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Updating the study

Ecological and energetic assessment of re-refining waste oils to base oils

Substitution of primarily produced base oils including semi-synthetic and synthetic compounds

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On behalf of GEIR

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Content

Glossary on terminology

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

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

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

Abbreviations

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
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
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
UBA	Umweltbundesamt, German Federal Environment Agency
UOP	Universal Oil Products (Company name)
VI	Viscosity index

1 Background and motivation

Legal basics

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

Need for an update

The identification of the option delivering the best overall environmental outcome has been scrutinized by means of a large number of life cycle assessments (LCA) since the late nineties of the last century and the beginning of the current one. One of these LCA studies was performed by ifeu on behalf of the GEIR (Fehrenbach 2005), and policymakers still refer to that study published more than ten years ago. Considering the current state of technology, the original set of data has to be regarded as outdated taking the actual state of technical practice into account. In 2005, some of the regeneration plants under assessment had been still in a pilot or testing phase of recently implemented new technologies.

Even the recently published LCA studies on regeneration in the USA refer to the GEIR study from 2005 to describe the situation in Europe (Geier et al. 2013, Grice et al. 2013).

Objective of this study

It is the objective of this study to provide an update of the outdated reference 2005 taking the most recent data into account. The study addresses the European Policymakers, all stakeholders as well as international discussion and shall provide a robust base of knowledge to assist decision making.

2 Definition of goal and scope

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

2.1 Goal of the study

Goal definition maintained

The goal of this study is to provide an updated and forward-looking view on the eco-logical and energetic aspects of regeneration of waste oil. The conclusions of the study by Fehrenbach (2005) representing more or less the situation of the last decade shall be amended to reflect the current situation. Information regarding the regeneration processes derived from common practice and process conditions of four leading companies operating in Europe. They comprise two thirds of European regeneration capacity in 2014. Key tasks of the study are:

- Modelling and comparing the four selected and advanced techniques of regeneration taking their environmental impact and benefits due to the substitution of primary products into account.
- Comparing the average result of the four advanced regeneration techniques considered with the reference case: the most relevant alternative treatment of waste oil in Europe.
- Disclosing and discussing the most decisive parameters in a transparent way.

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

2.1 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

2.1.1 Definition of the reference system

Waste oil management has changed in Europe

The study of 2005 considered alternatively waste oil combustion in a cement kiln as a substitution of standard fossil fuel. An analysis of the current situation of waste oil management in Europe shows that this type of recovery has lost its relevance. According to ascertainments by GEIR (2016), utilization of waste oil in Europe is dominated by regeneration to base oil: 42 % directly within the countries of collection and further 13 % after exporting for regeneration to some other European countries. The second most important pathway is treatment to fuel, which accounts for 31 % of the collected waste oil. In other words three quarters of the waste oil not regenerated to base oil are treated to produce fuel oil.

Reference system updated

Hence, there is need to adapt the reference system according to the strongly changed situation of waste oil management in Europe. The decided reference system for this study is therefore: treatment to fuel (further details see chapter 6).

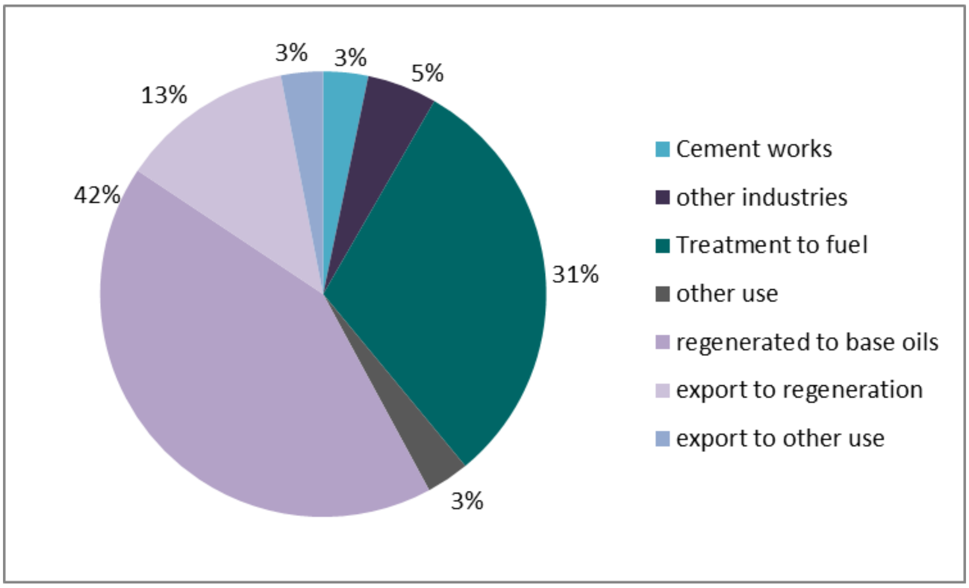

Figure 1 Waste oil utilization in Europe in 2014; total amount 1,739,500 tons; source: GEIR (2016)

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

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

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

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

The authors have developed an approach based on the viscosity index (VI) to define the equivalent virgin base oil by interpolation of groups I (standard base) and IV (PAO) because reliable data is at hand for these two groups. The approach provides explicit data for any quality of base oil and will be nonetheless checked by a sensitivity analysis. For comparison of regenerated base oil with virgin base oil, we still refer to the two-level approach: 1. Standard quality (viscosity index ≙ group I), 2. Advanced quality (viscosity index ≙ group I/IV).

2.1.3 Further basic settings

Reference volume and functional unit

The reference unit is the entire quantity of regenerated waste oil within the European Union. According to GEIR (2016), this is about **950,000 Mg per year** - apparently higher than the quantity of 800,000 Mg per year applied by the study in 2005.

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

System boundary

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

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

The definition of the system boundary as described in Figure 2 (taken from Fehrenbach 2005) is still valid.

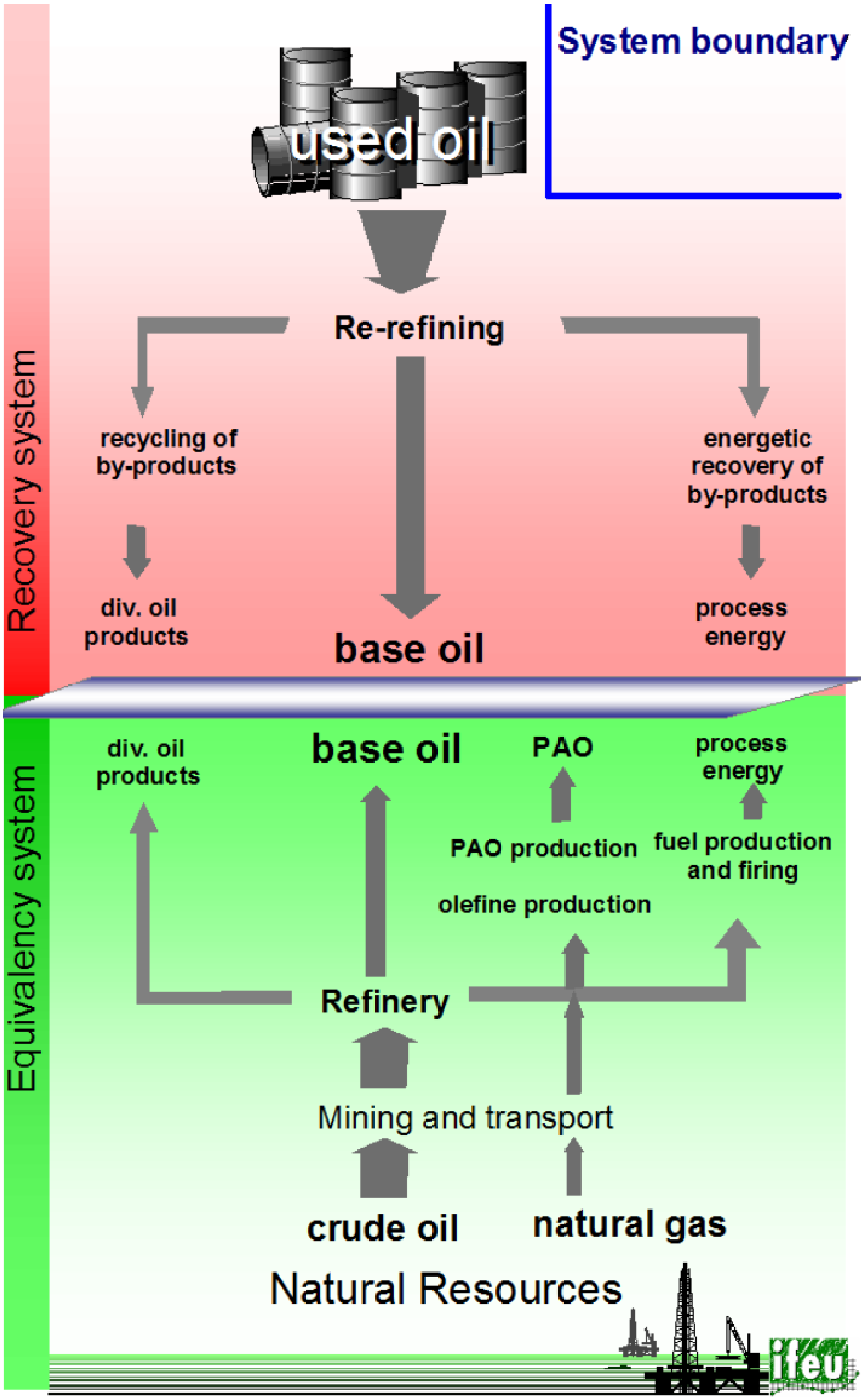

Figure 2 Simplified scheme of the system boundary calculating; Fehrenbach (2005)

3 Methodology

3.1 Framework and working steps

Basics

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

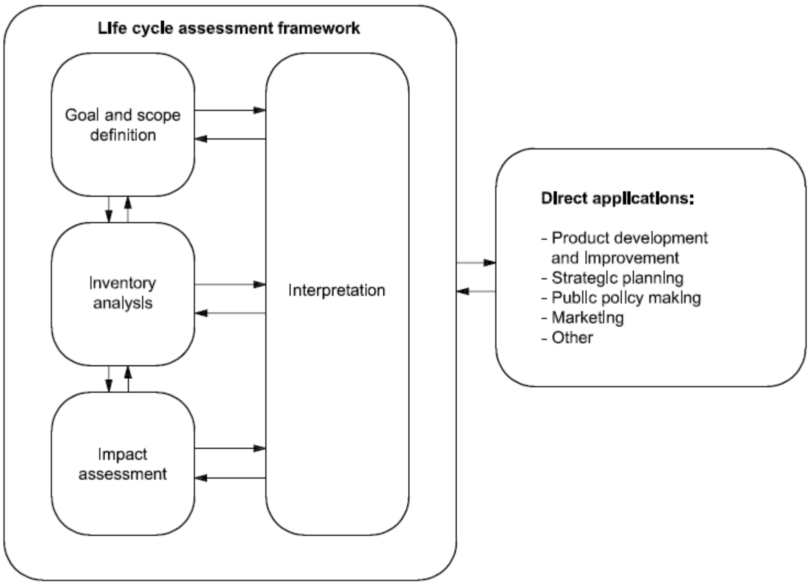

Figure 3 Phases of a life cycle assessment (LCA), according to ISO 14040:2006

Working steps

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

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

5. Discussion and interpretation of the results and comparison with the results obtained from the study 2005

3.2 Modelling of LC Inventories

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

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

3.3 LC Impact assessment

A review of the applied impact category has led the authors to maintain the set of categories with an adjustment of the indicator for resource depletion. The indicator “raw oil equivalents” is rather uncommon in application and therefore has been replaced by the cumulative energy demand (CED), focusing on fossil primary energy sources.

Impact category		**Data category**
Resource depletion:		Mineral oil, natural gas, hard coal, lignite (brown coal)
Global warming:		CO_2 (fossil), CH_4, N_2O
Acidification:		SO_2 NO_X NH_3 HCl HF H_2S
Eutrophication, terrestrial		NO_X NH_3
Human toxicity:	Carcinogenic risk Potential	As, Cd, Cr-VI, Ni, PCDD/F, Benzo(a)pyren, PCB
	fine particulates PM2.5	primary particulates PM2.5, SO_2, NO_X, NH_3, Hydrocarbons

Table 1 Waste impact categories and indicators, classified data categories and characterization factors

3.1 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.
- Grouping: Ranking the impact categories in a given order of hierarchy, such as very high, high, medium and low priority.

The *specific contribution*, which is the calculated result of the balance process (normalization of impact assessment), is given here as an absolute value expressed in Person Equivalency Values (PEV). The Person Equivalency Value represents the average per-capita load of one inhabitant (e.g. 13 Mg CO_2-equivalents per year). If the load caused by one recycling option or, respectively, the difference between two options is divided by this value, the result will be the number of inhabitants that corresponds to a particular option or the difference between two options respectively.

	Per-capita load German inhabitant PEV		**Reference**	**Ecological Priority**
Fossil energy resources	134,300	MJ/a	(a)	🟨 "medium"
Global warming	11,780	kg CO_2-Eq./a	(a)	🟪 "very high"
Eutrophication, terrestrial	5.03	kg PO_4^{3-} -Eq./a	(a)	🟥 "high"
Acidification	31.5	kg SO_2 -Eq./a	(a)	🟥 "high"
Carcinogenic pollutants	8.63	g As Eq./a	(a)	🟪 "very high"
Fine particulates (PM2.5)	233.9	kg $PM_{2.5}$ Eq./a	(a)	🟥 "high"

References: a) Aggregated data provided by UBA National trend tables for German reporting of airborne emissions
Ecological Priority based on UBA [1999]

Eq. = equivalents

Table 2 Total per-capita emission and consumption in the Federal Republic of Germany (Person Equivalency Value, PEV) and valuation suggested by UBA regarding ecological hazard potential and distance to goal of protection

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

4 Characterization of waste oil

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

5 Description of the considered regeneration techniques

The considered four techniques cover the whole range of base oil quality as described in section 2.1.2.

All below mentioned capacities refer to waste oil input.

5.1 Avista

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

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

5.2 LPC

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

5.3 Hylube process by PURAGLOBE

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

5.4 Viscolube

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

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

6 Description of the substituted and other inflicted processes

Overview of considered process (chains)

The processes substituted by regeneration of waste oil are:

- The complex production chain from crude mineral oil via waxy distillates to base oil group I (see also Figure 4).
- The complex production chain from natural gas via i-decene synthesis to poly-alpha-olefins (PAO, base oil group IV).
- The production chains for divers co-products from regeneration processes, such as:
  - naphtha
  - fuel oils
  - bitumen
  - excess energy

The reference system is described by:

- A common technique to process waste oil to fuel oil quality meeting the quality of low sulfur fuel oil (≤ 0,5 % S). Quality requirements for “processed fuel oil” are defginded e.g. by the environment Agency from UK (EA 2009).
- The processes substituted by the fuel oil production, i.e. the production chain from crude mineral oil via divers middle distillates and desulfurization to low sulfur fuel oil. The selection of light fuel oil is justified by a) low S-content, b) corresponding heating value and viscosity and c) the fact that such processed fuel oils are used to upgrade heavy fuels.

Process chains from study 2005 updated

Apart from the reference system, all of these processes have been modelled already by the study in 2005. Within the scope of this study the authors have applied an updated version of the refinery model, taking into account the developments at European level according to the BREF (Barthe et al. 2015). This includes the Life Cycle inventories of base oil group I and all the co-products including light fuel oil (substituted by the reference system).

waste oil to fuel oil

Unlike the other processes the technique to process waste oil to fuel oil (reference system) was modelled completely anew. The authors refer to a data set applied in former studies. The considered process steps include:

- Mixing the waste oil with sulfuric acid and other chemicals to precipitate heavy metals
- Decantation
- Thermal treatment to separate the fuel oil fraction from other fractions and residual water
- Filtration

The yield ratio is 850 kg fuel oil per ton waste oil. The input-output data are given in Table 3.

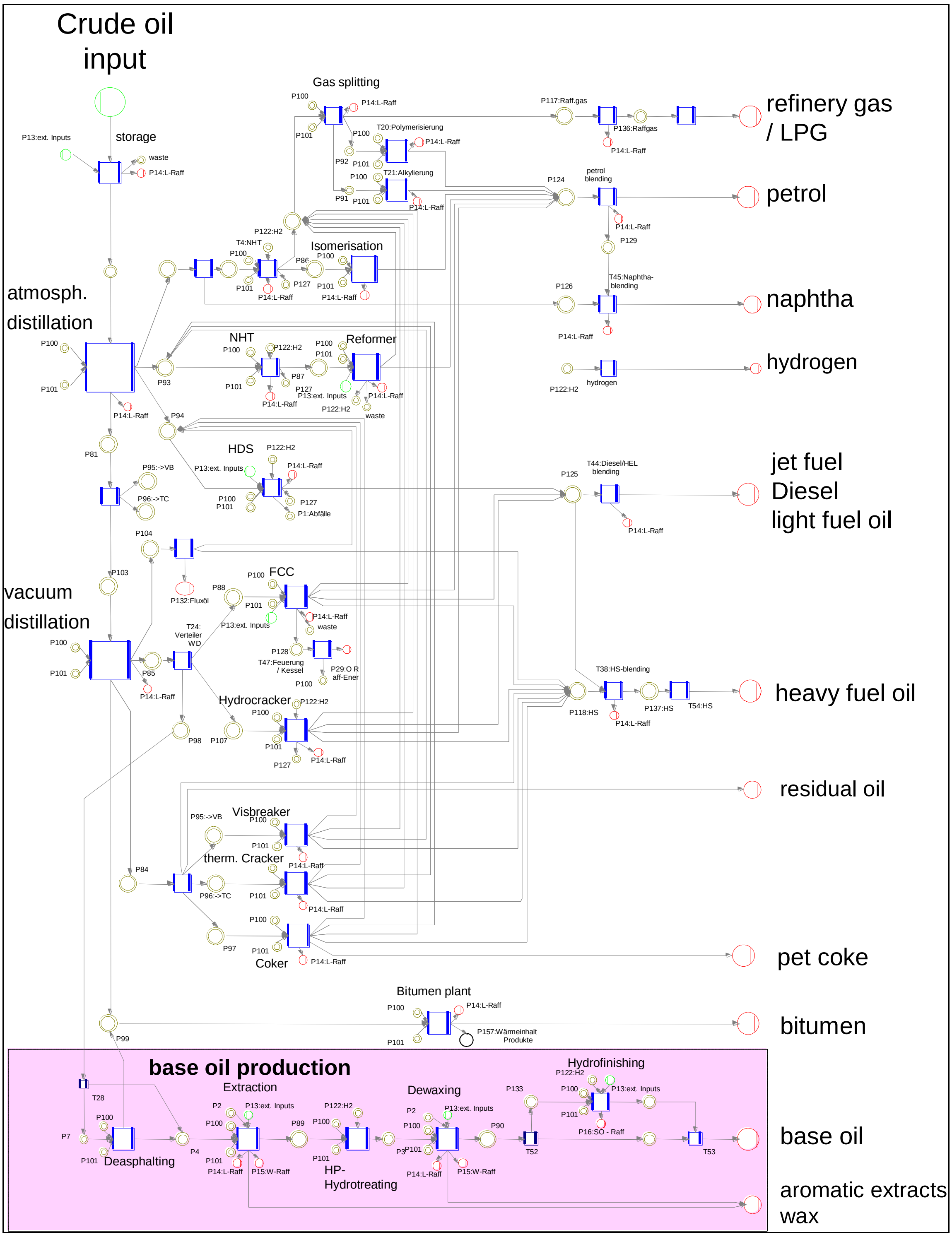

Figure 4 Network model for the calculation of mass and energy flow of a virtual mineral oil refinery

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

Table 3 Input (energy and auxiliary consumption) and output (yield an wastes) for processing waste oil to low sulfur fuel oil.

7 Results

In a first step, results are worked out for each of the four regeneration options assessed (section 7.1). The goal is to identify significant differences. In a second step, the average result of the four options will be compared to an alternative treatment and use as processed fuel oil (section 7.2).

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).

7.1Comparison of the four regeneration options

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 4 provides the impact category results for every regeneration option and the corresponding equivalency processes. To give an example:

1. Technique 1 leads to an emission of 365 kg of CO_2-equivalents per Mg waste oil, including combustion of by-products, natural gas for heat and steam, production of current, hydrogen and other auxiliaries.
2. The benefit of technique 1 (substitution of base oil and other by products) leads to a prevention of 827 kg of CO_2-equivalents per Mg waste oil, supposed the quality of the base oil substituted corresponds with group I in terms of VI. Supposed the quality equals the advanced case (VI ≙ group I/IV), the saved GHG emission extends to 1,072 kg CO_2-equivalents.
3. To get the “net impact” of the technique 1 of regeneration the omitted burden (827 or 1,072) is to be subtracted from the burden created (365). Hence, technique 1 releases the global warming in the range of 463 to 707 kg CO_2-equivalents per Mg waste oil.

Figure 5 gives a view on all the impact category results listed in Table 4. The figures are scaled on the particular result of “regeneration”. The bars representing the substituted primary processes show the factor relative to regeneration. The main bars stand for the average result of the four techniques. The deviation bars show the range of the four techniques in detail.

Table 4 and Figure 5 correspond to Table 7-2 and Figure 7-1 enclosed by the study 2005. Some differences appear to be obvious with focus on fossil resources and carcinogenic risk potential. These changes are due to the following reasons:

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

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

	Regeneration Technique			
Reference: 1 Mg waste oil	**1**	**2**	**3**	**4**
Resource depletion (MJ)				
Regeneration	5.36	9.12	2.52	5.56
Equivalency processes				
base oil standard (VI ≙ group I)	47.9	48.1	46.7	47.6
base oil advanced (VI ≙ group I/IV)	51.7	52.0	50.1	51.8
Global warming (kg CO_2-Eq.)				
Regeneration	365	577	190	516
Equivalency processes				
base oil standard (VI ≙ group I)	827	838	783	869
base oil advanced (VI ≙ group I/IV)	1 072	1 094	1 006	1 144
Acidification (kg SO_2-Eq.)				
Regeneration	1.02	1.36	0.41	0.75
Equivalency processes				
base oil standard (VI ≙ group I)	4.43	4.49	4.18	4.69
base oil advanced (VI ≙ group I/IV)	4.52	4.59	4.26	4.79
Eutrophication (kg PO_4^{3-}-Eq.)				
Regeneration	0.089	0.138	0.029	0.089
Equivalency processes				
base oil standard (VI ≙ group I)	0.181	0.181	0.174	0.182
base oil advanced (VI ≙ group I/IV)	0.252	0.256	0.239	0.262
Carcinogenic risk potential (mg As-Eq.)				
Regeneration	4.1	11	2.5	14
Equivalency processes				
base oil standard (VI ≙ group I)	242	239	235	246
base oil advanced (VI ≙ group I/IV)	242	239	235	246
Fine particulates (kg $PM_{2.5}$-Eq.)				
Regeneration	0.93	1.33	0.31	0.74
Equivalency processes				
base oil standard (VI ≙ group I)	3.13	3.17	2.97	3.28
base oil advanced (VI ≙ group I/IV)	3.48	3.53	3.29	3.67

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

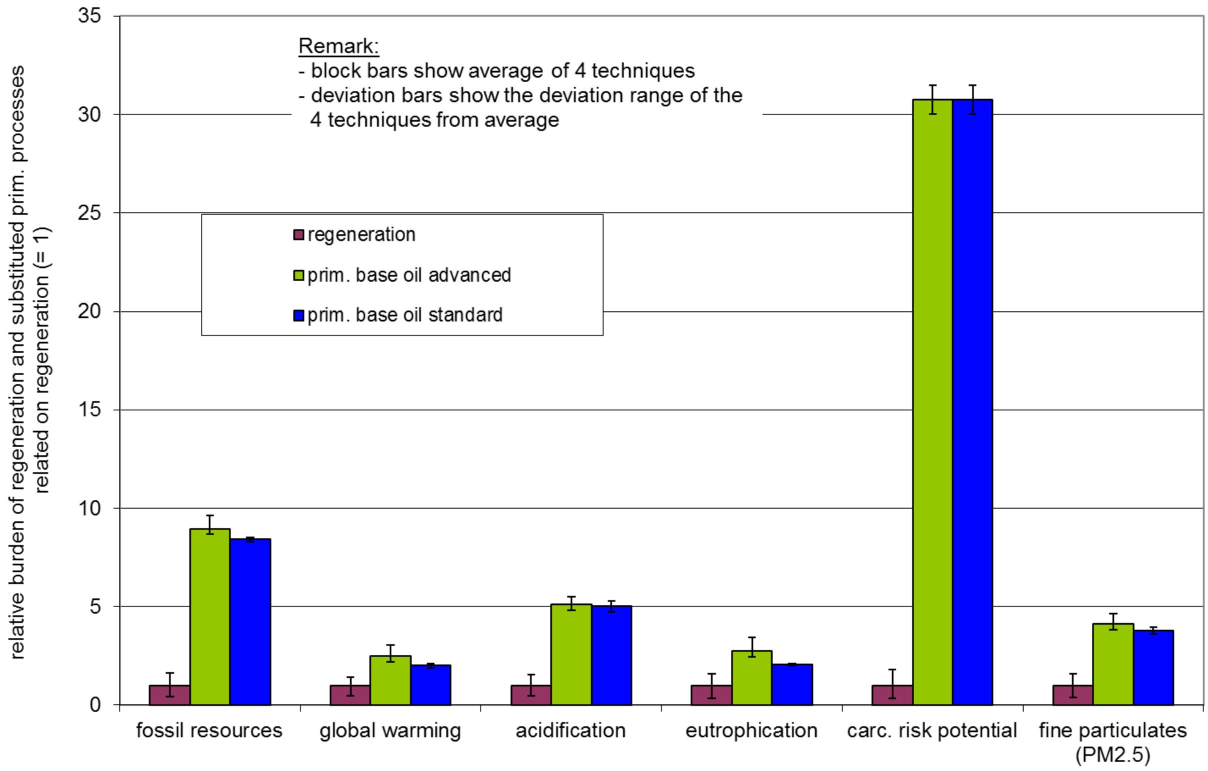

Figure 5 Total view on the impact assessment results; all figures related on the particular result of "regeneration", main bars: average result of the four techniques, deviation bars: range of the four techniques

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

7.2.1 Impact assessment results

In Table 5 the impact assessment results for:

- Regeneration; average of four, substituting either base oil standard (VI ≙ group I) or base oil advanced (VI ≙ group I/IV) and
- The treatment to fuel oil, substituting light fuel oil quality

are shown in comparison.

	Regeneration		treatment to fuel oil	
Fossil resources (MJ)	burden of …		burden of …	
	…regeneration	5,64	…treatment	0,27
	subst. base oil standard	47,6	…subst. light fuel oil	40,5
	subst. base oil advanced	51,4		
Global warming (kg CO$_2$-Eq.)	burden of …		burden of …	
	…regeneration	412	…treatment	234
	subst. base oil standard	830	…subst. light fuel oil	426
	subst. base oil advanced	1079		
Acidification (kg SO$_2$-Eq.)	burden of …		burden of …	
	…regeneration	0,88	…treatment	1,21
	subst. base oil standard	4,45	…subst. light fuel oil	1,89
	subst. base oil advanced	4,54		
Eutrophication (kg PO$_4^{3+}$-Eq.)	burden of …		burden of …	
	…regeneration	0,086	…treatment	0,019
	subst. base oil standard	0,18	…subst. light fuel oil	0,084
	subst. base oil advanced	0,236		
Carcinogenic risk potenial (g As-Eq.)	burden of …		burden of …	
	…regeneration	7,82	…treatment	24
	subst. base oil standard	240	…subst. light fuel oil	129
	subst. base oil advanced	240		
Fine particulates (kg PM$_{10}$-Eq.)	burden of …		burden of …	
	…regeneration	0,83	…treatment	0,66
	subst. base oil standard	3,14	…subst. light fuel oil	1,36
	subst. base oil advanced	3,49		

Explanations: “regeneration” stands for the average results of the four techniques (see Table 4)

Table 5 Line-up of impact results for regeneration (average of four) and treatment to fuel oil; all results based of 1 Mg of recovered waste oil

In Figure 6 the basic impact assessment results from Table 5 are aggregated to illustrate the relative advantages and disadvantages. To arrive there, the “net impact” is calculated first (“regeneration minus subst.” resp. “treatment minus subst.”). The value for regeneration (substituting base oil group I) is set to be 1 and the other values are scaled correspondingly. In fact all options considered contribute to environmental relief in all categories.

The diagram shows that:

- Treatment to fuel is disadvantageous throughout all impact categories compared with regeneration (base oil group I); in case of global warming, acidification, carcinogenic risk and fine particulates the relative advantage is higher than a factor 2.
- The advantage of regeneration to base oil of advanced quality (VI ≙ group I/IV) is even more significant.

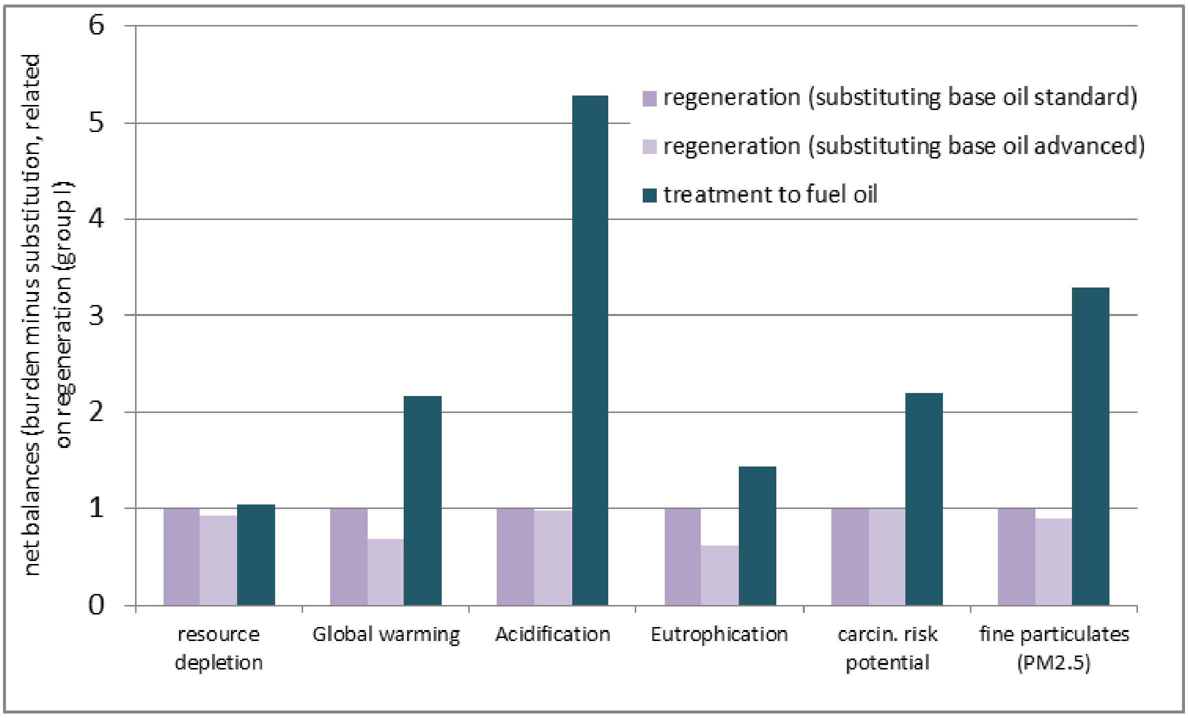

Figure 6 Total view on the comparable impact assessment results – regeneration (average) vs. treatment to fuel; values <1 describe better performance than regeneration (base oil group I) and vice versa.

7.2.2 Normalization of impact assessment results and grouping

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

These illustrations again show the distinct advantages of regeneration against treatment to fuel in all impact categories and the advantages of the substitution of base oil advanced (VI ≙ group I/IV) against base oil standard (VI ≙ group I). The advantages range between 90,000 PEV (acidification) and at least around 5,000 PEV (eutrophication).

In summary, a thorough benefit of regeneration can be observed when compared with the alternative use as is practiced most commonly within Europe.

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

Scaled by specific contribution in PEV related to 950,000 Mg of waste oil; the figures resp. the number of squares shows the deviation from the most beneficial option in each case, which is marked by ①;
1 square corresponds to 5,000 PEV (rounded); differences below 2,500 PEV are marked by •
Ecological priority: 🟪 = A (very high), 🟥 = B (high), 🟨 = C (medium).

Tab. 1 Overview of impact-related and normalized differences between regeneration to base oil and processing to fuel oil, expressed in PEV; scaled on 950,000 Mg waste oil

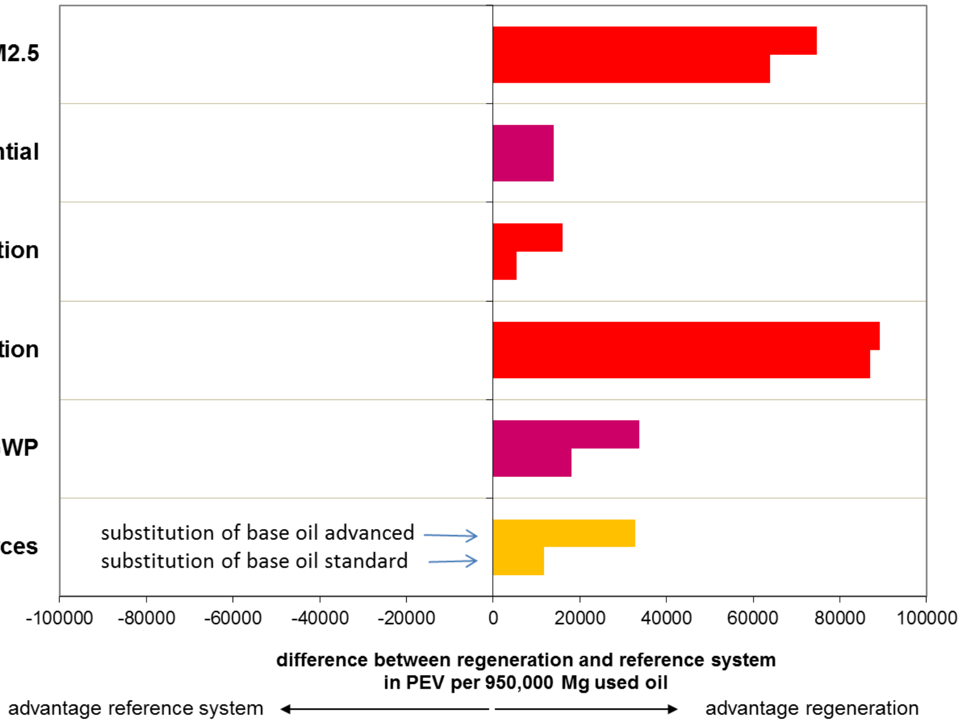

Figure 7 Overview of impact-related and normalized differences between average regeneration and treatment to fuel oil

7.3 Sensitivity analysis

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

- Allocation method
- Fuel substitution
- Distribution distances

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

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

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

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

Given that heavy fuel would be substituted by the treated waste oil, hypothetically, the results would slightly change in favor of regeneration within nearly all of the impact categories because the effort to produce heavy fuel is lower than for light heating oil.

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

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

8 Conclusion

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

- ➲ Most importantly, the environmental advantages of regeneration of waste oil to base oil was apparent in all applied impact categories. This holds true even in the case that just base oil group I quality is substituted
- ➲ Substitution of higher base oil groups (e.g. group II+) leads to even better results for all applied impact categories.

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

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

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

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

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

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

9 Literature

Barthe, P., Chaugny, M., Roudier, S., Sancho, L.D. (2015): Best Available Techniques (BAT) Reference Document for the Refining of Mineral Oil and Gas. European Integrated Pollution Prevention and Control Bureau (EIPPCB) of the European Commission's Joint Research Centre (JRC). http://eippcb.jrc.ec.europa.eu/reference/BREF/REF_BREF_2015.pdf

Fehrenbach, H. (2005): Ecological and energetic assessment of regeneration waste oils to base oils: Substitution of primarily produced base oils including semi-synthetic and synthetic compounds; behalf of GEIR - Groupement Européen de l'Industrie de la Régénération ; Heidelberg, 2005. http://www.geir-rerefining.org/documents/LCA_en_shortversion.pdf

GEIR (2016): Waste Oil Utilization -2014; fact sheet by GEIR.

GEMIS (2014): Globales Emissions-Modell Integrierter Systeme (GEMIS), version 4.9, http://www.iinas.org/gemis-download-de.html -

Geyer, R., Kuczenski, B., Henderson, A., Zink, T. (2013): Life Cycle Assessment of Waste Oil Management in California, on behalf of California Department of Resources Recycling and Recovery; Santa Barbara, 2003
http://www.calrecycle.ca.gov/Publications/Detail.aspx?PublicationID=1465

Grice, L. N., Nobel, C. E., Longshore, L., Huntley, R., DeVierno, A. L.: Life Cycle Carbon Footprint of Re-Refined versus Base Oil That Is Not Re-Refined; ACS Sustainable Chem. Eng., Publication Date (Web): October 25, 2013, American Chemical Society
http://pubs.acs.org/doi/abs/10.1021/sc400182k

ISO/TS 14067: Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification and communication; First edition 2013-05-15

Kolshorn, K.-U., Fehrenbach, H. (2000): Ökologische Bilanzierung von Altöl-Verwertungswegen; Report Texte 20/00, on behalf of the Federal Environment Agency (UBA); 2000

Nieschalk 2004: Ermittlung der Energieaufwendungen bei der Herstellung von Poly-alpha-Olefinen als Grundlage für einen ökobilanziellen Vergleich von Altölverwertungsoptionen; thesis submitted to the University of Cottbus, 2004

WRAP (2009): Processed Fuel Oil (PFO) - End of waste criteria for the production and use of processed fuel oil from waste lubricating oils; Quality report; Bristol 2009
https://www.gov.uk/government/publications/quality-protocol-processed-fuel-oil-pfo