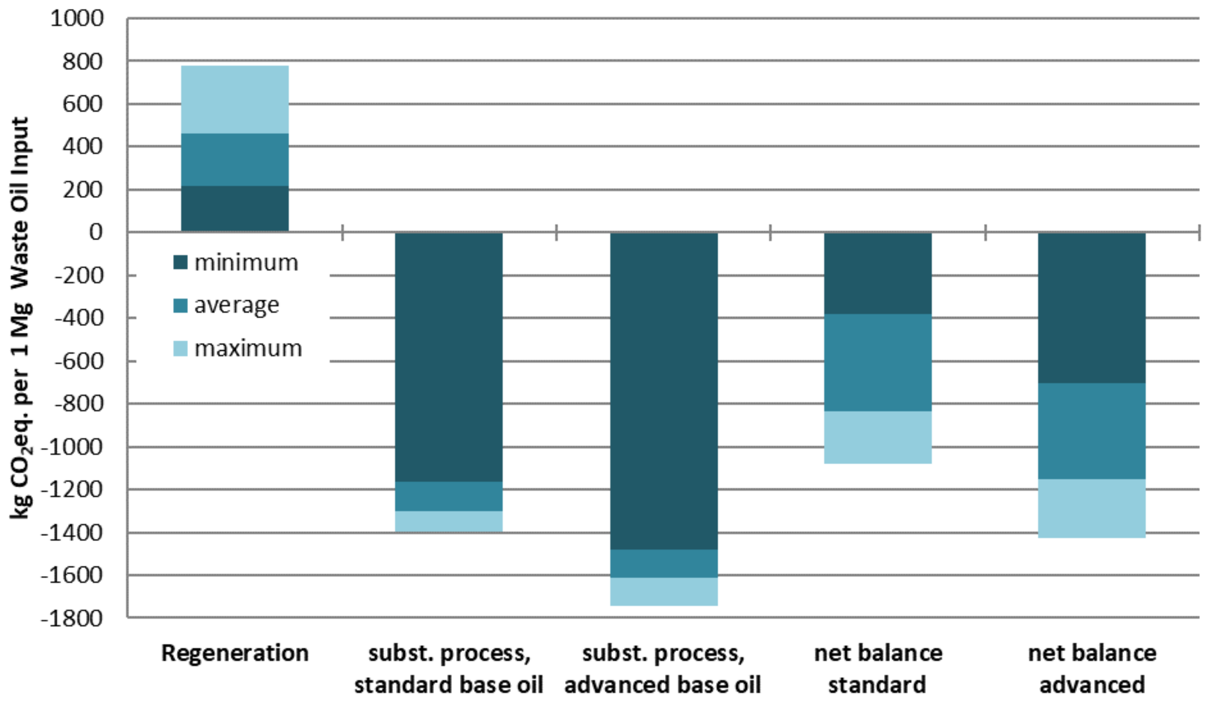

Figure 9: Impact assessment results for global warming; showing the average result of the six techniques as well as the individual minimum and maximum

Acidification

The net-balance of acidification (see Figure 10) shows a similar pattern than GWP. The impact of the regeneration system is much smaller than the equivalency system which is due to the rather high sulfur dioxide emissions related to primary mineral oil refining and further, especially when compared to previous studies, to the updated upstream crude oil and natural gas production. 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 11) gives a picture similar to GWP: the differences are even more substantial than for GWP: At its maximum, the impact of regeneration reaches only less than half of the average impact of the substituted equivalency processes. The range between the techniques is also greater here, but again, the minimum case still shows a clear advantage, compared to the equivalency processes.

Similar to the impact category climate change, the impact category terrestrial eutrophication shows 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.

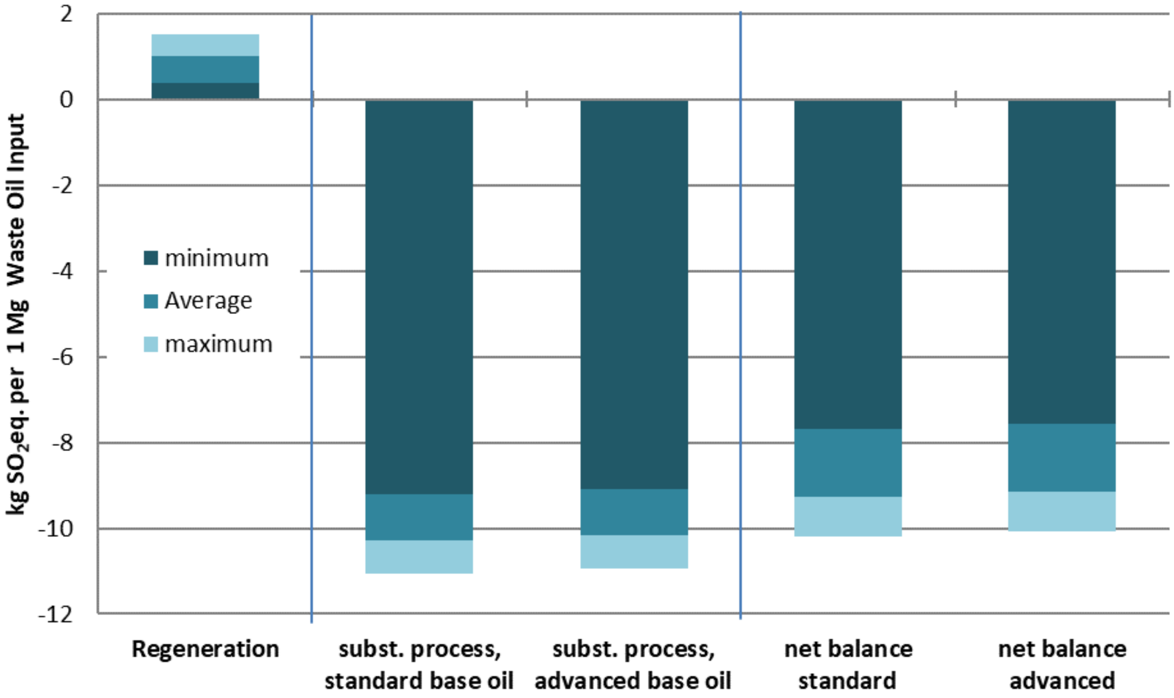

Figure 10: Impact assessment results for acidification; showing the average result of the six techniques as well as the individual minimum and maximum

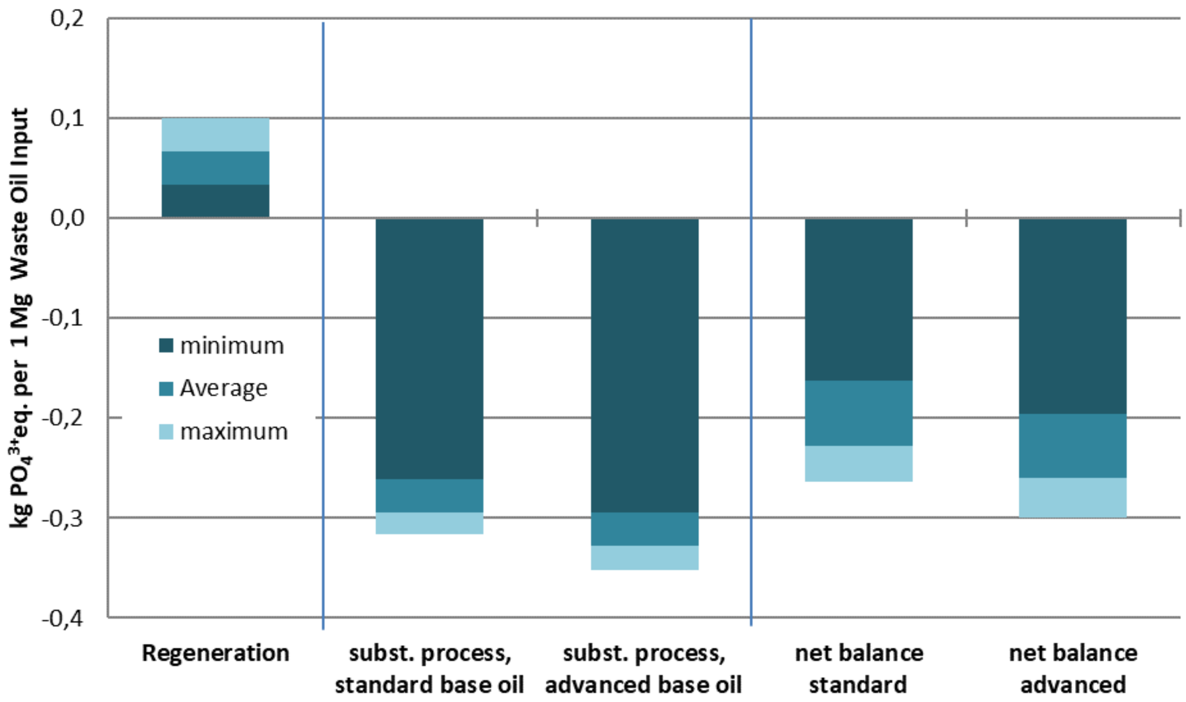

Figure 11: Impact assessment results for terrestrial eutrophication; showing the average result of the six techniques as well as the individual minimum and maximum

Human toxicity

This study covers the impact category human toxicity by the indicator fine particulate matter (PM2.5, see Figure 12). As already mentioned in chapter 3.3, due to probable data inconsistencies, carcinogenic risk will not be considered within this study.

The pattern of the net-balance for fine particulate matter (PM2.5) is similar to acidification. This is mainly due to the SO_2 -emissions related to the updated upstream chains for gas and oil.

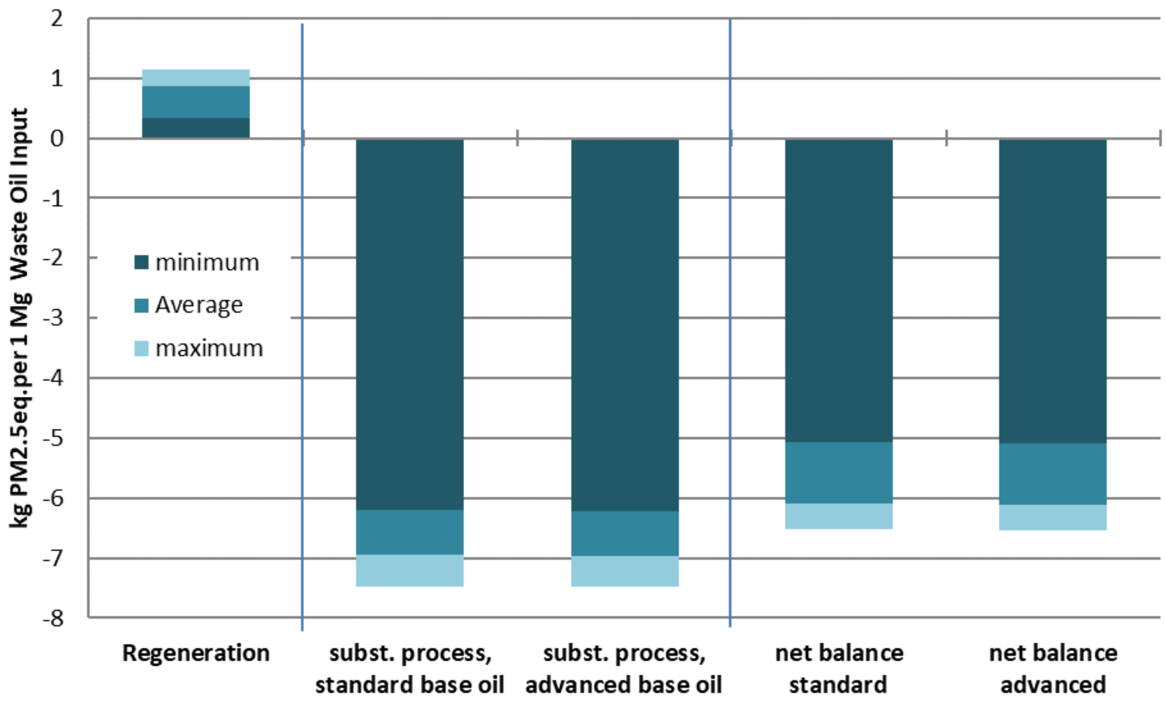

Figure 12: Impact assessment results for human toxicity represented by fine particulates (PM2.5) showing the average result of the six techniques as well as the individual minimum and maximum.

Synopsis of impact categories

Figure 13 gives a synopsis on all the impact category results listed in Table 7 and described within the text and diagrams above. The numbers are scaled to the particular result of "regeneration" (= 1, meaning that i.e. the impacts in the impact category Acidification Potential are both about ten times higher for the substituted primary base oil categories) 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 six techniques. The synopsis shows that environmental impacts from regeneration are substantially lower, compared to primary production of virgin base oils. The latter, on average, result in impacts greater by a factor of 2.8 (GWP) to 10.1 (Acidification).

One motivation to highlight this synopsis within this report is to allow a direct comparison with Abdalla & Fehrenbach (2018) and Fehrenbach (2005): Table 7 and Figure 13 correspond to the very same in Abdalla & Fehrenbach (2018) and Table 8 and Figure 7-1 enclosed by the study 2005.

Example: GWP100 (values in kg CO_2-Eq.) taken from Table 7		
-regeneration (average):	462	→ 1
- subst. base oil standard (average):	1299	→ 2,81 (= 1299/462)

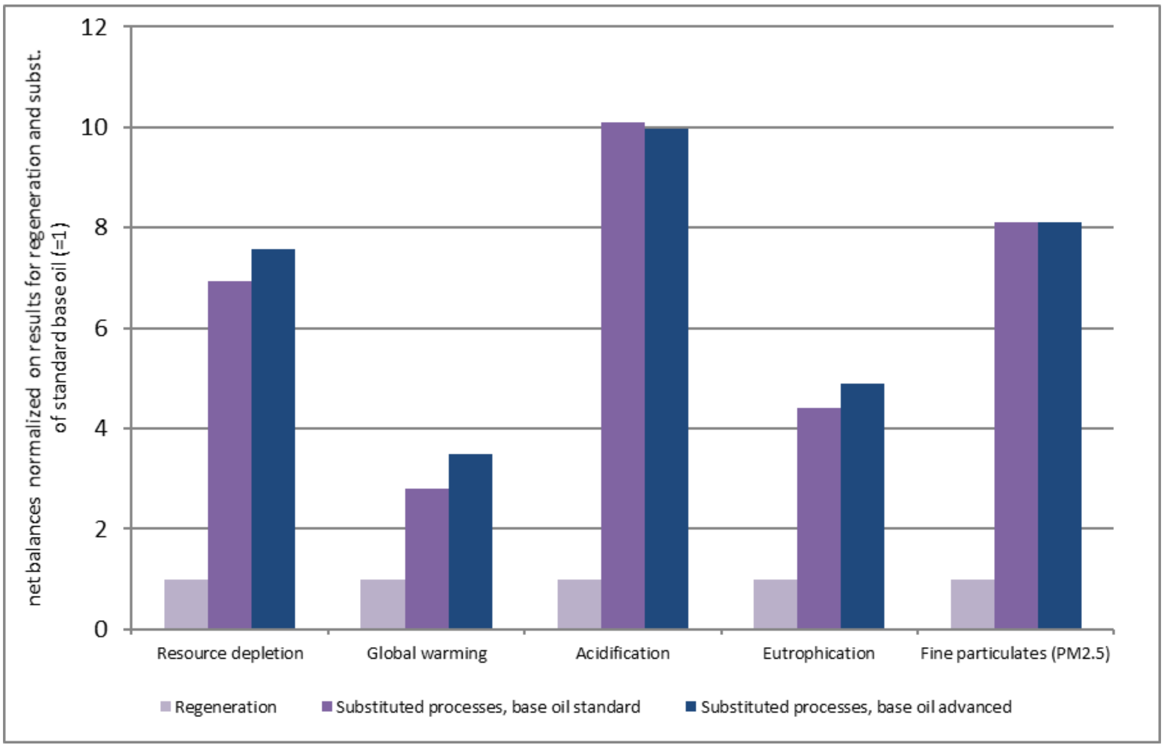

Figure 13: Total view on the impact assessment results; all figures related to the particular result of “regeneration”, main bars: average result (arithmetic mean) of the six techniques

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

7.2.1 Impact assessment results

In Table 8, the impact assessment results for:

- Regeneration; This comprises the arithmetic mean of the aformentioned six 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 gas oil quality

are shown in comparison. Within the middle column this table therefore repeats the average data from Table 7.

	Regeneration		Treatment to fuel oil	
Resource depletion (GJ)	burden of ...		burden of ...	
	...regeneration	7,44	...treatment	6,00
	subst. base oil standard	51,53	...subst. gas oil	47,4
	subst. base oil advanced	56,24		
Global warming	burden of ...		burden of ...	
(kg CO_2-Eq.)	...regeneration	461,9	...treatment	304
	subst. base oil standard	1299,1	...subst. gas oil	917
	subst. base oil advanced	1614,7		
Acidification	burden of ...		burden of ...	
(kg SO_2-Eq.)	...regeneration	1,02	...treatment	0,79
	subst. base oil standard	10,30	...subst. gas oil	6,92
	subst. base oil advanced	10,18		
Eutrophication	burden of ...		burden of ...	
(kg PO_4^{3+}-Eq.)	...regeneration	0,07	...treatment	0,07
	subst. base oil standard	0,29	...subst. gas oil	0,21
	subst. base oil advanced	0,33		
Fine particulates	burden of ...		burden of ...	
(kg $PM_{2.5}$-Eq.)	...regeneration	0,86	...treatment	0,59
	subst. base oil standard	6,95	...subst. gas oil	3,10
	subst. base oil advanced	6,97		
Explanations: "regeneration" stands for the average results of the six plants (see Table 4)				

Table 8: Summary of impact results for regeneration (average of six plants) and treatment to fuel oil; all results based of 1 Mg of recovered waste oil

Figure 8 to Figure 12 display the basic impact assessment results from Table 8. Within this section, this net balancing is also done for the reference system – treatment to fuel oil, based on the results given in Table 8 (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 8. It shows an advantage of 540 kg CO_2eq. per Mg waste oil in favor of regeneration to advanced base oil. This represents a slight improvement, when compared to the results of Abdalla & Fehrenbach (2018), where the net-benefit or regeneration compared to treatment to fuel oil was 474 kg CO_2eq. per Mg. In terms of the substitution of a standard base oil, the net-benefit of rerefining over treatment to fuel oil was still clearly visible. However, compared to Abdalla & Fehrenbach (2018), the net-benefit remained constant at 225 kg CO_2eq. per Mg. Both developments are significantly influenced by the changes in the upstream chains of natural gas and crude oil (for reference, see Meili (2021)).

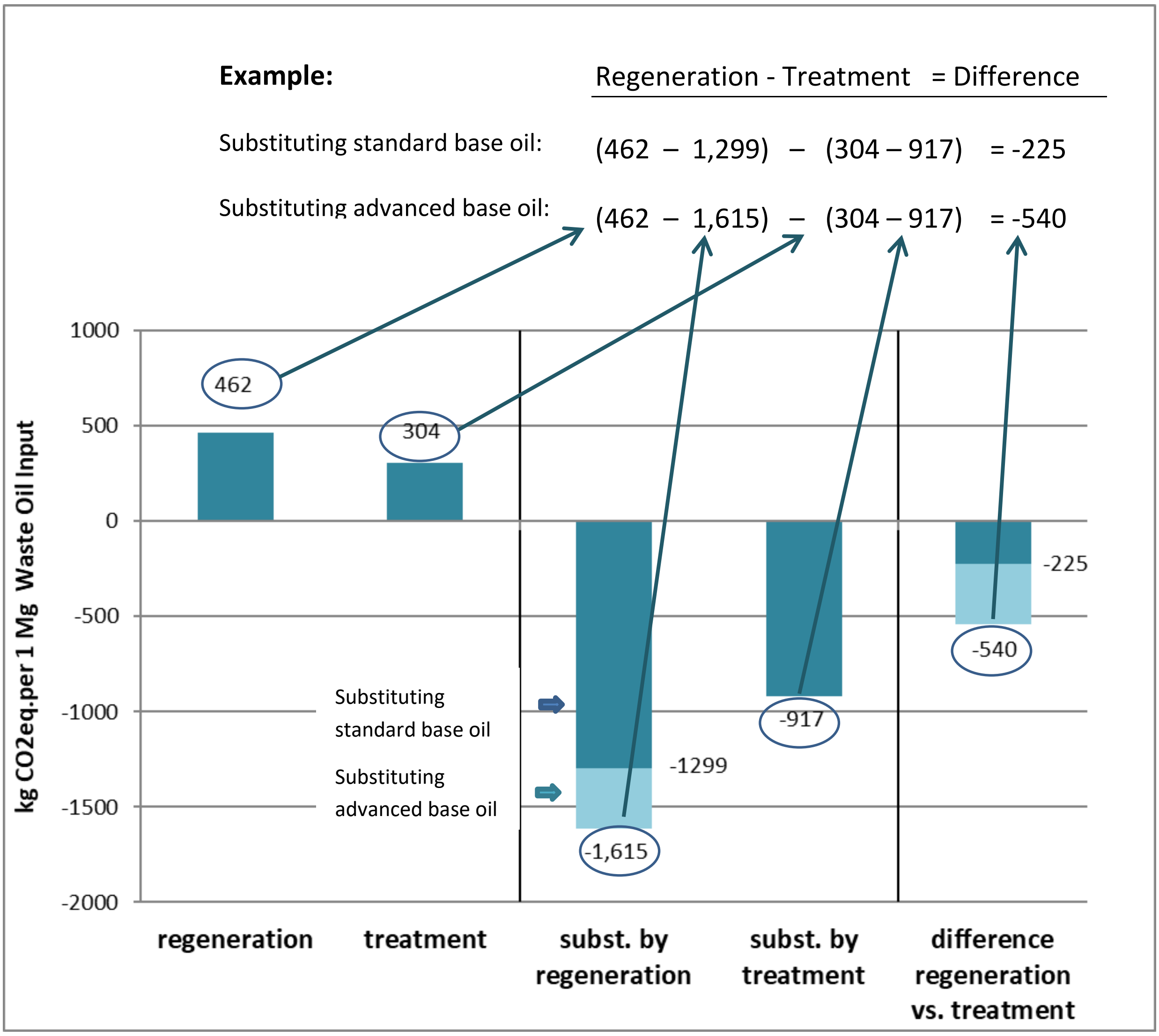

Figure 14: Illustrative example for the final combination of the impact assessment result to analyze the difference between regeneration and treatment to fuel oil.

For a synopsis of all impact categories, we refer once again to the diagram layout used in the previous studies by Fehrenbach (2005) and Abdalla & Fehrenbach (2018) in order to allow a direct comparison with the previous study. To that end, Figure 15 corresponds the very same in Abdalla & Fehrenbach (2018) and 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 oil) is set as 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:	462	burden of treatment:	304
- subst. base oil standard:	1299	subst. light fuel oil:	917
net balance:	- 837	net balance:	-612

advantage of regeneration: 225 (= 837– 612)

relation: -837 / -612 = 1,36

The diagram shows that:

- Regeneration to standard base oil offers advantages throughout all analysed impact categories compared with treatment to fuel oil for the average of the six plants under study; with ranges of the advantages for the average rerefining process in all investigated impact categories from a factor of 1.3 – 2.4. Only the impact category resource depletion is only slightly advantageous in favour of rerefining.
- The advantage of the average regeneration to base oil of advanced quality is even more significant. Here, in particular the impact categories global warming (factor 1.9) and eutrophication (factor 1.9) show even more pronounced advantages in favour of rerefining, compared to treatment to fuel oil. All other investigated categories show comparable results.

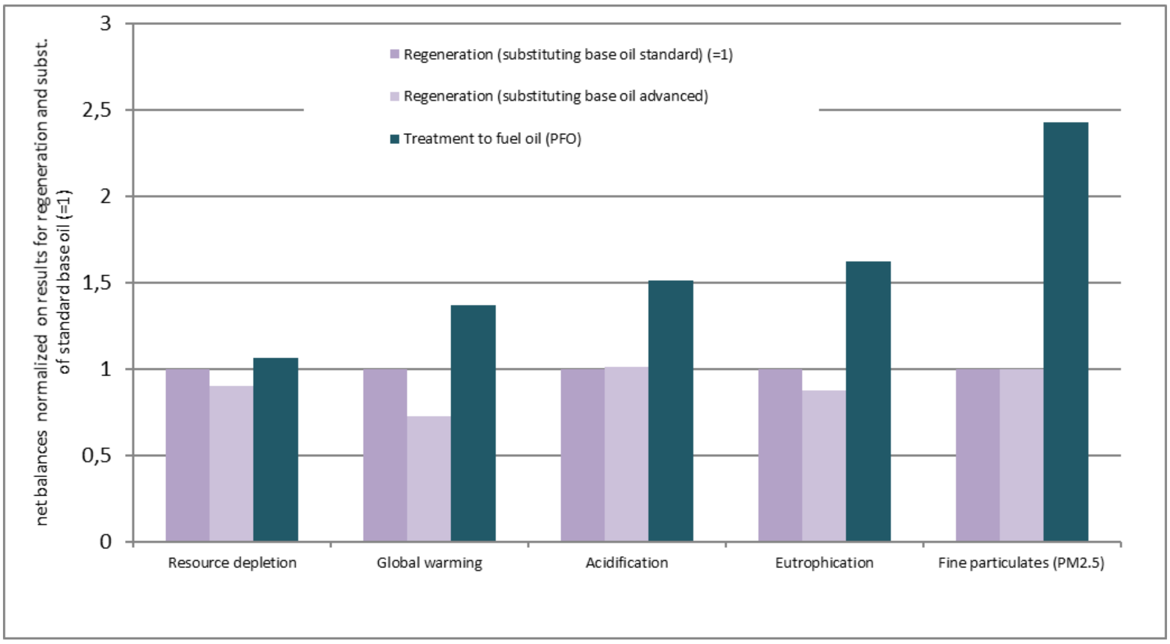

Figure 15: Synopsis on the comparable impact assessment results – regeneration (average) vs. treatment to fuel; values <1 describe better performance than regeneration and substitution of standard base oil and vice versa.

7.2.2 Normalization of impact assessment results

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 oil 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). In terms of Global Warming, the advantage of advanced base oil production vs. treatment to fuel oil corresponds to 54,000 PE, that is to say: were regeneration in Europe to stop and waste oil treated to fuel oil instead, the greenhouse gas emissions would increase by an amount equivalent to the cumulative emissions of 54,000 average German inhabitants in 2016[1].

Example: GWP100:	
- advantage of regeneration to base oil of advanced quality	
vs. treatment to fuel oil:	= 540 kg CO_2-Eq./Mg waste oil
- multiplied with 1,100,000 Mg waste oil per year	= 594,000 Mg CO_2-Eq. per year
- divided by the PEV	= 54,000 PEVs
(11.0 Mg CO_2-Eq. per year and person)	

Table 9 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 8 multiplied by the total amount of waste oil treated by regeneration in Europe per year (1,100,000 Mg) and divided by the specific PEV for each impact category (for reference, see example above

Fehler! Verweisquelle konnte nicht gefunden werden. 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.

[1] The avoided burdens described in this chapter are based on the assumption that base oil consumption remains unchanged.

	Regeneration (standard quality)	**Regeneration** (advanced quality)	**Reference case** (fuel oil)
Resource Depletion	39,500	○	61,900
Global Warming	31,500	○	53,900
Acidification	○	4,000	107,600
Eutrophication	7,000	○	25,500
Fine Particulates	600	○	165,200
Resource Depletion	■■■■■■■■	○	■■■■■■■■■■ ■■●
Global Warming	■■■■■■●	○	■■■■■■■■■■ ■
Acidification	○	■	■■■■■■■■■■ ■■■■■■■■■■ ■■
Eutrophication	■●	○	■■■■■●
Fine Particulates	●	○	■■■■■■■■■■ ■■■■■■■■■■ ■■■■■■■■■■ ■■■●

Scaled by specific contribution in PEV related to 1,100,000 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 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.

Table 9: Overview of impact-related and normalized differences between regeneration to base oil and processing to fuel oil; in PEV 2016.

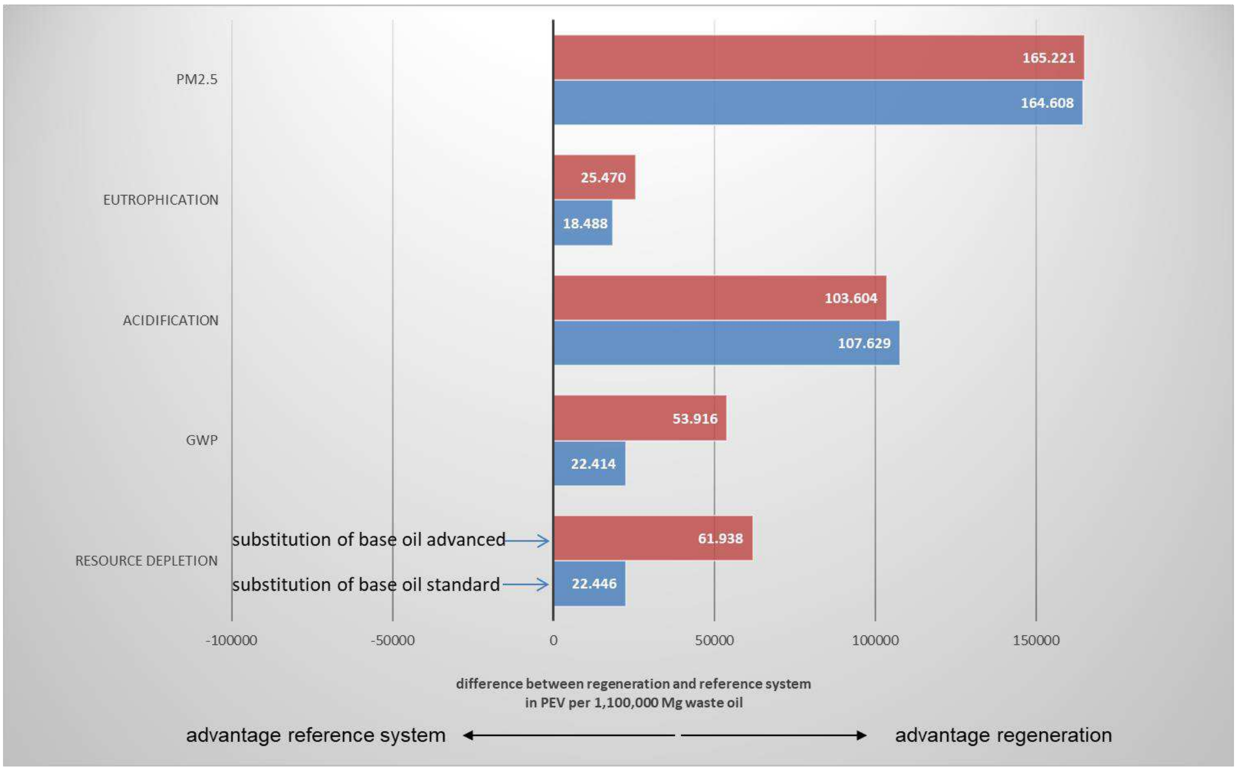

Figure 16 Overview of impact-related and normalized differences between average regeneration under study and treatment to fuel oil

Another option to illustrate these numbers might be a comparison with transport efforts: 594,000 Mg of CO_2-Eq. correspond to the GHG emissions caused by:

- one person traveling 5.5 billion km in a car[1], which would equal: traveling 594,000 times from Lisboa to Moscow back and forth.
- one waste oil truck driving 294 million km.
- or transporting 1,000,000 Mg of waste oil by truck over 5885 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 do not need any further examination. Their influence has been sufficiently evaluated within Fehrenbach (2005).

In addition, Abdalla & Fehrenbach (2018) highlighted the following points of attention:

- What kind of fuel is substituted?
- How strongly does the selection of regeneration technique affect the result – in other words: how robust is the average result[1]?
- Is there a bias concerning 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?

All the factors above have been thoroughly investigated within the previous studies. To this day, no additional factors regarding sensitivities have arisen. Moreover, the changes within this study compared to Abdalla & Fehrenbach (2018) in terms of their potential to influence sensitivity of results have been negligible with the exception of the scope of the investigated plants.

Since the study at hand involves a larger number of investigated plants, the potential for variance is subsequently greater. In addition, applied technologies differ quite significantly, as was the case in Abdalla & Fehrenbach (2018), too. This leads to significant ranges across all investigated impact categories (impacts exceeding the best result in each category (=1) range from 2.85 (Eutrophication Potential), meaning that the burdens of the worst result in this category exceeds the best one by a factor of 2.85 to 3.7 (Global Warming Potential)). However, for each impact category under study, the avoided impact through substitution was invariably greater, even when comparing the least advantageous option in each category with the most advantageous pendant within each category (e.g. the max. $GWP_{refining}$ vs. the min $GWP_{substitution}$). On average, the worst-case for the rerefining system showed 4 times lower impacts than the best-case substitution system of standard base oil.

These effects are even more pronounced when comparing an advanced base oil as a substitute. With the exception of the impact category Acidification Potential (factor 6.5 vs. factor 6.4), all impact categories showed better results for the rerefining system. On average, environmental burdens were 4.25 times lower for the worst-case rerefining, compared to the best-case substituted system.

[1] Note that the scope of Abdalla & Fehrenbach (2018) comprised four companies, which covered around two-thirds of the European rerefining market.

It can be summarized that the average result thus 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.

In terms of fuel substitution, the authors are not aware of substantial changes of the practice of admixing low-sulphur fuel oil for the purpose of upgrading heavier and more sulphur-rich fuel oils. To this end, the same trends as described in Abdalla & Fehrenbach (2018) still remain: substituting heavy fuel oil with accompanying lower efforts / expenditures would shift the scale even more in favour of rerefining.

In terms of temporal bias concerning the different applied data, the same trends as described in Abdalla & Fehrenbach (2018) could be observed. In this assessment, the burdens associated with treatment to fuel oil still were lower than the burdens of rerefining, given the general significant differences of both processes as well as their purpose. For instance, even assuming significant technological breakthroughs in terms of energy efficiency (factor 50 % less energy consumption), the GWP net-balance would still be in favour of the average rerefining system of a standard base oil. Here, too, results would even be more favourable, when assuming an advanced base oil rerefining system.

As outlined above, the base oil quality aimed at, influences results significantly. This has not changed compared to Abdalla & Fehrenbach (2018). Therefore, the observations made in Abdalla & Fehrenbach (2018) remain valid: if the environmental burdens associated with the production of an advanced base oil exceed those of a category I base oil, the conclusions of this study remain unchanged. However, an adjustment to Abdalla & Fehrenbach (2018) has to be made in terms of the impact category Acidification Potential, as in this case, production of a category II+ base oil carries slightly lower environmental burdens.

Considering the number of analyzed sensitive aspects, 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 studies in 2005 and 2018, we draw the following conclusions:

- Most importantly, the environmental advantages of the average regeneration of waste oil to base oil for the six plants under study were apparent in all applied impact categories. This holds true even in the case that just base oil group I ("standard") quality is substituted, but even more pronounced with respect to advanced base oils of group II+. This is in line with the findings of Abdalla & Fehrenbach 2018, with base oil group I regeneration achieving the same net-results, compared to the performance of the same category in Abdalla & Fehrenbach (2018). In contrast, however, regeneration of advanced base oil of groups II+ not only stands out as beneficial compared to both, the reference case and regeneration of standard base oil (group I) with respect to GWP, the net-benefit of regenerating of this category increased in comparison to Abdalla & Fehrenbach (2018). For reference, regeneration in Fehrenbach (2005) was disadvantageous in terms of the impact category global warming when compared with the – now outdated – reference system (energetic recovery in cement kiln production) in 2005 (see chapter 2.2).
- Substitution of higher base oil groups ("advanced" e.g. group II+) leads to even better results for all applied impact categories except in terms of Acidification Potential.[1] In this particular impact category, regeneration of category I base oil achieves the overall best results, even though results for both regeneration cases are fairly similar.

The most relevant reasons for this difference to the study of 2018 are changes in the energy background system, especially the implementation of data reflecting real-life practices (venting, flaring) in crude oil and natural gas production and processing. Both lead to higher burdens per unit of produced and supplied crude oil and crude natural gas, respectively. Moreover, the scope of the study was expanded to better portray the European rerefining market in terms of technologies applied and state of the art. In combination with the process data averages of two years[2] as input, the results can be considered as even more robust, compared to previous studies.

In summary, for the average of all six plants under study, the regeneration of waste oil for the recovery of base oils leads to advantages throughout all investigated impact categories, resulting in significant resource preservation and relief from environmental burdens.

This study underlines the results of the previous studies in 2018 and 2005: advanced regeneration technology shall be the favoured way to keep waste oil as long as possible as a high-graded material within the circular economy. In brief: this LCA supports the higher ranking

[1] As described in chapter 2.2 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.
[2] The reference years were chosen in particular to exclude any possible effects of the corona pandemic and to represent an adequate process flow as far as possible.

of regeneration[1] versus treatment to fuel oil[2] in accordance with 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 (version 5.6).

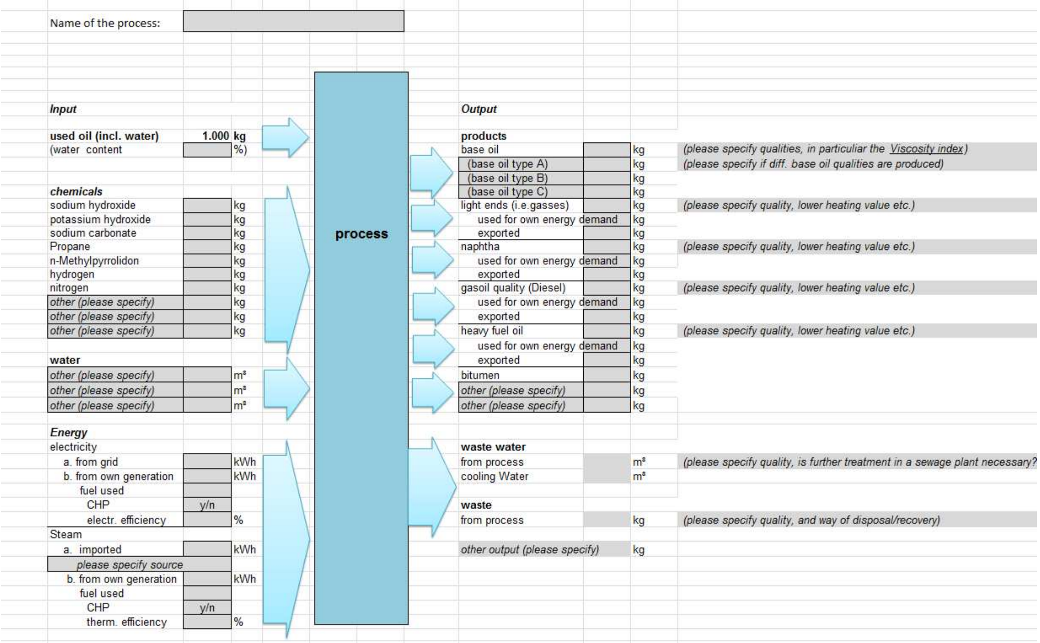

Figure 17: Questionnaire for the participating companies

Critical Review Statement

Critical Review Statement according to ISO 14040 and 14044

of the study

Updated LCA for regeneration of waste oil to base oil

at the end of the study

to the Commissioner:

GEIR (Groupement Européen de l'Industrie de la Régénération), Brussels

Conducted by ifeu GmbH, Heidelberg, Germany
(the “Practitioner”)

Performed for

GEIR (Groupement Européen de l'Industrie de la Régénération), Brussels
(the “Commissioner”)

by

Birgit Grahl (chair)

Chris Foster

Ivo Mersiowsky

02.08.2022

Content

1. Procedural Aspects of the Critical Review

The Critical Review (CR) was commissioned by GEIR (Groupement Européen de l'Industrie de la Régénération), Brussels, Belgium (GEIR) on 23rd November 2021 as Critical Review at the end of the study. The LCA study was conducted by ifeu GmbH, Heidelberg, Gemany (ifeu). The reviewers received the Report of the study on 25th March 2022.

This study is an update of the 2018 study "LCA for regeneration of waste oil to base oil", which in turn was an update of the initial study conducted in 2005. In chapter 1 of this study, links to the download of the two previous studies are integrated.

The reviewers sent a list of detailed comments on 27th April 2022 to the practitioner and the commissioner which were discussed in a telephone conference on 20th May 2022. An online model and data check was performed by Chris Foster and Ivo Mersiowsky on 11th May 2022.

Based on these and further discussions the reviewers received a revised report on 13th July 2022 and the Final Report 27th July 2022. Some required supplemental information was submitted to the panel by ifeu also on 27th July 2022.

The statements and comments below are based on the Final Report dated 27th July 2022.

Formally this critical review is a review by “interested parties” (panel method) according to ISO 14040 section 7.3.3 [1] and ISO 14044 section 4.2.3.7 and 6.3 [2] because the study includes comparative assertions intended for external communication. Different technological options for waste oil treatment besides re-refining are considered; thus competing technologies as well as primary production systems are included, and the results of the study are intended to be communicated to EU policymakers and stakeholders.

Despite this formal status, however, the inclusion of further representatives of "interested parties" is optional and was not explicitly intended in this study. The review panel is neutral with regard to and independent from any commercial interests of the commissioner. The panel had to be aware of issues relevant to other interested parties, as it was outside the scope of the present project to invite governmental or non-governmental organizations or other interested parties, e.g. competitors.

The reviewers emphasise the open and constructive atmosphere of the project. All necessary data were presented to the reviewers and all issues were discussed openly.

All comments of the panel have been treated by the practitioner with sufficient detail in the final report to which this CR statement refers. The resulting critical review statement represents the consensus between the reviewers.

Note: The present CR statement is delivered to GEIR (Groupement Européen de l'Industrie de la Régénération). The CR panel cannot be held responsible for the use of its work by any third party. The conclusions of the CR panel cover the full report from the study for GEIR " Updated LCA for regeneration of waste oil to base oil" - dated 27.07.2022 and no other report, extract or publication which may eventually be undertaken. The CR panel conclusions are stated with regard to the current state of the art and the information which has been received. The conclusions expressed by the CR panel are specific to the context and content of the present study only and shall not be generalised any further.

2. General Comments

Compared to the 2018 study, the number of companies included has been expanded from four to six, increasing the representativeness of the results. In addition, current process data and updated background data were taken into account. In particular, the updated greenhouse gas emission burden on primary oil and gas extraction (to account for venting, flaring) substantially affected the benchmark system. This is noteworthy in that the deterioration of the benchmark justifiably reflects current scientific view, but is not a conservative assumption.

The current study, as well as the 2018 and 2005 study, takes into account the modelling of re-refining waste oil to base oil considering the substitution of the primary production of base oil (equivalency system). In order to compare re-refining with other options for waste oil management a reference system as most relevant waste oil management technology besides re-refining, is investigated. All considered systems are plausibly derived, discussed in terms of their relevance and currency and briefly but sufficiently described.

The changes in the present study compared to the studies conducted in 2005 and 2018 are clearly presented in a table.

The goal of the study is stated as follows: "The goal of this study is to provide an updated view on the ecological and energetic aspects of the different treatment options of waste oil, with a focus on the re-refining of waste oil to base oil of various qualities as well as the treatment of waste oil to processed fuel oil (PFO)." To achieve this goal four key tasks listed:

- "Outline the current situation in the field of waste oil management in Europe and the key developments within the last years.
- Modelling and comparing the represented techniques of regeneration taking their environmental impact and benefits due to the substitution of primary products into account.
- Comparing the average result of the regeneration techniques considered with the reference case: the most significant alternative treatment of waste oil in Europe.
- Transparent disclosure and discussion of key parameters."

The key tasks are carried out properly. Methodology, results and interpretation are proportionate to the goal.

3. Statements by the reviewers as required by ISO 14044

According to ISO 14044 section 6.1
"The critical review process shall ensure that:

- *the methods used to carry out the LCA are consistent with this International Standard,*
- *the methods used to carry out the LCA are scientifically and technically valid,*
- *the data used are appropriate and reasonable in relation to the goal of the study,*
- *the interpretations reflect the limitations identified and the goal of the study and*
- *the study report is transparent and consistent."*

In the following sections 3.1 to 3.5, these items are discussed according to our best judgement and considering the ISO standards 14040 and 14044.

3.1 Consistency of the methods with ISO 14040 and 14044

The study has been performed according to the general structure of LCA required in ISO 14040 and also to the requirements stated in ISO 14044. Although the report does not strictly follow the general structure of LCA reporting (Goal & Scope definition – Life cycle inventory analysis (LCI) – Life cycle impact assessment (LCIA) - Interpretation) all relevant information can easily be identified.

The current study refers to the study published in 2018 and 2005. Important changes compared to previous studies are clearly presented.

The chosen functional unit and the reference flow are input related, which is common, established and reasonable for LCA in waste management.

The study adopts the entire quantity of regenerated waste oil in the European Union, of which the participating companies cover about 50%. The representativeness is therefore sufficiently good. A glossary gives an overview of the oil qualities involved to which the results relate and the handling of different technical qualities of the products is explained transparently.

Specifications on modelling, data and impact assessment will be discussed below.

Concerning sensitivity analyses the current update study refers to those performed in the 2005- and discussed in the 2018-study. Additional, semi-quantitative estimations concerning fuel substitution options are included and are plausible. The reviewers agree with the authors of the study that the model provides a sound basis for the environmental impacts of the regeneration technologies involved, and that therefore there was no need for new sensitivity analyses to be calculated.

The CR panel concludes that the methods used are consistent with the international standards.

3.2 Scientific and technical validity of the methods used

The methods used represent the scientific and technical state-of-the-art for such analyses. Some specific aspects performed in the study are highlighted below:

Within the critical review a database (primary and secondary data) and model check was conducted by Chris Foster and Ivo Mersiowsky via a web meeting held on 11th May 2022. The session was conducted with full openness and transparency, and the practitioner addressed all questions and challenges with competence and completeness. Overall, the data quality was considered to have improved over the 2018 data collection. Some discrepancies between sites of different ages were found, with one of the six companies having completed a full third party verification audit.

As in the previous studies Umberto software (here version 5.6) has been chosen for LCA modelling in the current update study and thus continuity regarding the software is ensured. An update of the ifeu refinery-model is considered. The technological system boundaries did not change. The modelling of the system is of a high standard, carried out as described in the report, and background data is consistently applied.

ISO 14040/1044 include no obligation to consider mandatory impact categories, but the choice of impact categories must be substantiated, meaningful and support the goal and scope of the study. In order to ensure continuity compared to the 2005- and 2018-study the same impact categories are addressed and few methodological changes are adequately justified. The impact categories considered in the study and the characterization models chosen are still common in LCA and thus conformity to ISO 14040 and 14044 can be stated.

The illustration of environmental burdens by normalization as optional element in impact assessment based on per-capita emission and consumption in Germany is a useful addition in terms of communication with the target group.

The CR panel concludes that the methods used are scientifically and technically valid.

3.3 Appropriateness of data in relation to the goal of the study

The inventory analysis of the current update study is based on process data collected for 2018 and 2019 (one company 2021/2022) by the companies involved. As is normal practice for Critical Reviews, it was not possible to check the correctness of all items of primary and other data, but the data used in the study were reviewed for appropriateness and plausibility. A summary of the practitioners' plausibility checks concerning company data, which was provided to the reviewers, shows that these were useful and sufficient.

In the data and model check the data was examined horizontally (general plausibility, plausibility of the relevance of certain impacts to the results) as well as vertically (detailed checks of parts of the calculation model). All data were available for the review panel on request.

Since the focus of the study is on the treatment of waste oils, the characterisation of the regenerates by means of base oil qualities and viscosity index seems appropriate. The question arose in how far the additives, which some of the recycling processes retain, affect any secondary use cases. This assessment of circularity is beyond the scope of the current analysis.

We understand the functional unit and reference flow of 1 Mg to be the basis for the interpretation, and not to suggest that scale-up of the operations of the contributing companies to that level of waste oil reprocessing is possible without changes to logistics, geographic dispersion of plants, or other aspects.

Also the background data such as electricity and developments concerning crude oil / natural gas production were updated to the most recent available information. The documentation of the background data used is transparent and the discussion of data quality using a semi-quantitative pedigree matrix is comprehensible.

Furthermore, it can be stated that no over-interpretation of the data has been detected.

The CR panel concludes that the data used and calculation methods are appropriate and reasonable in relation to the goal of the study.

3.4 Assessment of interpretation referring to limitations and goal of the study

The interpretation refers to the data presented as results of the impact assessment. Transparently described normalisation, calculation of Person Equivalency Values (PEV) helps the reader to have a clearer picture concerning the relevance of the potential impacts analysed. Data are not over-interpreted.

The derivation of the conclusions is comprehensible from the results and interpretation undertaken, although a detailed formal interpretation of the findings with regard to the European Waste Framework Directive was beyond the goal and scope of this study.

The CR panel concludes that the interpretations reflect the limitations identified and the goal of the study.

3.5 Transparency and consistency of study report

The report is clearly presented and follows the specification in ISO 14040 and 14044. The study is transparently structured. The data documentation in respective tables is supplemented by meaningful figures which enable an easy understanding of the results. Inconsistencies in the report could not be identified. The line of argument is transparent and comprehensible.

The CR panel concludes that the report is transparent and consistent.

4 Conclusion

The CR panel considers that the study has been conducted according to and in compliance with the ISO standards 14040 and 14044.

References:

[1] DIN EN ISO 14040:2006: Environmental management - Life cycle assessment - Principles and framework

[2] DIN EN ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines

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