FINAL REPORT

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

commissioned by
GEIR - Groupement Européen de l'Industrie de la Régénération

Author:
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Heidelberg, February 2005

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0 Abstract

The Council Directive on the disposal of used oils establishes priority for re-refining of used oil for recovery of base oil as long as there are no technical, economic or organisational obstacles. The priority given to re-refining is substantiated by the goal of resource preservation. The beneficial environmental effects of used oil regeneration compared to refining of virgin base oil have yet been proven by a number of Life Cycle Assessment studies (LCA) published in Europe in the past. Some of these earlier studies have concluded with an indifferent assessment when comparing the re-refining of used oil to combustion options in certain large-scale facilities, such as cement kilns.

Ongoing developments within regulatory agencies, the lubricants industry and the re-refining industry have all created changes to several important environmental and economic aspects affecting the re-refining industry. The European Association of the re-refining industry (GEIR) has reason to assert that the results of LCA studies published in the past and focusing on re-refining industry practices and lubricant qualities of the 1990's are no longer valid. Key developments supporting this view include:

- New regeneration technologies with improved performance have been developed and implemented;
- Regulatory requirements concerning motor vehicle emissions have enhanced the quality of lubricants; and
- in today's markets, the amounts of synthetic and semi-synthetic compounds have increased significantly and keep on increasing. These more sophisticated and stable oils require far more energy to manufacture and allow re-refiners to manufacture high quality base oils more easily because the inherent quality of collected used oils is substantially improving.

GEIR commissioned this study to consider these developments. The focus of the study is based on the core cycle: "base oil production –» used oil –» base oil re-refining". A key question is: What is the relationship between the ecological burdens for production of base oils (or lubricants) of equivalent quality by initial product manufacturing and by re-refining of used oils? In addition, comparisons are made in relation to combustion of used oils as a fuel substitution, compared to the re-refining option.

Within the scope of this study, the material and energy flows of advanced re-refining techniques – represented by four companies operating in Europe and one in the USA – are analyzed and evaluated to include impacts of auxiliary processes, such as electricity or fuel prechains. Primary lube industry processes and process chains that are substituted by recycling of base oils are also considered. To acknowledge the issue of improving quality of used feedstock and re-refined products, a range of 0 to 30 % synthetic components is taken into account in the analyses.

The methodology of this assessment follows requirements of the ISO standards 14040ff. The environmental impact categories to be analyzed include:

- resource depletion (with respect to fossil energy resources);
- global warming;

- terrestrial nutrification;
- acidification; and
- toxicity (with respect to carcinogenic pollutants and fine particulates).

For interpretation of the analyses the two processes described in ISO 14042 are applied:

- Normalization: Calculation of the magnitude of the impact 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 ecological and energetic assessment leads to following main conclusions:

1. For all five re-refining techniques considered, there are clear environmental benefits when compared to the production of base oils in standard oil refineries. This is apparent in all of the impact categories considered.
2. The trend towards using more synthetic or semi-synthetic compounds in lubricants is reflected in significant increases in these environmental benefits as the proportion of the compounds in used oil grows toward the 30% limit used in this study.
3. Assessment and comparison with direct combustion of used oils is conducted presuming an average situation in the European cement industry (mainly using coal and pet coke as primary fuel). It also takes into account utilities substituting fuel oil by combustion of used oil.
   - For the majority of impact categories regeneration is shown to be more beneficial than direct burning. In the case of the global warming impact however direct burning is shown to be more beneficial when coal is displaced.
   - As the proportion of synthetic compounds in used oil increases, the benefit for global warming by burning used oil directly is significantly reduced.
   - The conclusion in relation to global warming is sensitive to the type of fuel that is displaced by the burning of used oil. If fuels other than coal or pet coke were to be displaced in cement kilns by the direct burning of used oil the analysis would conclude that the regeneration of used oil is overall beneficial compared to direct burning.
4. The analysis of some sensitive parameters shows additional aspects developing in favour of regeneration, especially with regard to allocation method and when an increasing pool of secondary fuels starting to compete is taken into account.

In summary, re-refining of used oil for recovery of base oils leads to significant resource preservation and relief from environmental burdens when compared to the production of base oils in large-scale crude oil refineries.

Most of the LCA studies performed in the past have concluded with an indifferent evaluation when re-refining was compared with the combustion option for used oil. This study shows that efficient regeneration technology, the future potential of the re-refining industry, and other sensitive environmental aspects lead to conclusions favouring re-refining of used oils to recover base oil. This LCA is evidence of improved environmental benefits from re-refining: supporting the priority given it by EU policies.

1 Introduction

With the implementation of Council Directive on the disposal of used oils (75/439/EEC, amended by Directive 2000/76/EC), re-refining of used oil to base oil is given priority as long as there are no technical, economical or organisational obstacles.

Contrary to the clear and unmistakable requirement of the Council Directive, legislation in several member states had not been implemented giving priority to the regeneration of base oils from used oil within time limits. The Federal Government of Germany was the first to be charged by the European Court of Justice, and found guilty in proceedings during 1999. In the meantime, 13 cases of violations have been prosecuted. The latest cases undertaken include a court procedure against the United Kingdom and North Ireland, and another against Sweden.

The objective of the Council Directive on the disposal of used oils is to prevent harmful impacts on the environment caused by the discharge, storage and treatment of these oils. The Sixth Environment Action Programme of the European Community [EC 2001] emphasises the significance of recycling. The reuse and recycling of materials are favoured to minimize resource consumption. However, the program also requires ecological sensibility in practice. Hence, reuse and recycling has to benefit the environment in an economical sound manner.

A large number of LCA studies up-to-date have proved the beneficial effects of used oil regeneration. Vold et al. [1995] were the first to analyse the environmental impacts of re-refining and combustion from a Norwegian point of view. In France, a study was carried out in order of Ademe [2000]. In Germany two studies were conducted by Arcadis/ifeu [2000] and Ökopol [1997]. Monier and Labouze [2001] evaluated the Norwegian, the French and the two German cases, as well as, three other assessments. The latest study was delivered by Winberg [2002] who focussed on a plant in Denmark.

The LCA done by Arcadis/ifeu [2000] commissioned by the German Federal Environmental Agency (UBA) was done in response to the charge by the Court of Justice. The study objective was to identify, in environmental sense, the most compatible approach for used oil recovery. The result of the UBA study is that none of the options examined stood out from the others for ecological reasons. Each of the assessed recycling, recovery and combustion options had an advantage in at least one of the considered environmental aspects.

So, why another LCA?

In the meantime the situation has developed regarding different aspects and the European Association of re-refining industry has reasons to assume that the results from 1999, which focuses on the practices and lubricant quality experiences of the 1990's, are no longer valid:

- New regeneration technologies with improved performance have been developed and implemented;

- Regulatory requirements concerning motor vehicle emissions have enhanced the quality of lubricants.[1] The recycling products from the new regeneration techniques comply with these requirements; and

- In today's markets, the amounts of synthetic and semi-synthetic compounds in lubricants have increased significantly and keep increasing – from about 9 percent of total lubricant volumes in the year 2000, it is estimated to rise to 12 percent in 2005 and around 30 percent in 2030. Along with this trend the inherent quality of collected used oils is substantially improving.

Recognizing these developments, GEIR has commissioned a study to assess these developments concentrating on the core cycle "base oil production → used oil → base oil re-refining". A key question to be addressed is:

How is the relation between ecological burden of re-refining and ecological burden of primary production of base oil (or lubricants) of equivalent quality?

In addition, a brief assessment of direct combustion in cement kilns or other thermal processes will illustrate the ecological differences between these disposition alternatives for used oil. [2]

This study has been reviewed by panel of experts in accordance to ISO 14040 section 7.3. The review process had started after finalising a draft report of the assessment. The majority of amendments have been considered during the final editing.

1 API group II (content of saturates >90%, of sulphur <0.03%, viscosity index from 80 to 120.

2 **Remark:** The terms "re-refining" and "regeneration" are used synonymously to denote the recycling of used oil to recover base oil; the term combustion refers to burning of used oil for recovery of heat energy.

2 Goal of the study

The goal of this study is to provide an updated and forward-looking vision on the ecological and energetic aspects of re-refining of used oil. The conclusions of the previous LCA studies representing the situation of the 1990's shall be modified to reflect the current situation and the predicted development in the following decades. Information used regarding the re-refining processes draws upon the conditions practiced at five companies operating in Europe, and one in the US.

- Five advanced techniques of re-refining shall be modelled and compared considering their environmental impact and their environmental benefits because of substituting primary products.
- An average of the advanced re-refining techniques considered shall be compared with combustion.
- The most decisive parameters shall be worked out in a transparent way

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

3 Scope and Methods

The methodology of this assessment follows the study of Arcadis/ifeu [2000] closely, in order to provide opportunity to track changes in results. Of course, further developments in LCA procedure are likewise followed.

The general steps of LCA as indicated by ISO 14040 are given in Figure 3-1.

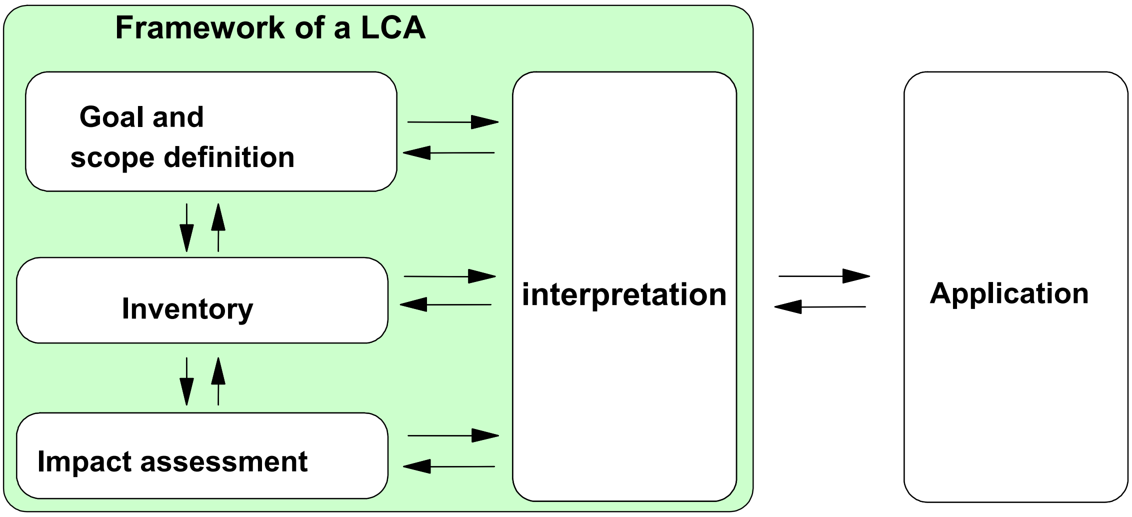

Figure 3-1 Phases of a life cycle assessment [ISO 14040]

3.1 Scope

The reference unit is the entire quantity of re-refinable used oil within the European Union. According to the study of Monier and Labouze [2001] this is about 600,000 Mg per year, corresponding to 25 percent of the total collectable quantity of used oil in Europe. All inventory data offered by the participating re-refining companies will be taken as baseline data to identify the average quality of used oil for this assessment.

Today this number has increased to 800.000 Mg per year according to GEIR [2004] statistics.

The calculations will refer to empiric data given by the considered re-refining companies. In average they are presumed to represent a typical situation. It is not within goal and scope to analyse the used oil market with all its flows.

Therefore the **functional unit** for calculation of inventory and impacts can be focussed on the **treatment of 1 Mg of collected and re-refinable used oil**. For Normalisation purpose the results will be scaled up on the reference quantity of 600,000 Mg.

3.1.1 Number of re-refining techniques

The assessment will provide a complete survey on the currently practised techniques in Europe. Techniques that have been being established in other countries – e.g. USA will also be considered. Each plant has been modelled on its own. So in principle a "ranking"[3] and calculation of an intermediate situation[4] are possible.

Representatives of GEIR distributed a questionnaire to all participating companies, requesting data concerning processes, energy consumption, and other environmental themes. The completed questionnaires serve as the major data base for modelling and assessing the re-refining processes.

3.1.2 System boundaries

To compare re-refining of used lubricants it is not sufficient to restrict the scope to the re-refining plant level. At first it is necessary to include **transport** from the waste producer to the re-refiner. But in all recycling, every waste management system for used oil has to collect and deliver the materials. Actually there is no reliable analysis available, proofing different transport distances according to different ways of recovery. Hence there is a unitary delivery distance assumed basically for all options. But it might be objected, that re-refining plants are less densely dispersed than combusting sites. Therefore longer distances from source to re-refining plant might be consequential. The sensitivity of this aspect will be addressed in the study.

3 Documentation only in an internal report

4 The result presented in the final report for publication will contain only averaged or at least highly anonymous data.

It is indisputable that all **external processes** due to re-refining (e.g. fuel production or electrical power supply, crude oil drilling and production, digging and mining) have to be taken into account. Also, downstream processes like waste disposal should be included.

The analysis of a re-refining option ends when a **specified product** enters the economic cycle. The quality specification has to be recognized because production of an equivalent product has to be analysed considering all elements in its primary production chain.

Likewise **by-products** of the re-refining process – e.g. surplus of process energy – will be assessed. 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 used oil and technical standard. Imported materials – like crude oil or coal from overseas – are likewise considered as far as they are consumed within the systems.

In terms of **time scale** the study assesses techniques that are at the edge of entering practise. The data concerning production and delivery of energy and raw materials are as current 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 extend 1 % of mass of the reference flow (e.g. used oil in the re-refining plant) is not considered. The sum of neglected materials within one process shall not extend 5 % of the reference flow.

Some data are taken from highly integrated data banks. It is not possible to proof in all cases whether these cut-off criteria are given there as well. From experience we estimate that uncertainties to have minor to no impact on the results of this study.

Nor construction of the plants is not mentioned neither other capital goods.

3.1.3 Substituted primary products and their production processes

Assessments 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. So for an ecological assessment of used oil recovery, this aspect takes central importance.

The products of the re-refining techniques will be specified in terms of the substantial equivalency to products they substitute within the lubricant market. Listed by increasing quality these are:

- Classical base oils, refined from waxy distillates, extracted, de-waxed and mostly hydrotreated;
- XHVI oils -- a wax isomerate made from slack wax by catalytic isomerization and hydrofinishing;
- hydrocracked oils (also extracted and de-waxed); and
- polyalpha olefins (PAO).

A recognized increase over time in volumes of higher quality lubricant compounds found in the pool of used oil can be traced by certain characteristics analyzed in used oils, and the certain improved properties of re-refined products. Currently, about 9 percent of synthetic compounds are found in automotive lubricants. With the steadily more demanding specifications and requirements of the automotive industry for better lubricant quality, a maximum scenario of 30 percent synthetics in lubricants formulations can be assumed in the future. To illustrate the full range of impact, two scenarios are drawn:

1. the “worst case”: 0 percent of synthetic or semi-synthetic compounds in lubricant formulations, respectively 100 percent of classical base oil
2. the “presumed best case”: 30 percent of synthetic compounds in lubricant formulations; for calculation, PAO are used as representative for the entire range of synthetic or semi-synthetic substance groups (HVI, XHVI, hydro-cracked oils) that might constitute more than 30 percent of formulations.

Data for the production of PAO are available from the literature. ifeu has worked on environmental data of refineries for a significant period of time. During this time, the ifeu institute has updated and expanded its data base for refinery products. Additional developments in desulphurisation will be made and this effort will be taken into account.

Figure 3-2 gives a very simplified scheme of the re-refining system and the system of equivalent primary processes substituted by the benefits of re-refining. Analogically Figure 3-3 shows the system boundary for combustion.

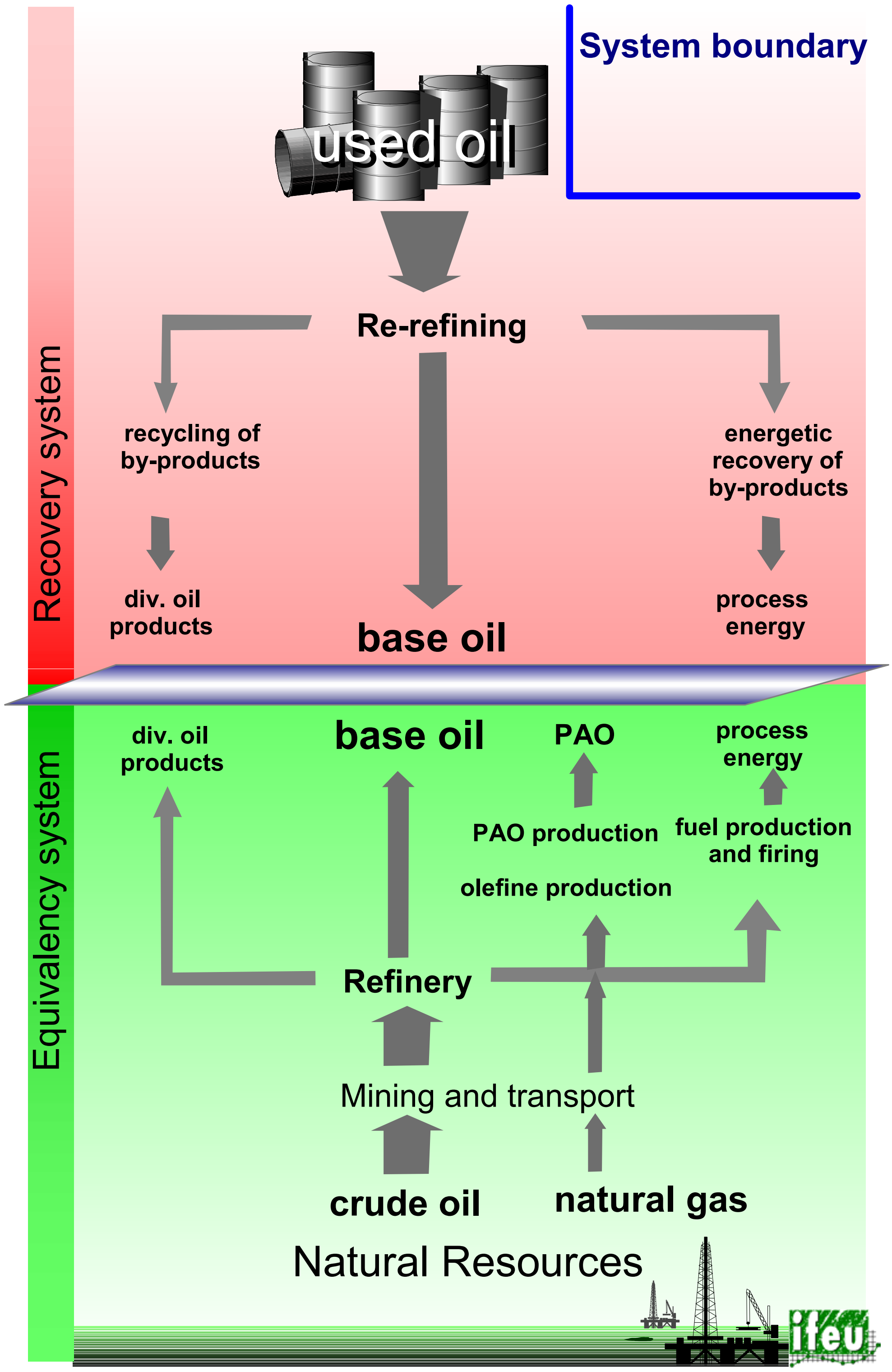

Figure 3-2 Simplified scheme of the system boundary calculating re-refining

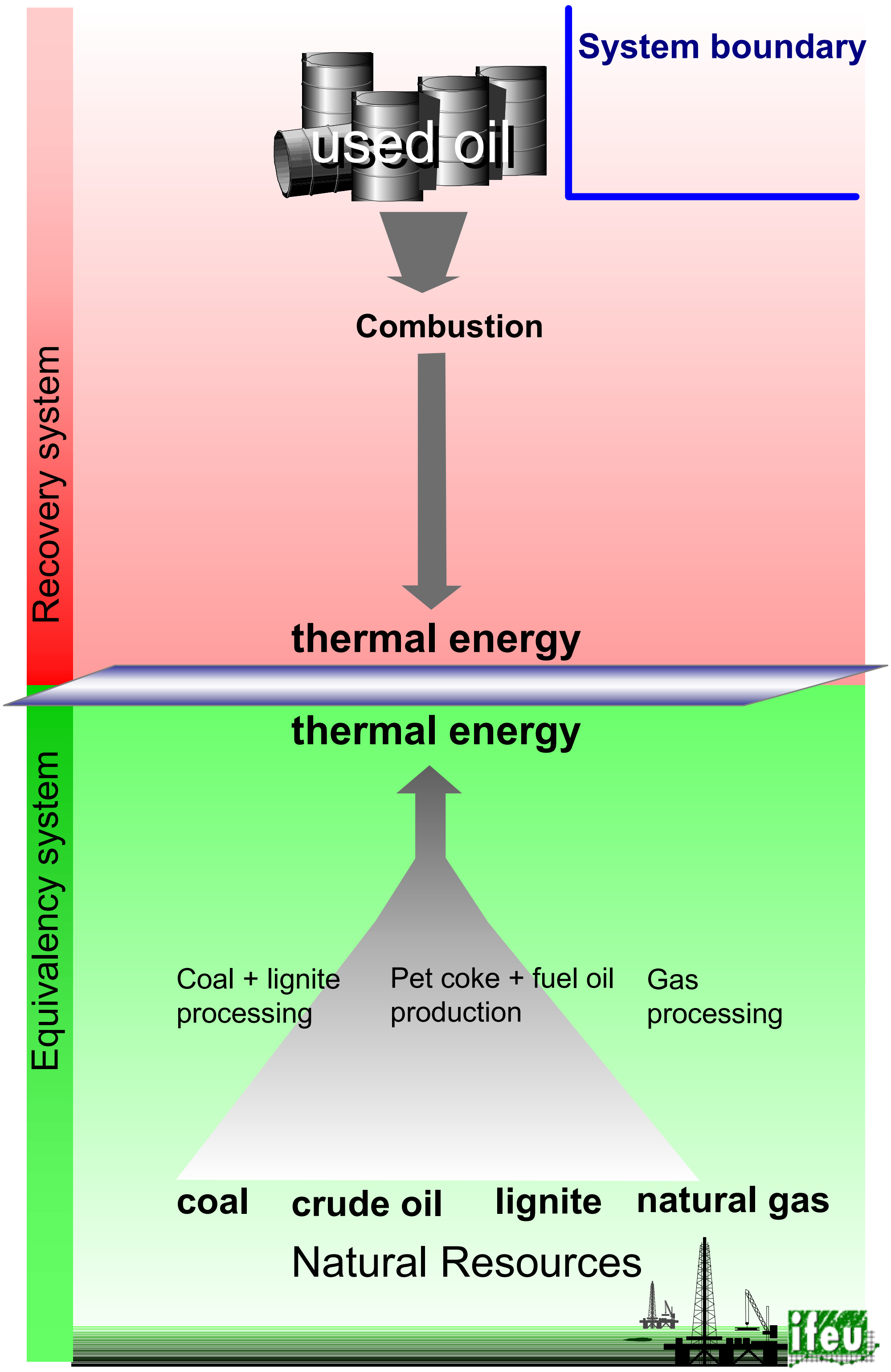

Figure 3-3 **Simplified scheme of the system boundary calculating combustion**

3.2 LC Impact Assessment

In order to restrict the amount of the inventory data to a manageable size, all substances released to or taken from the environment and having a similar impact are grouped (*classification*, e.g. carbon dioxide and methane contribute to the greenhouse effect). If the degree to which the different substances contribute to the respective impact is known they may be offset against equivalence factors and aggregated (*characterization*, 1 kg of methane has the same impact as 21 kg carbon dioxide).

The selection of impact categories follows widely the approach of Arcadis/ifeu [2000]. Global warming, acidification and terrestrial nutrification are generally addressed themes in LCAs. The impact category “resource depletion” is implemented here in compliance with the German UBA-method [UBA 1999], combining the heat value of the primary energy resource with the rate of depletion of the resource.

Table 3-1 Used impact categories and indicators, classified data categories and characterization factors

Impact category	Data category	Characterization factors	Unit
Resource depletion:	Mineral oil	1	kg Raw-Oil-Eq. / kg
	natural gas	0.627	kg Raw-Oil-Eq. / kg
	coal	0.1836	kg Raw-Oil-Eq. / kg
	lignite	0.0409	kg Raw-Oil-Eq. / kg
Global warming:	CO_2 (fossil)	1	kg CO_2-Eq. / kg
	CH_4	21	kg CO_2-Eq. / kg
	N_2O	310	kg CO_2-Eq. / kg
Acidification:	SO_2	1	kg SO_2-Eq. / kg
	NO_X	0.7	kg SO_2-Eq. / kg
	NH_3	1.88	kg SO_2-Eq. / kg
	HCl	0.88	kg SO_2-Eq. / kg
	HF	1.6	kg SO_2-Eq. / kg
	H_2S	1.88	kg SO_2-Eq. / kg
Nutrification,	NO_X	0.13	kg PO_4^{3+}-Eq. / kg
terrestrial:	NH_3	0.346	kg PO_4^{3+}-Eq. / kg
Human toxicity:			
Carcinogenic risk	As	1	kg As-Eq. / kg
Potential:	Cd	0.42	kg As-Eq. / kg
	Cr (10 % Cr-VI presumed)	0.279	kg As-Eq. / kg
	Ni	0.056	kg As-Eq. / kg
	PCDD/F	10,200	kg As-Eq. / kg
	Benzo(a)pyren	20.9	kg As-Eq. / kg
	PCB	0.279	kg As-Eq. / kg
fine particulates	Primary particulates	1	kg PM10-Eq. / kg
(PM10):	SO_2	0.087	kg PM10-Eq. / kg
	NO_X	0.216	kg PM10-Eq. / kg
	NH_3	0.159	kg PM10-Eq. / kg
	Hydrocarbons	0.012	kg PM10-Eq. / kg

Concerning the impact category “human toxicity”, a generally accepted approach covering the whole scale of toxicological concerns is not yet available. In this assessment two indicators are presumed to be representative: carcinogenic pollutants and fine particulates (primary particulates as well as precursors).

Waste water data are addressed within the inventory. Re-refining causes definitively effluents. But all considered plants are connected to a sewage plant (on-site or municipal). Furthermore the LCA studies (esp. Arcadis/ifeu [2000]) the past have shown on the one hand, that the impact of re-refining is generally lower than the one caused by primary refineries. On the other hand the differences concerning waterborne impacts had turned out to be of low significance. Due to that experience aquatic impact indicators are neglected in this assessment.

By the same arguments the impact category “photosmog” is left out of this study.

3.3 Interpretation

A valuation approach developed by the German Federal Environmental Agency [UBA 1999] and based on various scientific research studies will be used. The approach is based on two procedures described in ISO 14042:

- Normalisation: 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 (normalisation 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.

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.

The results are given as follows: Differences between the options are given as number of PEV, the bar colours represent the priority level of respective impact category (black for A, dark grey for B, etc.).

Table 3-2 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

	Normalisation		Ranking
	Per-capita load German inhabitant PEV	Reference	Ecological Priority
Fossil energy resources	2382 kg ROE/a	(a)	"medium"
Global warming	11,820 kg CO_2-Eq./a	(a)	"very high"
Nutrification, terrestrial	5.22 kg PO_4-$^{3+}$ -Eq./a	(a)	"high"
Acidification	40.8 kg SO_2 -Eq./a	(a)	"high"
Carcinogenic pollutants	4.8 g As Eq./a	(b)	"very high"
Fine particulates (PM10)	9.25 kg PM10 Eq./a	(a)	"high"

References: a) UBA - Daten zur Umwelt 2000
b) Calculation by ifeu
c) Estimation by ifeu

Ecological Priority based on UBA [1999]

Eq. = equivalents

4 Characterisation of used oil

The following table (Table 4-1) shows the typical average composition of used oil handled by re-refining companies. From these data reference values are calculated and presented below (Table 4-2):

Table 4-1 Physical properties and contents of used oil according to the specifications of five re-refining companies

		1	2	3	4	5
Water	wt. %	5	6 – 8	6.0	8	6
Flash Point COC	°C	220				
Flash Point PM	°C		> 61	> 70		
Flash Point VA	° C				110	
Heating Value (Hu)	MJ/kg		39.8	39.8		
Heating Value (Ho)	KCal/kg				42.6	
Sulphur	wt. %	0.6	0.5 – 0.7	0.70	0.8	0.23
Density 15°C	kg/m³	902	875 - 890	890	900	
Chlorine	wt. %	0.07	< 0.09	0.04	0.1	0.1
Sediment Content	vol. %			< 3		0.4
Acid Number	mg KOH/g	1.2	3	3.0	3.8	
Saponification No	mg KOH/g	1.8	10	7.0	12.0	
PCB	mg/kg	20	< 3	n.d.	10 - 11	<2
PCDM	mg/kg		n.b.	n.d.	N.A.	
Pour Point	° C	-3		-25	N.A. (*)	
Viscosity @ 40°C	mm²/s		45 - 55	60	50	60
Viscosity @ 100°C	mm²/s	7.3		9		
Oxide ash	wt. %	1.1	0.75 – 1.05	0.8	0.8	
PAH (= PCA = PNA)	wt. %			0.022	4	
Aluminium	mg/kg	15	50	30	29	
Arsenic	mg/kg			< 0.5	0.6	
Barium	mg/kg	5	25	35	15	
Lead	mg/kg		35	30	60	50
Calcium	mg/kg	1000	1500	1000	1490	0 - 3000
Cadmium	mg/kg			< 0.2	<1	0 - 5
Chromium	mg/kg	2	5	5	5	
Fluorine	mg/kg			< 0.02	absent	
Cobalt	mg/kg			< 0.5	1.3	
Copper	mg/kg	10	30	35	40	
Manganese	mg/kg		10	18	6	
Magnesium	mg/kg	250	200	180	150	
Nickel	mg/kg	< 1	3	2.5	6	
Phosphorus	mg/kg	400	750	700	949	700
Mercury	mg/kg		< 0.1	< 0.1	0.05	
Silicon	mg/kg	20	190	50	150	100
Thallium	mg/kg		< 0.1	< 0.1	29	
Titanium	mg/kg	< 1	< 8		7	
Vanadium	mg/kg	< 1	2	< 1.0	< 1	
Tin	mg/kg	< 1	3	4	33	
Zinc	mg/kg	500	800	760	700	

These qualities represent separately collected used engine and gear oil suitable for regeneration to base oil. Qualities which don't meet the specification for regeneration, but only for combustion, are not in the scope of this assessment (see section 3.1).

About 85 to 90 percent of the used oil handled on the European market meets this specification.
A decrease of the so called SAPS (sulphated ash, phosphorous and sulphur) is observable due to increasing quality standards. This will effect a decrease of operating expenses of re-refining.

Table 4-2 Reference values for the used oil in this assessment

	Reference value (original substance)	
Water	6	wt.%
Heating Value (Hu)	40	MJ/kg
Ash	1	wt.%
Carbon	80	wt.%
Sulphur	0.7	wt.%
Chlorine	0.07	wt.%
Fluorine	0.1	wt.%
Arsenic	0.5	mg/kg
Lead	40	mg/kg
Cadmium	0.2	mg/kg
Chromium	5	mg/kg
Cobalt	0.7	mg/kg
Copper	30	mg/kg
Manganese	10	mg/kg
Nickel	5	mg/kg
Mercury	0.05	mg/kg
Thallium	0.1	mg/kg
Vanadium	0.5	mg/kg
Tin	15	mg/kg
Zinc	700	mg/kg
PCB	10	mg/kg
PAH	1	mg/kg

Table 4-3 provides a selection of quality data of re-refined base oil by the regeneration companies.

Table 4-3 Quality data of re-refined base oil

	unit	Typical quality re-refined base oil (SN150)	Typical quality virgin base oil (SN 150)	Method
Viscosity @ 40°C	mm²/s	29 - 32	29 - 31	ASTM D-445/ DIN 51562-1
Viscosity Index		105 - 115	95 - 100	ASTM D-2270/ DIN ISO 2909
Colour		L 0.5	L 1.0	ASTM D-1500/ DIN ISO 2049
Sulfur	ppm	10 - 2000	2000 - 6000	ASTM D-4294 /DIN EN ISO 8754/ ASTM D-5453
Total Acid No.	mg KOH/g	<0.03	<0.05	ASTM D-974/ DIN 51558-1,2,3/ IP 1A
Vapour Loss (Noack)	wt. %	8 - 12	12 - 16	ASTM D-5800/ DIN 51581/ CEC L40 A93
PAC	wt. %	<0.2	<1.0	IP-346
Benzo(a)pyrene	ppm	<0.3	not available	Grimmer (GC)/ICP

5 Description of the considered regeneration techniques

In this study regeneration of used oil to recover lubricants is highlighted by five technical concepts. These represent high technical standards aiming for high quality products. Four of them are based on hydrogenation technology and one on extraction technology. In the following, they are briefly characterised with a basic data set on the process inventory. Concepts adopted by the companies are alphabetically listed.

Figure 5-1 shows a simplified process scheme of a re-refining process as it resembles most of the considered techniques. In detail there can be differences in number and sequence of sub-processes. Some of the processes use by-products for their own energy production. Some of them deliver an energy surplus.

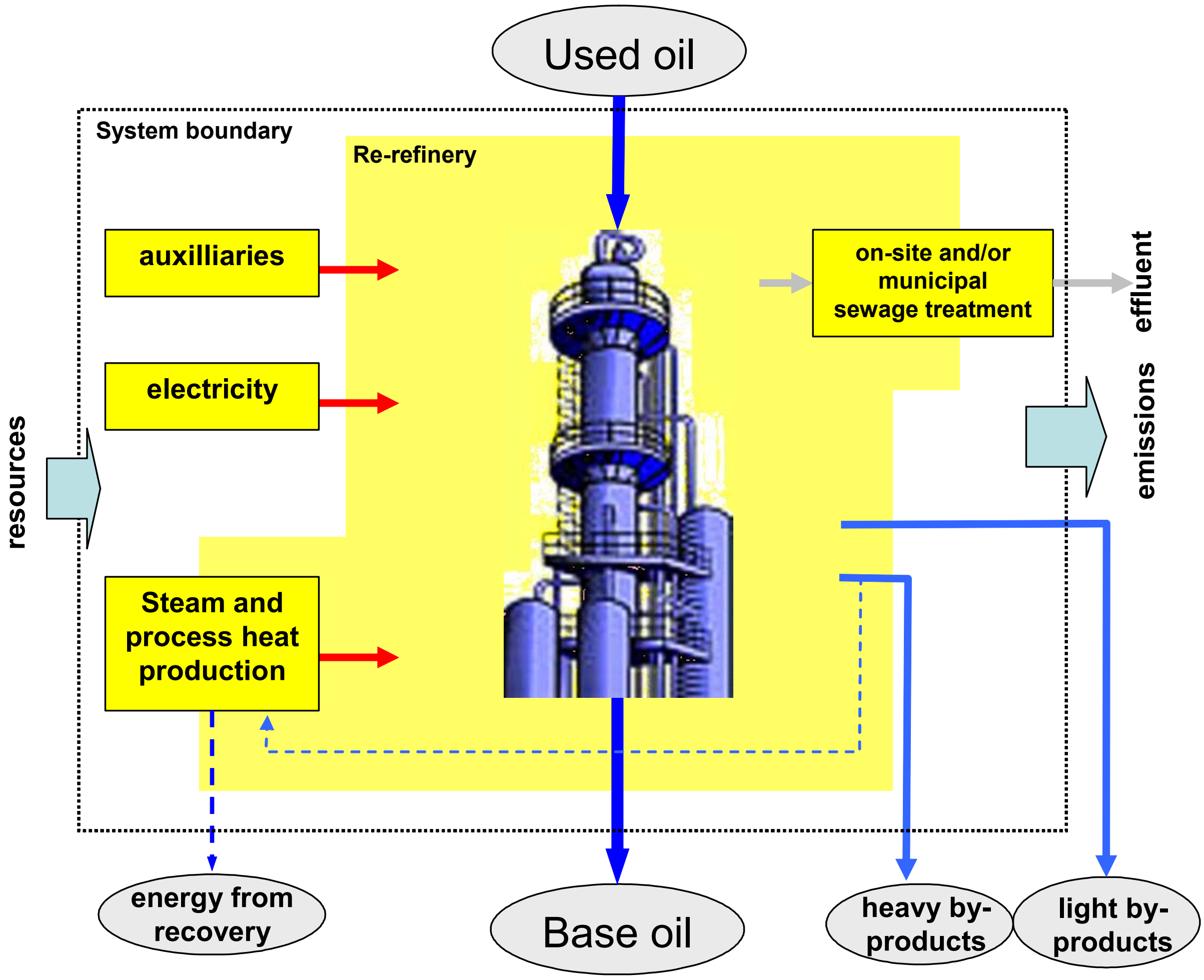

Figure 5-1 Simplified and generalized process scheme of a re-refining process

The following sections give brief descriptions of the five techniques.

5.1 Cyclon

Cyclon Hellas SA operates a re-refining plant based hydro treatment technology in Aspropyrgo, Attica (Greece). It constitutes a modern unit which regenerates annually 38,000 Mg of mineral oils 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).

5.2 Evergreen

CEP (Chemical Engineering Partners) is the engineering affiliate of U.S. company Evergreen Oil, Inc. consigned to the re-refining business. CEP's technology for re-refining is based on vacuum distillation (using Thin Film Evaporation) and hydrotreating (also known as hydrofinishing). In fact, all the existing commercial re-refiners in North America use this technology.

5.3 Hylube

As a subsidiary of the PURALUBE Inc. (Wayne, USA) the PURALUBE GmbH has build up a modern waste oil refinery in the Industriepark Zeitz (Saxony-Anhalt). It is the world-wide first facility which uses the HyLube™ technology which has been developed by UOP. The speciality of this process is the hydrogenation of base oils which is executed parallely 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 has an auxiliary material as well as an energy source. The refinery has a capacity of about 90,000 Mg per year and is operating since spring 2004. The plant produces high quality base oils of API group II which are characterized by nearly water clear colour, low sulphur content and a high viscosity index.

The process can be summarised as follows:

1. Pre-Treatment
Intimate mixing of hot hydrogen gas with the feed results in the separation of the high value lubricating oil molecules in a high pressure / high temperature environment, which avoids coking and fouling. The inorganic molecules, metals and heavy asphaltic components (bottoms) are separated before entering the catalytic section and are desirable for use as paving grade asphalts.

2. Catalytic Hydrotreatment
Two high pressure hydrotreating reactors are loaded with specially designed catalyst systems:

- The first reactor (guard reactor) removes any last traces of metals as well as initiating the desulphurisation process.
- The second reactor is loaded with catalysts designed to saturate the olefinic and aromatic molecules as well as completing deep desulphurisation and denitrification of the lubricating molecules.

3. Product Recovery and Finishing
After hot and cold depressurisation, whereby the surplus hydrogen is scrubbed to remove the chlorides and sulphides generated in the hydrogenation stages, the hydrogen is recycled to the beginning of the process. The purified liquid lube boiling range molecules are further processed in the vacuum distillation unit. Strippers are installed on each side-stream to produce the very narrow boiling range lube stocks desired by the industry.

Diesel produced in the hydrogenation stage has a very high cetane blending value as well as a very low sulphur content.

5.4 MRD

Mineralöl-Raffinerie Dollbergen (MRD) is an integrated plant processing various recycled hydrocarbon and oily water feedstocks and is situated in Lower Saxony, Germany. Extraction technique is applied there. The former concept of clay treatment was substituted by a modern solvent extraction unit. Below are the elementary steps.

1 Dehydration - Basic Distillation I and II
All used oil in the Mineralöl-Raffinerie Dollbergen is thermally distilled under light vacuum. The initial separation steps serve to distill away water and highly volatile components. The remaining bottom product is designated as dewatered oil. It has a flash point of above 61°C and contains approx. 0.1 - 0.2 % water by weight. The dewatered oils are classified according to quality and transferred to the following process steps.

2 Flash distillation
Used oil is dried by atmospheric distillation and transferred from storage tanks to the flash distillation unit, where multiple distillations are performed. As with distillation of flux oil, a fraction similar to light heating oil is first removed by distillation.

The product on the bottom of the column is then separated by a so-called flash distillation - consisting of a flash drum and two thin film evaporators - into crude base oil distillate, the so-called “flash distillate”, and a distillation residue, the so-called “bottom product.”

This distillation residue is composed of all additive compounds in the dry oil, soot particles, metal fines and other components of used oil.

3 Solvent extraction
The introduction of solvent for extracting aromatics and other unwanted compounds replaces the formerly applied clay treatment unit and makes the entire process more efficient.

The heating furnaces for the plant are fed by fuel produced as by-products. Exhaust gases are treated with an exhaust scrubber in such a way that the purified gases adhere to all regulatory requirements. Waste waters are fed to the refinery water treatment plant.

A high temperature combustion chamber is used for incinerating waste refinery vent gases, and heat recovery is practiced making major contributions to the performance of the plant.

5.5 Viscolube

Present in Italy with two production facilities – Ceccano (Frosinone) and Pieve Fissiraga (Lodi) – Viscolube treats about 130,000 tonnes of used oil every year, thus producing about 90,000 tonnes of re-refined base oil.

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

This assessment focuses on the advanced technique of the Fissiraga plant, which can be described by three major steps:

1 Preflash
The used oil is heated up to 140°C and then distilled in a vacuum column where water and light ends are separated.

2 Thermal De-Asphalting (TDA)
The dehydrated oil is distilled at 360°C in a vacuum de-asphalting column (TDA) where the asphaltic and bituminous products remain on the bottom. Three side cuts at different viscosity are fractionated. An intermediate gas oil is distilled at the top of the column. The three side fractions and the gas oil are sent to storage to be subsequently hydrofinished by campaign in a high pressure (100 bar) catalytic plant.

3 Hydrofinishing
Hydrofinishing process starts in a fired heater where the oil and hydrogen are heated up to 300°C and are subsequently sent to a reactor containing a catalyst favouring the hydrogen reaction with the unsaturated compounds, sulphur and nitrogen. The reactor effluent is then separated into two phases, the vapour phase and the liquid phase; the first one is washed with water in order to remove the chlorine and sulphur compounds, the second one is stripped with steam to eliminate the most volatile compounds and restore the flash point. The water contained in the oil after stripping is then removed in a vacuum dryer.

The streams containing sulphur are sent to an amine plant where the hydrogen sulphide is separated from the other compounds and then to a Claus plant where H_2S is transformed into pure liquid sulphur.

The final result is clear oil with very low sulphur and Polynuclear Aromatics (PNAs) content.

5.6 Technical data

IFEU obtained confidential data by the companies to describe energy and material demands of the processes. These data are subsumed in Table 5-1. To grant anonymity the order in the table doesn't fit the order of descriptions.

These data have been elaborated early in 2003 and early in 2004. They are based on operating experiences as well as on long-term trial runs.

Table 5-1 On-site inventory of the five techniques considered

Input	**Technique 1**	**Technique 2**	**Technique 3**	**Technique 4**	**Technique 5**	Unit
Used oil	1000	1000	1000	1000	1000	kg
Auxiliaries						
caustic soda	4.67	10		0.71	2.69	kg
potassium hydroxide			0.06			kg
hydrogen	5.16	4.32		2.02	0.30	kg
nitrogen					1.42	kg
Soda	8.41					kg
propane				2.25		kg
n-Methylpyrrolidon			0.06			kg
energy demand						
electricity	875	226	122	283	223	MJ
process heat	1360 a)		622	2420		MJ
process heat (gross demand)		2020 b)			3390 b)	MJ
process heat (net demand)		264 b)			*902* b)	MJ
process steam	632	2360 c)	1630	617	216 a)	MJ
process water	374				360	kg
Output						
base oil	770.8	694.9	544.5	725.2	695.6	kg
Naphtha	37.6					kg
light ends		47.0 d)	25.0 e)	14.2 e)	141.0 h)	kg
extracts			78.0 e)			kg
flux oil			29.3 h)	82.2 h)		kg
light fuel oil	75.2 f)			99.2 e)		kg
gas oil		68.6 f)			37.6 g)	kg
heavy oil	56.4 i)		137.3 e)		65.8 j)	kg
bitumen additive		134.8 k)				kg
Residue			123.6 i)			kg
used process water	433.8	60	59,7	79	420	kg
						kg
net energy deliverance						
process heat			7500	707 l)		MJ
Explanatory legend see following page						

Source: Cyclon, Evergreen, Puralube, MRD, Viscolube

a) Process heat and steam is produced by a natural gas fired furnace resp. boiler

b) After combustion of light ends (a) and covering partly the “gross” demand on process heat there rests a “net demand”. This is normally covered by by-products of other refining sites of the company. For this balancing natural gas firing is applied to avoid additional complications due to allocation.

c) Steam is produced also by by-products. Here is also natural gas firing presumed.

d) Light ends (naphtha quality) are applied as fuel on the regeneration site and cover partly the process heat demand (input: “gross demand” minus “net demand”).

e) Light ends, extracts and fuel oil (DIN quality) is applied as fuel on the regeneration site; they cover the process heat and process steam demand (input) and leave a “*net energy deliverance”* (Output).

f) Gas oil (Diesel quality) applied as fuel off the regeneration site but within the system boundary; equivalency process is a light fuel oil combustion with pre chain.

g) Diesel quality; equivalency process is production of hydro finished diesel

h) “Flux oil”, residues and light ends are applied as additive to bitumen; equivalency process is an application of vacuum distillate (flux oil) with pre chain.

i) Heavy oil and residues are applied as reduction material within a blast furnace; equivalency process is an application of heavy fuel oil with pre chain.

j) Heavy oil is applied on-site as fuel and covers partly the process heat demand (input: “gross demand” minus “net demand”).

k) Residues are applied within the manufacture of bitumen layers; equivalency process is an application of bitumen distillate with pre chain and partly of polypropylene fibres (1 kg of residue substitutes 1 kg of bitumen and allows in addition to reduce the polypropylene demand about 420 g.

l) After combustion of light ends and light oil (a) and covering the process demand on heat, this amount is another benefit of the process; equivalency process is a fuel oil combustion with pre chain.

6 Description of the substituted and other inflicted processes

In this chapter the basic processes involved in production of new base oils for the lubricants industry are described. They are on the one hand primary processes that are substituted by used oil regeneration, and on the other hand represent several processes up or down stream of regeneration characterised in terms of inventory.

6.1 Processing primary refinery products from mineral oil

6.1.1 Methodical issues of modelling life cycle inventories

Mineral oil refineries are highly integrated and multiple-output production plants. A waxy distillate – basic feedstock for base oils – will not be produced without producing petrol, diesel or fuel oil. Nearly each step creates co-products, and, therefore, a clear and consistent way of calculating total input (consumptions) and total output (emissions) has to be carried out. In this assessment, the principles of allocation follow the scheme as used by Arcadis/ifeu [2000], which follows the requirements of ISO 14041 (6.5):

1. The sum of allocated inputs and outputs equals to the unallocated inputs and outputs of the process unit.
2. The factors to partition inputs and outputs between the co-products underlie physical relationships; in this case, **mass proportion** is selected.
3. When a co-product does not gain any upgrading through a process, it is not “held responsible” for the consumptions and emissions of this process; instead of using the co-product, the feedstock itself can be used to the purpose.
4. ISO 14041 demands a sensitivity analysis whenever several allocation procedures seem applicable; this requirement will be conformed (see section 7.3).

A software model aids in calculating the complex network of refinery processes step by step (atmospheric distillation, vacuum distillation, Visbreaker, hydro cracker, etc.), and an integrated sum of all connected modules. Within each module the relations concerning inputs and outputs and the allocation rules are defined. Figure 6-1 shows a plot of the network model. At the bottom the base oil production is illustrated. Not shown but considered in the calculation model are the energy processes (furnaces, boilers and power supply) and diverse secondary processes (sewage plant, Claus plant, torch/flare, waste treatment, etc.).

Consumption data are taken from diverse sources (direct information given by single plants, reference document on Best Available Techniques for Mineral Oil and Gas Refineries [EIPPC 2001], Patyk [2001] and data from Arcadis/ifeu [2000]). The data used reflect the emission and consumption levels of mineral oil refineries in Europe.

The pathway in modelling the process chains to generate the core products needed in this assessment is described below.

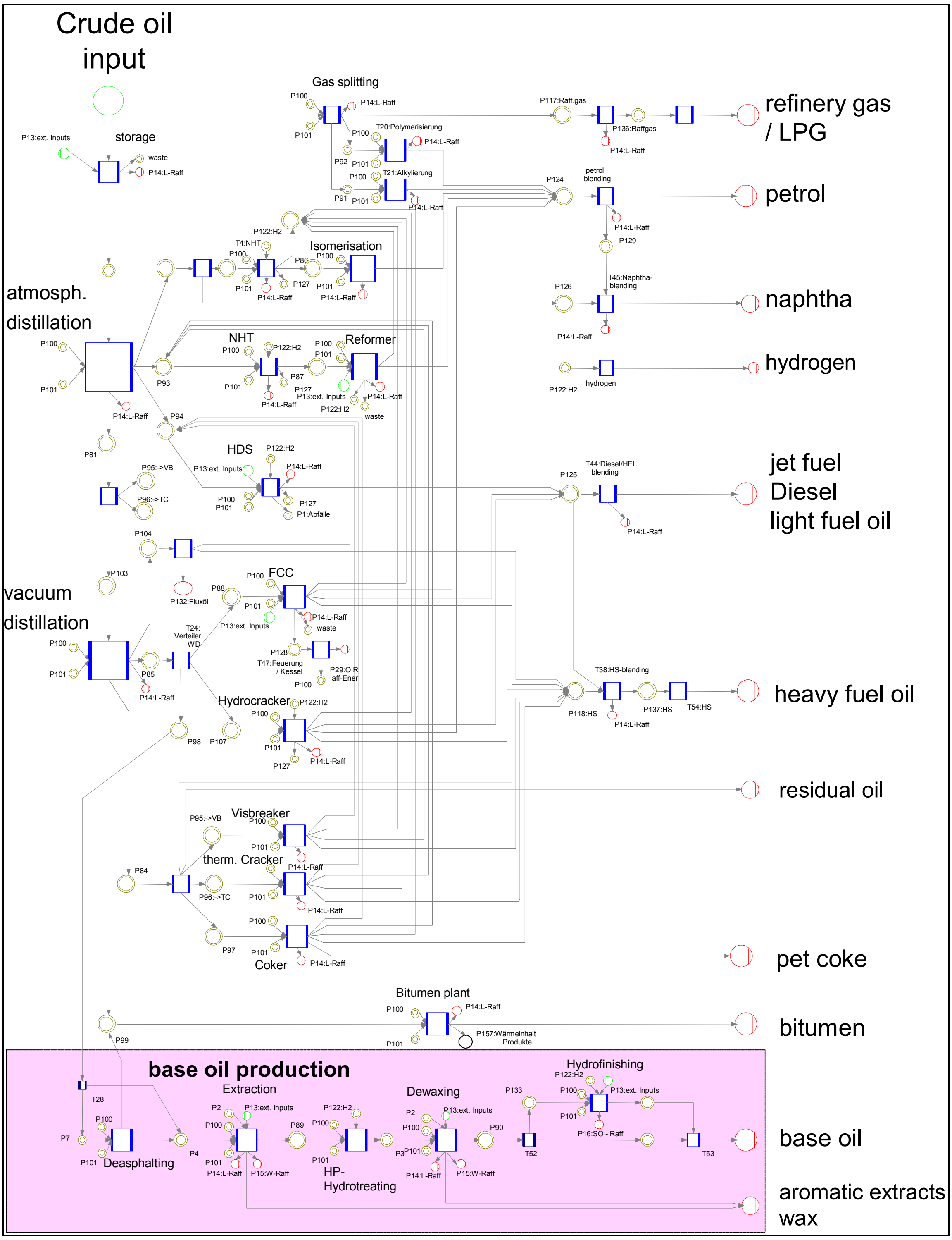

Figure 6-1 **Network model for the calculation of mass and energy flow of a virtual mineral oil refinery**

6.1.2 Base oil refinery

The process chain of primary base oil production is of central importance in this ecological assessment. Figure 6-2 displays the steps of the processing chain of base oil production from the model shown in Figure 6-1. In this section the stages within the inner rectangle (base oil production) will be described. The following section will focus on basic distillation.

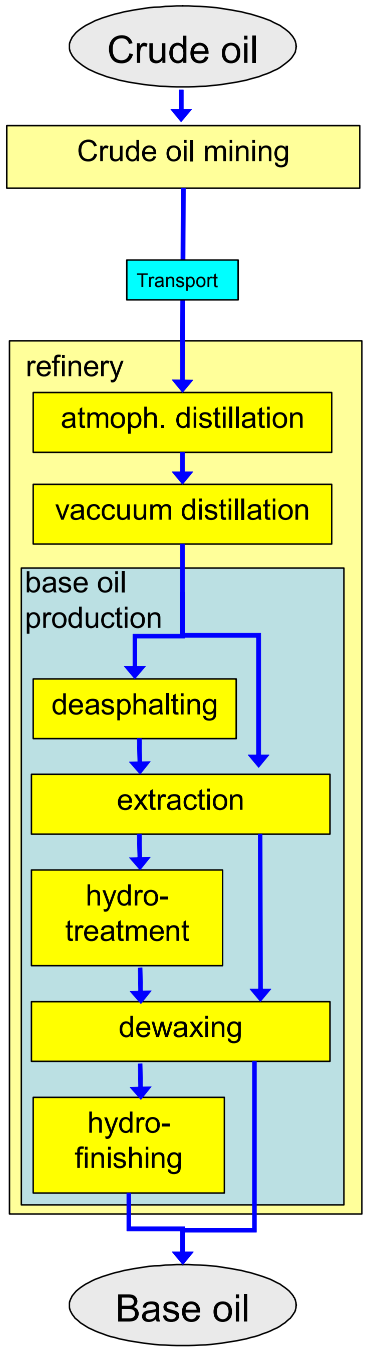

Figure 6-2 Process chain for the production of primary base oil

Two major data bases were used to model mass and energy flow along the base oil production chain:

1. The data from Arcadis/ifeu [2000] where a best estimated average of German production sites has been composed.
2. The reference document on Best Available Techniques for Mineral Oil and Gas Refineries [EIPPC 2001], where the current European emission and consumption levels are documented.

Drawing upon these two sources the specific process data in Table 6-1 and Table 6-2 are elaborated.

Table 6-1 Energy and auxiliary consumption of the process steps of base oil refining

All data per Mg Input		**Arcadis/ifeu [2000]**	**Data from BREF** [EIPPC 2001] from	to	**Set Value**
Deasphalting					
Electricity	MJ		43.9	76	**60**
Process heat	MJ		151	167	**159**
Process steam	MJ		498	2700	**1599**
Aromatic extraction					
Electricity	MJ	47	21.2		**21**
Process heat	MJ	1613	913		**913**
Process steam	MJ	194	(8 m^3)		**194**
Furfurole	kg	0.50			**0.5**
NMP	kg	0.3			**0.3**
Process water	kg	49.1			**49**
Cooling water	kg	17551			**17551**
Effluent	kg	65			**65**
High pressure Hydrotreatment					
Electricity	MJ		94		**94**
Process heat	MJ		460		**460**
Process steam	MJ		600		**600**
Dewaxing					
Electricity	MJ	264	216	576	**396**
Process heat	MJ	338	900	1170	**1035**
Process steam	MJ	1637	900	2400	**1650**
Di-Me	kg	0.6			**0.6**
MEK	kg	0.4			**0.4**
Process water	kg	169			**169**
Cooling water	kg	59355			**59355**
Effluent	kg	182			**182**
Hydro finishing					
Electricity	MJ	62.7	90	144	**117**
Process heat	MJ	356.7	270	495	**383**
Process steam	MJ	351	300	450	**375**
Process water	kg	72.8			**73**
Cooling water	kg	19502			**19502**

Table 6-2 Yield ratios of products by the process steps of base oil refining

	Yield per process step	Percentage of absolute Input
Deasphalting		
Input into process step		20 %
Deasphalted fraction	70 %	14 %
Asphalt fraction	30%	6 %
Aromatic extraction		
Input into process step		94 %
Dearomatized Fraction	65 %	61.1 %
Aromatic extracts	35 %	32.9 %
Dewaxing		
Input into process step		61.1 %
Dewaxed Fraction	80 %	48.9 %
Wax	20 %	12.2 %
Total products yields by the base oil refinery chain		
Base oil		48.9 %
Asphalt		6.0 %
Aromatic extracts		32.9 %
Wax		12.2 %
Source: Arcadis/ifeu [2000], EIPPC [2001]		

As Table 6-2 shows roughly 500 kg of base oil are processed from 1 Mg of waxy distillate. By allocation according to physical relationships, base oil will be charged with clearly more than half of the total energy consumption of the base oil production chain. This is shown in Table 6-3 where for each co-product stepwise a specific heat consumption value is calculated – using the factors from Table 6-1 and the yield ratios from Table 6-2. This example clearly shows that less than 50 % of base oil as total yield is responsible for nearly 70 % of the heat consumption of the total base oil production chain.

But with respect to the allocation principles laid down in section 6.1.1 it could be argued that aromatic extracts tend more and more to be an undesired co-product. The market for a useful application (rubber industry or ink) is decreasing and now few refineries feed the extracts into a catalytic cracking unit (FCC). To this end an extraction is not necessary. Waxy distillate can be used directly. This aspect will be followed by the sensitivity analysis. Following this argumentation the specific burden of base oil will increase from 1,380 MJ to 1,630 MJ (see Table 6-4).

Table 6-3 Example for allocation of heat consumption within the base oil production chain to the co-products

	Base oil	Asphalt	Aromatic extracts	Wax	*total*
Total yield ratio	48.9%	6.0%	32.9%	12.2%	*100%*
	heat consumption in MJ per Mg waxy distillate input				
Deasphalting	15.5	1.9	10.5	3.9	*31.8*
Aromatic extraction	446		300	111	*858*
HP Hydrotreatment	225			56	*281*
Dewaxing	506			126	*632*
Hydrofinishing	187				*187*
Sum per product	**1380**	**1.9**	**310.7**	**297.6**	***1990***
Total ratio of allocated heat demand	69.3%	0.1%	15.6%	15.0%	*100%*

2 examples to show the way of calculation:

1. 200 kg from 1 kg of waxy distillate passes a deasphalting unit, so the total demand is 159 MJ (taken from Table 6-1) times 0,2 Mg equal 31.8 MJ (total), a share of 48.9 % gives the portion allocated to the base oil: 15.5 MJ.
2. the aromatic extraction takes 913 MJ/Mg input, therefore 858 MJ per 940 kg input. The share of base oil takes 52 % (48.9/94 for the asphalt fraction doesn't pass the extraction) which equals 446 MJ.

Table 6-4 Example for allocation of heat consumption within the base oil production chain to the co-products not charging aromatic extracts by the burden of extraction

	Base oil	Asphalt	Aromatic extracts	Wax	*total*
Total yield ratio	48.9%	6.0%	32.9%	12.2%	*100%*
	heat consumption in MJ per Mg waxy distillate input				
Deasphalting	23.2	2.8	0	5.8	*31.8*
Aromatic extraction	687		0	171	*858*
HP Hydrotreatment	225			56	*281*
Dewaxing	506			126	*632*
Hydrofinishing	187				*187*
Sum per product	**1628**	**2.8**	**0**	**359.5**	***1990***
Total ratio of allocated heat demand	81.8%	0.1%	0%	18,1%	*100%*

In contrast to Table 6-3 the 32.9% aromatic extracts here are disregarded when the heat consumption is partitioned

6.1.3 General mineral oil refinery

The previous section concentrated on the original base oil refining steps. But base oil production demands further upstream process in the refinery, such as, the basic distillation steps (atmospheric and vacuum distillation) to produce feed stock for base oil refining: waxy distillate or vacuum distillate.

Table 6-5 Energy consumption of the basic distillation steps of refining

All data per Mg Input		**Arcadis / ifeu [2000]**	**Data from BREF** From	To	**Set Value**
Atmospheric distillation					
Electricity	MJ	52.3	5.4	16.2	**52.3**
Process heat	MJ	614	400	680	**614**
Process steam	MJ	26.2	70	84	**26.2**
Vacuum distillation					
Electricity	MJ	52.3	14.4	21.6	**52.3**
Process heat	MJ	614	400	800	**614**
Process steam	MJ	26.2	56	168	**26.2**

The other basic refinery process steps (catalytic reforming, catalytic cracking, hydro cracking, thermal cracking, and so on) are modelled in the same way. These steps have to be considered when inventories for other refinery products of importance within the scope of this assessment are calculated. It includes fuel oil (heavy and light), diesel, naphtha, flux oil and pet coke.

Table 6-6 Yield per main process step and share of the process along the mass flow

	Product yields in percent of process input	**Share in mass flow** in percent of total refinery input
Atmospheric distillation		
Gas	**2**	**2**
Naphtha	**21**	**21**
Gas oil	**36**	**36**
Residue	**41**	**41**
Vacuum distillation		
Gas oil	**4**	**1.6**
Waxy distillate	**56**	**23**
Residue	**40**	**16.4**

Source: Arcadis/ifeu [2000], EIPPC [2001]

Table 6-7 Fuel selection for energy supply for the model refinery

		Electricity	Process heat	Process steam
Fuel type				
Refinery gas	%	45	63	20
Heavy fuel oil	%	43	29	80
Pet coke	%	13	5	0
Natural gas	%	0	3	0
Contribution to total fuel consumption of the model refinery	%	15	80	5
Source: EIPPC [2001], Patyk [2001]				

6.2 PAO production

In this assessment poly alpha olefins (PAO) are selected to be the representative substance group for synthetic lubricants. The chain of production steps to produce PAO is drawn schematically in Figure 6-3.

PAO are synthesized from 1-decene monomers to branched trimmers of 30 carbon atoms. 1-decene is gained from a fraction of linear α-olefins (LAO) which is polymerized from ethylene molecules. So two basic process steps are needed to produce PAO from ethylene:

- LAO synthesis (with fractionation to gain 1-decene)
- and final PAO synthesis.

Nieschalk [2003] has analyzed the production chain of PAO and worked out data concerning energy demand. These internal data based on confidential information are available to perform this assessment.

Concerning ethylene production there are public data available [APME 2003][5]. In addition ifeu possesses diverse data from the petrochemical industry. Steam cracking is the central process concerning ethylene production. It is fed mainly by naphtha. Some plants in Europe use gas condensates from natural gas processing. Naphtha again is a product from mineral oil refineries. An inventory is calculated by the model described above.

This production chain also leads to a variety of co-products. Those from LAO-synthesis (mostly 1-octene and 1-dodecene) are applied to produce detergents. The mass compounds from steam cracking are ethylene and propylene, but this process creates at least about ten additional products or product fractions. For all these processes the

5 Ecoprofiles can be downloaded in XLS-format from website: www.apme.org

same allocation principles are executed as explicated in section 6.1.1. Nieschalk [2003] proposed an alternative way of allocation. This shall be discussed in section 7.3.2.

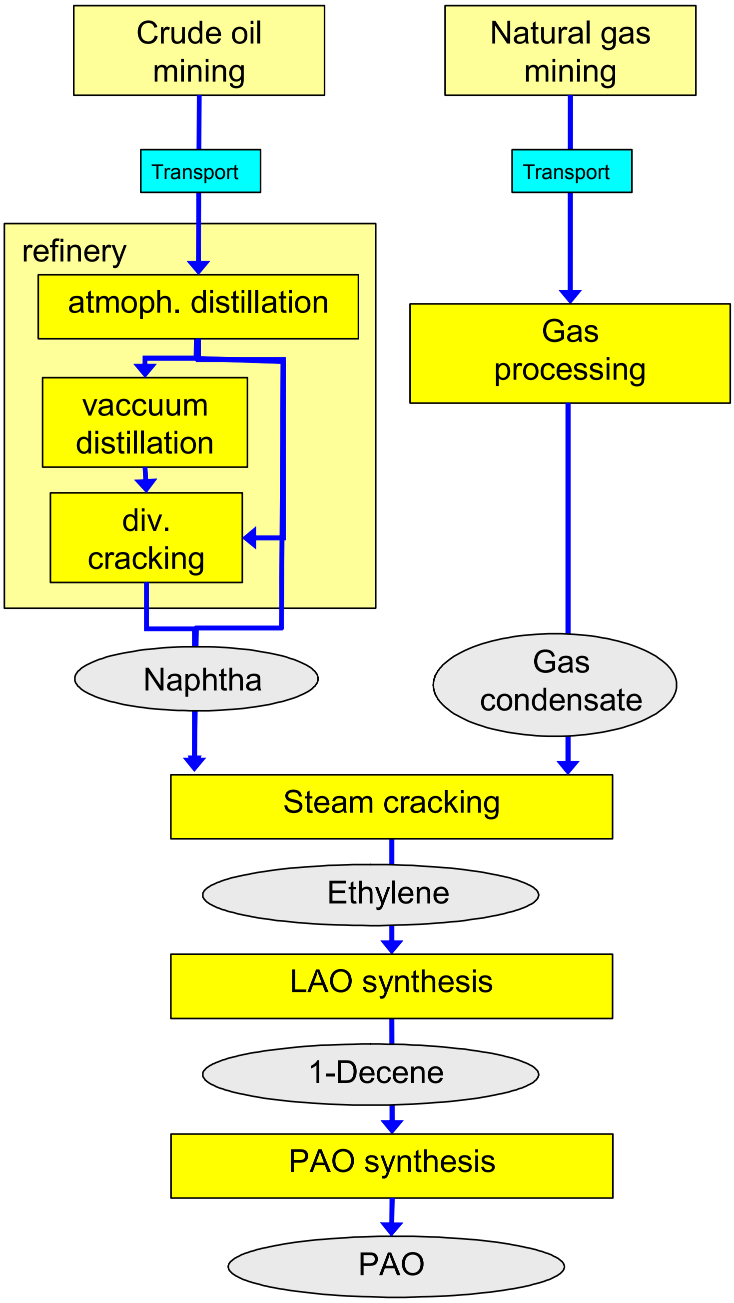

Figure 6-3 Process chain for the production of PAO

6.2.1 Ethylene production (steam cracking)

Table 6-8 gives a condensed overview on the data base for steam cracking. The data are based on one Mg of product. Allocation by mass will assign this inventory to the product fractions equally.

Table 6-8 Material and energy consumption and on site emissions of steam cracking

Material/energy	amount	unit
Product [a]	**1,000**	**kg**
Feedstock input [b]		
Naphtha	*729*	kg
gas condensate (from natural gas processing)	*304*	kg
other feedstocks (propane, refinery gas)	*100*	*kg*
	1,133	**kg**
Thermal energy input [c]	**4,640**	**MJ**
Electric energy input	**503**	**MJ**
Selected emissions by on site heat and steam production		
CO_2	681	
SO_2	0.26	
NO_X	0.64	
CH_4	0.9	

a) Major products: Ethylene, propylene
Typical by-products: Other short chained olefins, aromatics or mixed cuts like pyrolysis gasoline
b) According to site-specific conditions some plants feed a variety of additional organic compounds materials (e.g. LPG-cuts, aromatic cuts)
c) Process heat and steam production summed; diverse fuels applied (gas, fuel oil), energy efficiency of 85% is respected concerning heat and steam production
Data base: internal data from several steam cracking plants; APME [2003]

6.2.2 LAO and PAO production

Some selected energy data taken from Nieschalk [2003] are shown in Table 6-9. More detailed data are not available. As process losses are neglected and heat supply is figured by gas firing, the data can be presumed to represent an optimised status of production.

Table 6-9 Energy consumption of LAO and PAO production

Material/energy	amount	unit
LAO process		
Product yield		
1-Decene	116	kg
Other LAOs	884	kg
Feedstock input (Ethylene)	1,000	kg
Thermal energy input [a)]	7,660	MJ
Electric energy input	1,340	MJ
PAO process		
Product yield: PAO [b)]	1,000	kg
Feedstock input (1-Decene)	1,000	kg
Thermal energy input [c)]	1,940	MJ
Electric energy input	1,030	MJ

a) diverse fuels applied (gas, fuel oil), energy efficiency of 85% is respected concerning heat production
b) losses are neglected because of lack of data.
c) Process heat and steam production summed; natural gas presumed as fuel, energy efficiency of 85% is respected concerning heat and steam production
Data base: Nieschalk [2003]

6.3 Energy and energy recovery processes

The precedent sections have shown some data on energy demand of the specified distillation, refining, cracking or synthesizing processes. Airborne emissions come predominantly from the energy conversion processes as furnaces (heat production), boilers (steam production) or power stations. The results concerning emission rate and resource consumption are determined by fuel type and quality, efficiency and flue gas treatment (where applied). Table 6-10 shows a selection of specific emission data used for this assessment. The table is narrowed to process heat processing, but in principle the data can be transferred to steam production.

Table 6-10 Selection of data on emissions from process heat generation

Reference: 1 GJ process heat	unit	Primary fuels: Natural gas	Primary fuels: Light fuel oil	Primary fuels: Heavy fuel oil	Fuels from regeneration: Light ends	Fuels from regeneration: Gas oil (low sulphur)
fuel input	Mg	24.9	26	27.4	25.8	26.8
emissions						
CO_2 (fossil)	kg	61.3	82.2	85.5	84.7	83.4
SO_2	kg	0.0005	0.0781	0.549	0.0333	0.0333
NO_X	kg	0.0065	0.0333	0.0333	0.00805	0.00794
dust	kg	0.00015	0.0011	0.0011	0.00111	0.00111
As	g	0	0.0078	0.019	0	0.0027
Cd	g	0	0.013	0.027	0	0.0027
Cr	g	0	0.052	0.027	0	0.0027
Ni	g	0	0.065	0.66	0	0.0027
Benzo(a)pyren	mg	0	0.033	0.33	0.27	0.27

Source: calculations by ifeu

Table 6-11 shows selections of specific emissions caused by application of different fuels in a cement kiln. Table 6-12 shows the emissions caused by several most implemented waste types. The latter are considered in the context of sensitivity analysis.

Table 6-11 Selection of data on emissions from fuel use in a cement kiln

Reference: 40 GJ process heat (equiv. to 1 Mg of used oil)	unit	**Hard coal** (SA/AUS)[a)]	**Hard coal** (EU) [b)]	**Lignite**	**Pet coke**	**Heavy oil**	**Natural gas**
fuel input	kg	1730	1421	3980	1076	983	890
Emissions [c)]							
CO_2 (fossil)	kg	3550	3540	3790	3630	3060	2550
SO_2	kg	0.934	0.768	0.318	0.43	0.393	0.000356
As	g	0.00104	0.00114	0.000199	0.000172	0.000157	0
Cd	g	0.000173	0.000107	0.000498	0.00108	0.000983	0
Cr	g	0.000519	0.0032	0.000995	0.0000538	0.0000491	0
Ni	g	0.0013	0.00156	0.000995	0.00215	0.00197	0

a) SA/AUS: import from South Africa, Australia;
b) Hard coal from Europe (mix from Germany, France, Poland, UK, Spain etc.)
c) Some pollutants (e.g. NOx, dust) do not depend on the type of fuel but only on the type of combustion; their emission levels refer to the firing performance, according to this used oil combustion and the equivalency process are identical by definition

Source: calculations by ifeu

Table 6-12 Selection of data on emissions from some common secondary fuel use in a cement kiln

Reference: 40 GJ process heat (equ.1 Mg used oil)	unit	**Used oil**	**Used tyres** (31 MJ/Mg)	**Used solvents** (38 MJ/Mg)	**Meat and bone meal** (19 MJ/Mg)
fuel input	Mg	1000	1290	1045	2105
Emissions [a)]					
CO_2 (fossil)	kg	2933	3034	3080	0
SO_2	kg	0.13	0.5	0.61	0.335
As	g	0.00002	0,0066	0,00022	0,00082
Cd	g	0.0013	0,0066	0,00013	0,0006
Cr	g	0.000016	0,0080	0,00055	0,00051
Ni	g	0.00043	0,0064	0,00055	0,00073

a) Some pollutants (e.g. NOx, dust) do not depend on the type of fuel but only on the type of combustion; their emission levels refer to the firing performance, according to this used oil combustion and the equivalency process are identical by definition
b) Data base for used tyres UBA [1999], for used solvents ifeu/ABAG [2000] for meat and bone meal ifeu internal data.

Concerning electricity, data is derived from the national grids respectively (Germany, Italy, Greece, UK). Table 6-13 gives an overview on the specific mix of energy resources used in the nationals grids of the countries considered in this assessment.

Table 6-13 Contribution of energy sources concerning the power generation according to the national grid

	Germany	**Italy**	**Greece**	**U.K.**
Coal	22	8.5	-	38.3
Lignite	29	0.3	67.8	-
Gases	8.3	27.2	3.7	27
Fuel oil	0.7	38.2	19.1	1.6
Nuclear power	33	-	-	29.5
Water	3.8	14.7	7.0	1.7
Other	3.2	11.1	2,4	1.9

Source: European Communities [2001], VDEW [2004]

6.4 Primary energy resources

The inventory of primary fuel use has to been completed by supply of fuel. Table 6-14 shows a selection of emission data according to extraction, processing and transport of coal, lignite, natural gas and concerning pet coke and heavy fuel including refinery processes. These data refer to an energy content (lower heat value) of 40 GJ which corresponds to 1 Mg of used oil.

Table 6-14 Selection of data on emissions from primary fuel supply (cradle to gate)

Reference: 40 GJ process heat (equivalent to 1 Mg of used oil)	unit	**Hard coal (SA/AUS)[a)]**	**Hard coal (EU)[b)]**	**Lignite**	**Pet coke**	**Heavy fuel oil**	**Natural gas**
Fuel	Mg	1.73	1.42	3.98	1.076	0.983	0.89
Demand on resources							
Hard coal	kg	1740	1490	0	6.55	4.92	0
Lignite	kg	0	0	4060	22	15.9	0
Mineral oil	kg	72	0	0	1180	1080	0
Natural gas	kg	0	0	0	6.95	5.95	1170
Cumulated energy demand	*GJ*	*46*	*43.9*	*40.6*	*50.8*	*46.4*	*47.2*
emissions							
CO_2 (fossil)	kg	266	176	57.7	396	366	238
SO_2	kg	3.04	0.201	0.0412	1.49	1.45	0.0516
NO_X	kg	2.95	0.188	0.0378	1.19	1.1	1.27
Dust	kg	0.374	0.0167	0.00343	0.164	0.141	0.0479
CH_4	kg	16.6	22.6	0.0618	2.87	2.59	6.92
N_2O	kg	0.00372	4.18	0	0.0274	0.0147	0.0103
As	g	0.00638	0.00546	0.0115	0.0302	0.037	0.00317
Cd	g	0.000767	0.000657	0.000254	0.0531	0.0536	0.00792
Cr	g	0.00938	0.00803	0.00873	0.0388	0.0506	0.00396
Ni	g	5.25	0.0000231	0.0218	1.62	2.07	0.322
PCDD/F	µg	0.0213	0.0066	0.00311	0.0036	0.00244	0.000745
Benzo(a)pyren	mg	0.931	0.0504	0.0186	0.406	0.394	0.0405

a) SA/AUS: import from South Africa, Australia;
b) Hard coal from Europe (mix from Germany, France, Poland, UK, Spain etc.)

Source: coal pre-chain data by GEMIS, natural gas and crude oil pre-chain data by ECOINVENT, refinery data and combustion data calculation by ifeu

7 Results

In a first step, results are worked out for each of the five re-refining options assessed (section 7.1). The goal is to identify significant differences. In a second step, the average result of the five options will be compared to an alternative combustion of used oil as secondary fuel (section 7.2). Primarily a cement kiln is chosen, for cement works are currently one the most important thermal users of used oil in Europe. Alternatively, combustion of used oil by utilities replacing fuel oil is considered.

As 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 five 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. The company names are replaced by numbers and the order in which data is presented is changed compared to chapter 5.

7.1.1 Some Life Cycle Impact (LCI) results

In the area of LCI there is no further aggregation of data categories in terms of impact categories yet. It is possible to make interpretations on a restricted part of the system boundary to highlight some specific differences of the compared options.

In this respect, it is meaningful to make a direct comparison of the energy demand of the different regeneration techniques compared to primary (classical) base oil refining. It is to understand that this specific comparison does not harmonize with the functional unit postulated for the ecological assessment. The reason is the restriction of the system boundary. But to this purpose it can be tolerated that used oil is not identical with waxy distillate, and by producing 1 Mg of base oil, the mass and quality of the co-products differ immensely. To keep these inequalities within limits, the values in Table 7-1 are presented in one case based on 1 Mg of produced base oil (secondary and primary), and in another based on 1 Mg of feedstock input (used oil or waxy distillate) into the plant.

The secondary energy values are translated to primary energy values and summed up to make an overall valuation of the different energy types possible. Focussing on the lines "*total primary energy*", direct comparison of secondary and primary base oil production shows a clear advantage for regeneration. The consumption level is even lower when the process balance is scaled on equal feedstock quantity (primary refining yields less than 0.5 kg base oil per kg input, while regeneration reaches about 0.7 kg).

In this brief analysis of secondary energy consumption, no other upstream burden of regeneration other than that from collecting used oil is taken into account. Primary production of base oils, however, must take into account other processes back to the crude oil production well.

Table 7-1 Comparison of energy demand used oil regeneration and base oil refining

		Secondary base oil production					Primary base oil production
		1	**2**	**3**	**4**	**5**	
Scaled on 1 Mg base oil							
Input							
Used oil	Mg	1.30	1.44	1.84	1.38	1.44	
Waxy dist.	Mg						2.03
Electricity	MJ	1135	325	224	390	321	664
Heat	MJ	1769	2901	1143	3342	4872	4469
Steam	MJ	820	3395	2995	851	311	4148
total primary energy	*MJ*	*6659*	*8080*	*5345*	*5959*	*6828*	*11789*
Output							
Additional co-products	Mg	0.30	0.44	0.84	0.38	0.44	1.03
Based on 1 Mg used oil resp. waxy distillate							
Input							
Used oil	Mg	0.771	0.695	0.545	0.725	0.696	
Waxy dist.	Mg						0.494
Electricity	MJ	875	226	122	283	223	328
Heat	MJ	1363	2016	622	2423	3389	2206
Steam	MJ	632	2359	1631	617	216	2048
total primary energy	*MJ*	*5133*	*5615*	*2910*	*4322*	*4750*	*5820*
Output							
Additional co-products	Mg	0.229	0.305	0.455	0.275	0.304	0.506

7.1.2 Impact assessment

In this step of the assessment, the data from inventory are condensed to a number of selected impact categories. The data categories and their characterization factors are given in Table 3-1.

Table 7-2 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 754 kg of CO_2-equivalents per Mg used 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 1,290 kg of CO_2-equivalents per Mg used oil, if only base oil substitution is presumed. If quality mix of 70 % base oil and 30 % PAO is presumed the prevention extends to 1,560 kg CO_2-equivalents.
3. To get the “net impact” of the technique 1 of regeneration the omitted burden (1,290 or 1,560) is to be subtracted from the burden created (754). Hence, technique 1 releases the global warming in the range of 530 to 810 kg CO_2-equivalents per Mg used oil.

Figure 7-1 gives a view on all the impact category results listed in Table 7-2. The figures are scaled each 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 five techniques. The deviation bars show the range of the five techniques in detail.

The featuring interpretations at this state of balance are:

1. It is clear to see that **in all cases the avoidance of burden is higher than the burden caused by the regeneration system itself**. Regeneration in total reduces environmental drawbacks.
2. In case of *global warming,* about two times of regeneration-driven greenhouse gas emission is zeroed out. Regarding the other environmental themes this numeric effect is even higher:
   - *nutrification*: 3 to 4 times,
   - *acidification* and *fine particulates* (PM10) 5 times and more,
   - *carcinogenic risk potential*: 10 to 20 times and
   - *fossil resources*: more than 30 times.
3. Another observation is that differences between the five techniques are relatively low. The average result given in Figure 7-1 is (roughly seen) a sensible point of reference for the whole band of modern regeneration technology.
4. Rising quality of the used oil feedstock (subjecting 30 % PAO content as future optimum) will be most obviously reflected in the categories of *global warming* and *nutrification.* The significantly higher consumption levels of the synthetic compounds

result in a 20 % (GWP) to 35 % (nutrification) increase.
Concerning *acidification* and *carcinogenic risk potential* there is no significant difference between pure base oil and synthetic compounds. This is because base oil is 100% a mineral oil refinery product and this sector is a predominant producer of pollutants SO_2 and nickel (from heavy fuel oil). Petrochemical industry is applying gas as fuel and so the process steps form naphtha to PAO cause rather low specific SO_2 and nickel emissions.

Table 7-2 Results of impact assessment for the five technical options according to burdens by regeneration system and equivalency system (two scenarios: only base oil and 30% PAO within the regenerated lubricant)

	Re-refining Technique				
Reference: 1 Mg used oil	**1**	**2**	**3**	**4**	**5**
Resource depletion (kg raw oil-Eq.)					
Regeneration	59.0	61.3	5.2	10.2	29.3
Equivalency processes					
70% base oil, 30 % PAO	1201	1215	1087	1084	1114
100% base oil, 0 % PAO	1169	1186	1064	1054	1085
Global warming (kg CO_2-Eq.)					
Regeneration	754	610	1292	377	347
Equivalency processes					
70% base oil, 30 % PAO	1563	1385	1867	1132	1058
100% base oil, 0 % PAO	1288	1137	1672	873	809
Acidification (kg SO_2-Eq.)					
Regeneration	0.76	0.53	1.55	0.35	0.99
Equivalency processes					
70% base oil, 30 % PAO	5.12	5.10	5.27	4.78	4.35
100% base oil, 0 % PAO	5.25	5.21	5.36	4.90	4.46
Nutrification (kg PO_4^{3-}-Eq.)					
Regeneration	0.08	0.07	0.06	0.04	0.03
Equivalency processes					
70% base oil, 30 % PAO	0.26	0.28	0.23	0.23	0.23
100% base oil, 0 % PAO	0.19	0.21	0.18	0.17	0.17
Carcinogenic risk potential (g As-Eq.)					
Regeneration	0.007	0.015	0.037	0.019	0.012
Equivalency processes					
70% base oil, 30 % PAO	0.288	0.281	0.380	0.250	0.204
100% base oil, 0 % PAO	0.293	0.285	0.376	0.253	0.204
Fine particulates (kg PM_{10}-Eq.)					
Regeneration	0.23	0.16	0.21	0.09	0.15
Equivalency processes					
70% base oil, 30 % PAO	0.97	0.99	0.90	0.88	0.84
100% base oil, 0 % PAO	0.86	0.90	0.83	0.78	0.75

Remark: Equivalency processes are “avoided” primary processes.

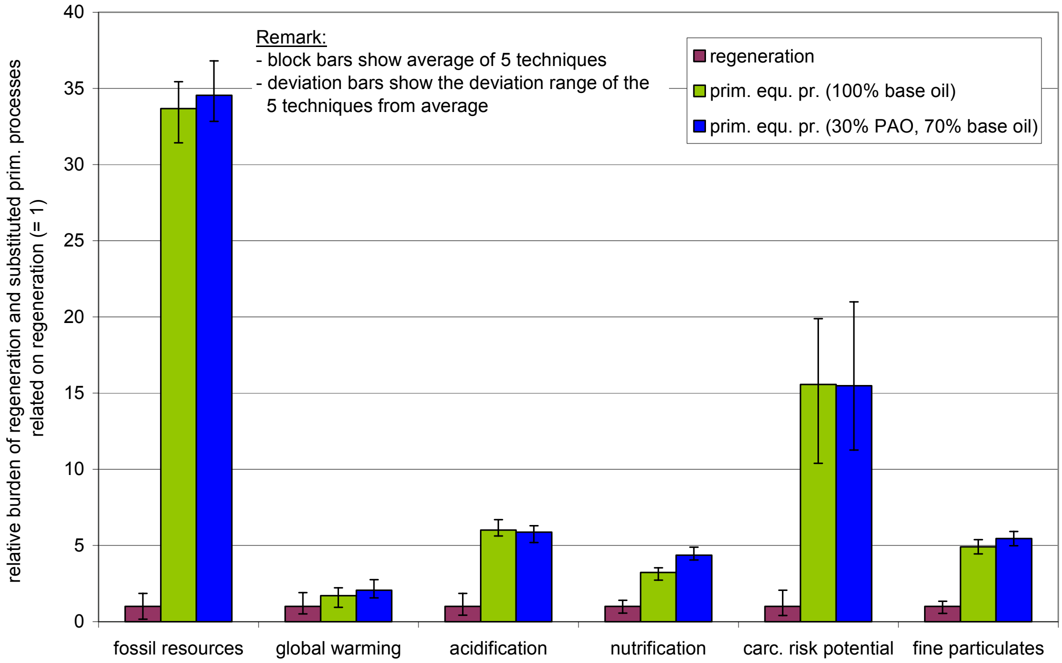

Figure 7-1 Total view on the impact assessment results; all figures related on the particular result of "regeneration", main bars: average result of the five techniques, deviation bars: range of the five techniques.

7.1.3 Interpretation by normalization and grouping

The precedent sections have proved that **regeneration of used oil** (including all up- and downstream processes) **causes less environmental burden than the processes substituted by regeneration**. This can be stated for all five technical options and for all regarded environmental impacts.

➲ This statement is the first conclusion to be pointed out within the interpretation step of the assessment.

As described in section 3.3, interpretation will give a deeper analysis of the results. To act on the suggestions of ISO 14042 (optional elements “normalization” and “grouping”) the relevance of the differences among the options or the total environmental effects can be rated.

Before all figures have been based on the functional unit of 1 Mg used oil treated in a regeneration plant. In the following these results are scaled up to the total capacity for regeneration of used oil in Europe to illuminate the magnitude of the environmental effects and to make normalization meaningful. A capacity 600,000 Mg per year is estimated.

The comparison may keep to the differences among the five options. In Table 7-3 these differences are itemized and divided by the specific person equivalency value (PEV) normalized. The option with the best result within a category is marked with ①. The number of PEV will show the deviation of the corresponding option to the best option.

Example to show the mode of calculation: According to Table 7-2 there is a “net saving” of 1,110 kg of raw-oil-equivalents per Mg of used oil (presuming only the 100 % base oil scenario), “technique 2” “saves” 1,125 kg. The difference takes 15 kg raw-oil-equivalents per 1 Mg used oil. The person equivalency value (PEV) for 2.34 Mg raw-oil-equivalents per person and year, so the difference in PEV per 600,000 Mg takes: 15 kg/Mg x 600,000 Mg/a / 2,340 kg/p/a ≅ **3,800 PEV**

Table 7-3 Differences among the five options normalized and expressed in PEV; scaled on 600,000 Mg used oil

	Re-refining Technique				
	1	2	3	4	5
100% base oil 0% PAO					
fossil resources	3800	①	17000	21000	16000
GWP	①	400	7800	2000	3700
acidification	2800	①	13000	2000	18000
nutrification	3100	①	2900	1300	660
carc. risk potential	6700	8600	①	13000	19000
PM 10	7000	①	8400	3300	9700
70% base oil 30% PAO					
fossil resource depletion	3000	①	18000	21000	16000
GWP	①	1800	12000	2800	5000
acidification	3000	①	12000	2100	18000
nutrification	2200	①	4500	920	650
carc. risk potential	7800	9700	①	14000	19000
PM 10	6300	①	9700	3100	9700

The most beneficial option in each case is marked by ①

Table 7-4 following displays again these differences in a graphical way: Per 5,000 PEV (rounded) a square is given. This figure contains also the information concerning “grouping”: According to the environmental priority of the impact categories, the squares are shaded in different colours (black = very high priority down to light grey = medium priority; the priorities low and very low are not found).

The following conclusions can be drawn:

1. Differences in total are not very large; by normalization and scaled on the total quantity of used oil in Europe, they range within the magnitude of some thousand person equivalency values, maximum 20,000 PEV.
2. Two of the techniques dominate most of the beneficial rankings, they may claim to be better than average. The reasons are: high yield of regenerated base oil and additional benefits from by-products.
3. Taking inaccuracies into account, it can be stated that all the techniques considered represent a more or less equally high standard of used oil regeneration.

Table 7-4 Overview of impact-related and normalized differences between the options

	Re-refining Technique				
	1	2	3	4	5
100% base oil 0% PAO					
Fossil energy resources	■	①	■■■	■■■■	■■■
Global warming	①	•	■■	•	■
Acidification	■	①	■■■	•	■■■■
Nutrification, terrestrial	■	①	■	•	•
Carcinogenic pollutants	■	■■	①	■■■	■■■■
PM10	■	①	■■	■	■■
30% PAO 70% base oil					
Fossil energy resources	■	①	■■■■	■■■■	■■■
Global warming	①	•	■■	■	■
Acidification	■	①	■■	•	■■■■
Nutrification, terrestrial	•	•	■	•	•
Carcinogenic pollutants	■■	■■	①	■■■	■■■■
PM10	■	①	■■	■	■■

Scaled by specific contribution in PEV related to 600,000 Mg of used oil; 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).

7.2 Comparison of regeneration and direct combustion

The major disposition of used oil other than regeneration is direct combustion. Following the numbers from Monier and Labouze [2001] nearly half of the collected used oil quantity all over the European Union has been incinerated for energy recovery.

In countries like Germany, France and Austria, cement works are the main consumers. In the UK (also the Netherlands) used oil is mostly combusted in coal fired power plants for supplemental fuelling, or used by steel works for reduction of iron ore. Also waste incinerators apply used oil for supplemental fuelling. Recently, the lime industry also tends to increase the rate of using secondary fuels and used oil is a preferable one. In many member states most of the collected used oil is recycled to fuel oil. In the EC acceding countries, used oil is mostly applied for heating purposes in garages.

The most decisive aspect concerning comparative ecobalancing of combustion is the character of fuel substituted, as former studies show. In section 6.3 and 6.4 some data are already given to illuminate the inventory of a fuel application and the fuel pre-chains.

The comparison in this assessment will be carried out with:

- basic focus on fuel management of cement industry where hard coal, pet coke and lignite are predominant primary fuels; and
- a secondary view on the fuel situation of coal power plants and steel works, where heavy fuel oil is being substituted.

To round up the variety of possibilities of other fuels like natural gas (e.g. applied in lime works), or even alternative secondary fuels (increasing in cement industry in several European countries) are screened with a sensitivity analysis.

According to CEMBUREAU's activity report 2003, about 17 % of the fossil fuel is replaced by secondary fuels in the cement works all over Europe. In the context of sensitive parameters another issue has to be faced: the quantity of 600,000 mg of used oil (= 24 Mio. GJ) meets about half of the total fossil fuel input of German cement works in 2002, and about three-quarters of the total fossil fuel input of French cement works in 2003. With the ongoing increase of secondary fuels in cement industry (Netherlands: 72%, Germany, France, Austria and Switzerland each 30 %) substitution of primary fuel will partly switch to competition for different secondary fuels.

The choice of primary or secondary fuel type by thermal facilities is nearly exclusively decided on economic criteria. When prices and market situations change, the facility will adapt the fuel band. So the determination of a certain fuel type for an ecobalancing assessment reflecting the current situation is naturally a snap-shot that might differ in the near future. The predominance of coal and pet coke in European cement industry is a current reality but not an inherent necessity.

7.2.1 Impact assessment results

In Table 7-5 different impact assessment results concerning the combustion of used oil and different primary fuels are displayed. Also the contributions of the fuel pre-chains (mining, extraction, refining, transport etc.) are documented. As a sample case, the fuel mix for European cement industry is presumed (see bottom of Table 7-5). In Table 7-6 the regeneration and the combustion results are compared.

Table 7-5 Impacts of combusted used oil, equivalent amounts of different primary fuel

	used oil	Hard coal SA/AUS[a)]	Hard coal EUR[b)]	Lignite	Pet coke	Heavy fuel oil	Natural gas
Input	1 Mg	1.73 Mg	1.42 Mg	3.98 Mg	1.08 Mg	0.98 Mg	0.89 Mg
Fossil resources (kg ROE-Eq.)							
combustion	0	0	0	0	0	0	0
pre-chain	0	353	274	166	1180	1080	724
Global warming (kg CO_2-Eq.)							
combustion	2930	3550	3540	3790	3630	3060	2550
pre-chain	11.3	840	652	59	465	425	387
Acidification [c)] (kg SO_2-Eq.)							
combustion	0.126	0.936	0.769	0.319	0.43	0.393	0.000364
pre-chain	0.0843	6.99	0.332	0.0677	2.34	2.22	0.946
Nutrification [c)] (kg PO_4^{3+}-Eq.)							
combustion	0	0	0	0	0	0	0
pre-chain	0.013	0.409	0.0244	0.00491	0.155	0.143	0.165
Carcinogenic risk potenial (g As-Eq.)							
combustion	0.000591	0.0012	0.00136	0.0135	0.000746	0.000681	0
pre-chain	0.00101	0.353	0.00838	0.000491	0.153	0.185	0.0255
Fine particulates (kg PM_{10}-Eq.)							
combustion	0.0109	0.0813	0.0668	0.0277	0.0374	0.0342	0.000031
pre-chain	0	1.6	0.0749	0.0152	0.514	0.475	0.329
Primary fuel mix [d)] **cement works EU**		33%	11%	10%	40%	5%	1%

a) SA/AUS: import from South Africa, Australia;
b) Hard coal from Europe (mix from Germany, France, Poland, UK, Spain etc.)
c) Some pollutants (e.g. NOx) do not depend on the type of fuel but only on the type of combustion; their emission levels refer to the firing performance, according to this used oil combustion and the equivalency process are identical by definition
d) Estimation based on several single statistics [Cembureau; VDZ; AITEC]

Table 7-6 Line-up of impact results for regeneration (average of five, scenario “30% PAO” and “0%PAO”) and combustion (with substitution of cement work fuel mix and fuel oil); all results based of 1 Mg of recovered used oil

	Regeneration		Combustion	
Fossil resources (kg ROE-Eq.)	burden of …		burden of …	
	…regeneration	33	…combustion	3
	…subst. (70/30)	1140	…subst. fuel mix (c.w.)	319
	…subst. (100/0)	1112	…subst. fuel oil	1082
Global warming (kg CO_2-Eq.)	burden of …		burden of …	
	…regeneration	676	…combustion	2940
	…subst. (70/30)	1400	…subst. fuel mix (c.w.)	4060
	…subst. (100/0)	1160	…subst. fuel oil	3488
Acidification (kg SO_2-Eq.)	burden of …		burden of …	
	…regeneration	0.837	…combustion	0.126
	…subst. (70/30)	4.92	…subst. fuel mix (c.w.)	3.09
	…subst. (100/0)	5.03	…subst. fuel oil	2.6
Nutrification (kg PO_4^{3+}-Eq.)	burden of …		burden of …	
	…regeneration	0.0565	…combustion	0.000215
	…subst. (70/30)	0.247	…subst. fuel mix (c.w.)	0.183
	…subst. (100/0)	0.182	…subst. fuel oil	0.14
Carcinogenic risk potenial (g As-Eq.)	burden of …		burden of …	
	…regeneration	0.018	…combustion	0.001
	…subst. (70/30)	0.281	…subst. fuel mix (c.w.)	0.145
	…subst. (100/0)	0.282	…subst. fuel oil	0.19
Fine particulates (kg PM_{10}-Eq.)	burden of …		burden of …	
	…regeneration	0.168	…combustion	0.0109
	…subst. (70/30)	0.916	…subst. fuel mix (c.w.)	0.662
	…subst. (100/0)	0.826	…subst. fuel oil	0.509

Explanations:
“regeneration” stands for the average results of the five techniques (see Table 7-2)
”subst. (70/30)” stands for the omitted burden by regeneration respecting 30% PAO in the used oil,
”subst. (100/0)” stands for the omitted burden by regeneration respecting no PAO in the used oil,
”combustion” stands for combusting used oil in a cement kiln (power plant) (see Table 7-5)
”subst. fuel mix (c.w.)” stands for the omitted burden by substituting the primary fuel in cement work
”subst. fuel oil” stands for the omitted burden by substituting heavy fuel oil in power plant or steel work

In Figure 7-2 and Figure 7-3 the basic impact assessment results from the precedent tables are aggregated to illustrate the relative advantages and disadvantages. To arrive there the “net impact” is calculated first (“regeneration minus subst.” resp. “combustion minus subst."). Then the lowest value is set to be 1 and the other values are scaled correspondingly. In fact all options considered contribute to environmental relief in all categories.

Example: Concerning fossil resources the burden of recovery is 33 MJ per Mg use oil, the benefit is 1,140 MJ (100% base oil), so the "net impact" is -1,107 MJ; the burden of combustion is 3 MJ per Mg, the benefit (cement work fuel mix) is 319 MJ, so the "net impact" equals -316 MJ; here recovery is the more advantageous one (1,107 is scaled to 1) and combustion is 3.5 times less beneficial (1,107 divided by 319).

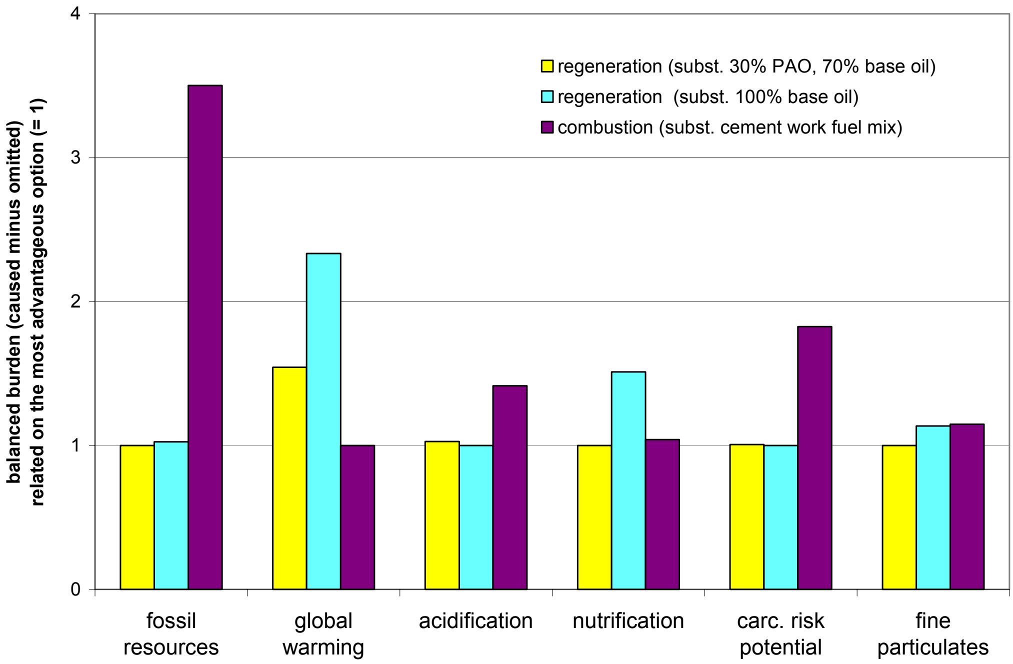

Figure 7-2 **Total view on the comparable impact assessment results – regeneration (average) vs. combustion (cement work primary fuel mix substituted); All figures related to the most advantageous option within each category.**

Figure 7-2 shows that regeneration is favoured clearly in terms of resources, acidification, carcinogenic risk potential and fine particulates. In terms of global warming used oil combustion (substituting used oil mainly for coal and pet coke) leads to higher benefits. The results concerning nutrification is ambivalent and depends on the share of synthetic compounds.

Figure 7-3 gives the alternative view on a combustion scenario replacing heavy fuel as it is observed in coal power plants and steel works. There the regeneration option is always the leading one. Concerning global warming and nutrification, combustion is only in advance when synthetic compounds are neglected.

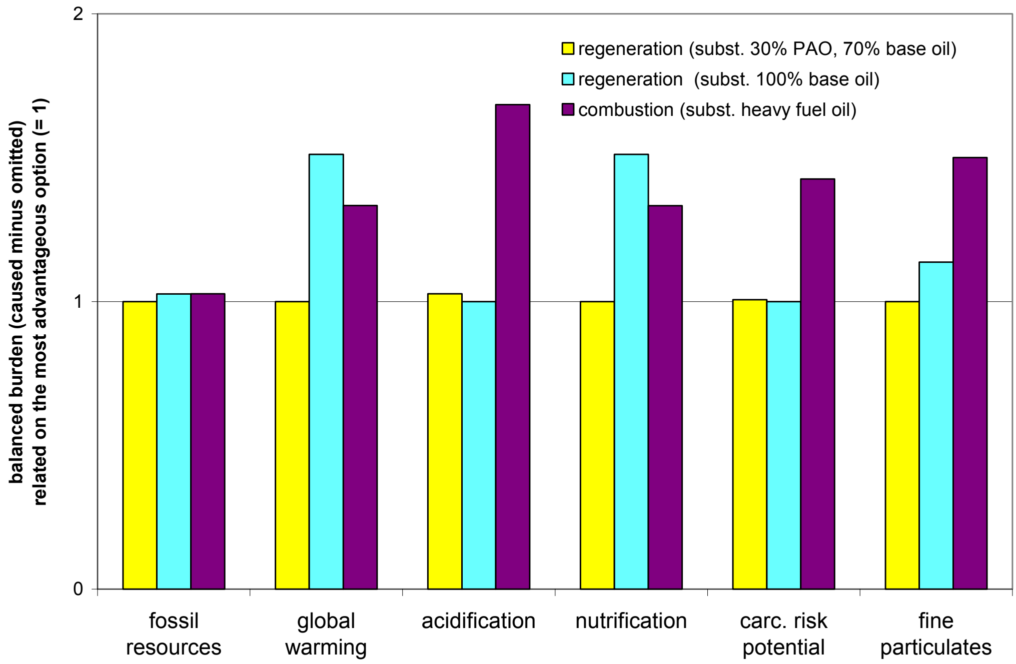

Figure 7-3 **Total view on the comparable impact assessment results – regeneration (average) vs. combustion (coal power plant/steel work primary fuel mix substituted);**
All figures related to the most advantageous option within each category.

The scaled differences between the "net results" of regeneration and combustion just show the ranking within the single categories or indicators. For judging the "significance" of the individual advantages and disadvantages normalization has to be performed.

7.2.2 Normalization of impact assessment results and grouping

In the same way as in section 7.1.3, the differences among the options in the impact assessment results are calculated and normalized using person equivalency values (PEV).

For the **"cement work fuel mix scenario"** this is presented in Table 7-7 and the results again illustrated in Figure 7-4. Table 7-8 and Figure 7-5 show the corresponding results for the scenario "fuel oil" – the substituted fuel type with regard to power plants and steel works.

Table 7-7 Overview of impact-related and normalized differences between regeneration and combustion of used oil (substitution of cement work fuel mix), expressed in PEV; scaled on 600,000 Mg used oil

	Regeneration (100 % base oil)	**Regeneration** (70 % base oil, 30% PAO)	**Combustion** (cement work fuel mix)
Fossil resources	7300	①	200000
Global warming	32000	20000	①
Acidification	①	1600	18000
Nutrification	7400	①	870
carc. risk potential	①	200	15000
Fine particulates	5800	①	6200
Fossil resources	■■	①	■■■■■■■■■■ ■■■■■■■■■■
Global warming	■■■■■■	■■■■	①
Acidification	①	•	■■■
Nutrification, terrestrial	■	①	•
Carc. risk potential	①	•	■■■
Fine particulates	■	①	■

Scaled by specific contribution in PEV related to 600,000 Mg of used 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).

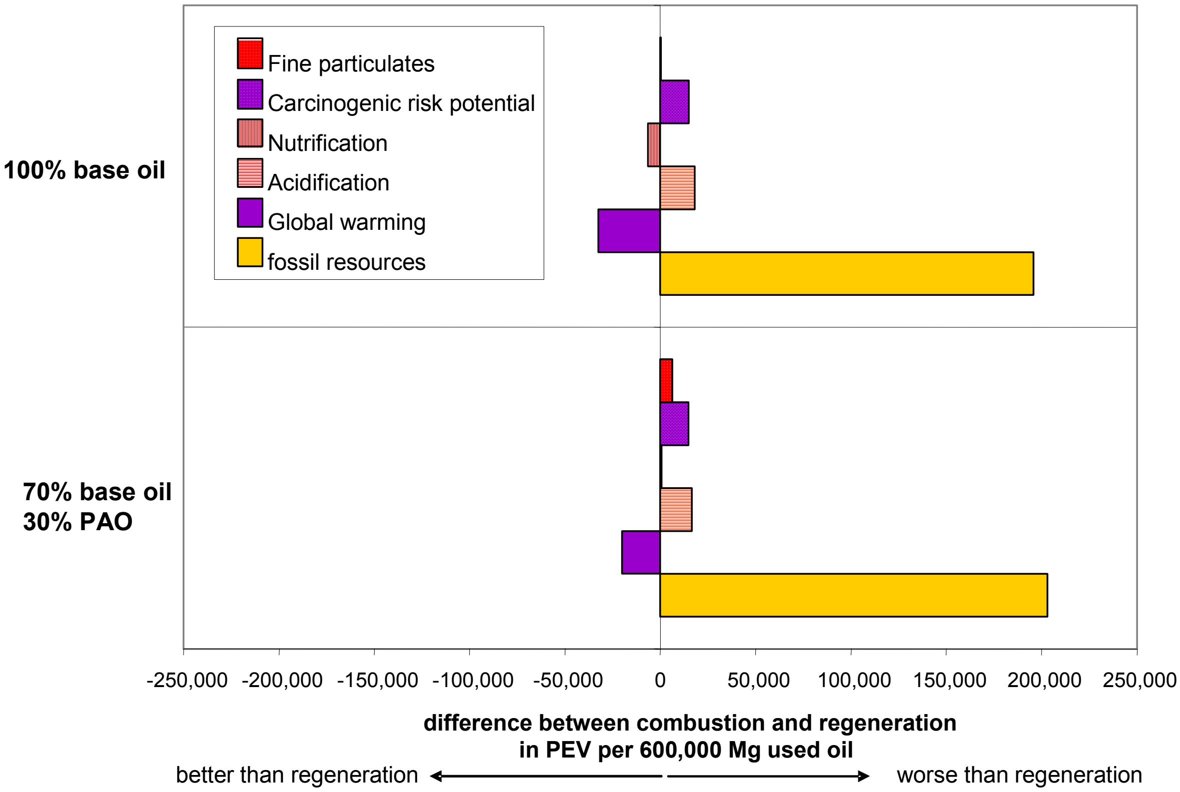

Figure 7-4 **Overview of impact-related and normalized differences between average regeneration and combustion (substitution of cement work fuel mix)**

These illustrations show the clear advantages of regeneration concerning “fossil resources”, “acidification”, “toxic air pollutants” compared to a direct combustion (average situation in European cement industry). The highest specific effect is given by “fossil resources” for mineral oil is higher weighted than coal and lignite dependant on the shorter range of deposit.

Concerning “nutrification” the discrepancies between regeneration and combustion are low, with the ratio of synthetic compounds tipping the scales in favour of regeneration.

With weight on a coal substitution by used oil combustion the relieving effect concerning “global warming” is higher when combusted. Compared to Arcadis/ifeu [2000] the edge of combustion has diminished: from 1,070 kg CO_2-eq. per Mg used oil to 636 kg (without synthetics) respectively to 396 kg CO_2-eq. (30 % synthetics considered).

For the **“fuel oil substituting scenario”** the differences between combustion and regeneration are mostly smaller. On the other hand the unambiguous advantage is on the regeneration option respecting 30 % PAO. Likewise the two drawbacks of "100% base oil scenario" (global warming and nutrification) are significantly reduced, whereas the advantages in all other categories remain.

In summary a directional benefit of regeneration can be observed when compared with a coal substituting combustion, and a distinct benefit is shown when compared with a fuel oil substituting combustion.

Table 7-8 Overview of impact-related and normalized differences between regeneration and combustion of used oil (substitution of heavy fuel oil), expressed in PEV; scaled on 600,000 Mg used oil

	Regeneration (100 % base oil)	**Regeneration** (70 % base oil, 30% PAO)	**Combustion** (fuel oil)
Fossil resources	7300		7700
Global warming	12000	①	9200
Acidification	①	1600	25000
Nutrification	7400	①	5500
carc. risk potential	①	200	10000
Fine particulates	5800	①	16000
Fossil resources	■■	①	■■
Global warming	■■	①	■■
Acidification	①	•	■
Nutrification, terrestrial	■	①	■
Carc. risk potential	①	•	■■
Fine particulates	■	①	■■■

Scaled by specific contribution in PEV related to 600,000 Mg of used 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).

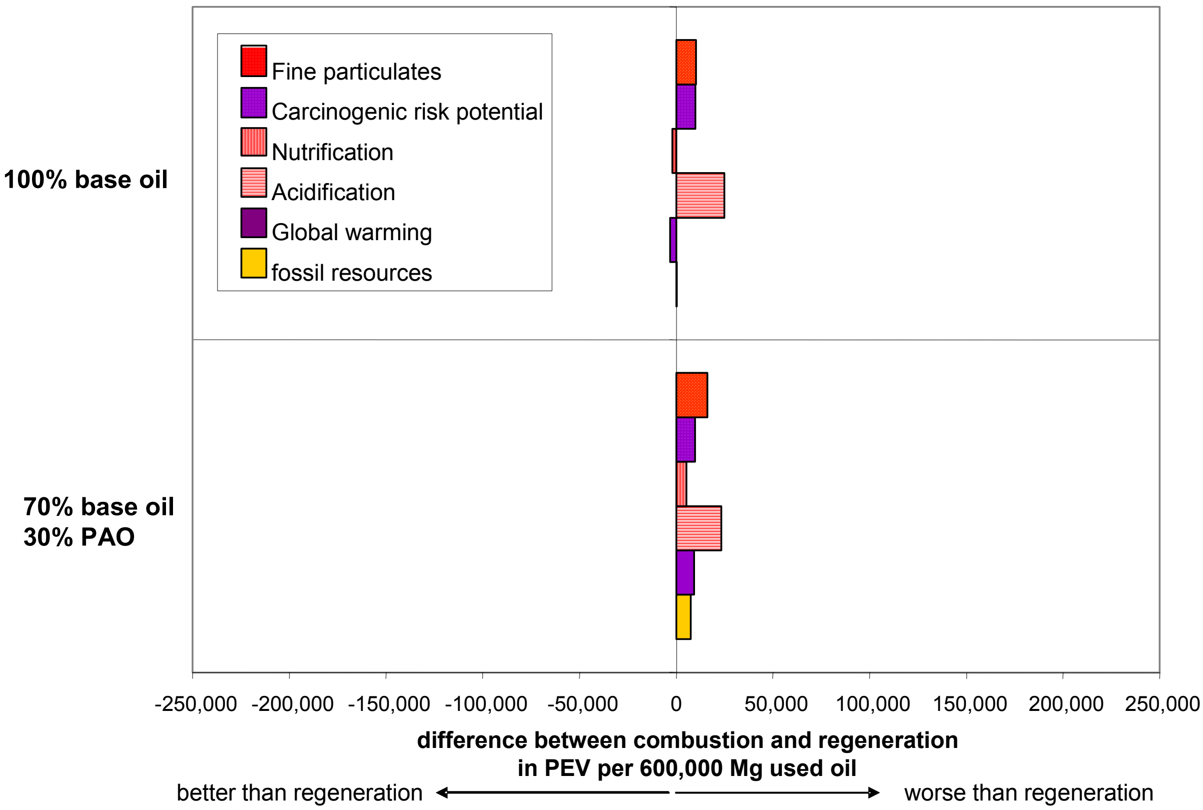

Figure 7-5 Overview of impact-related and normalized differences between average regeneration and combustion (substitution of heavy fuel oil)

7.3 Other sensitive parameters

The following items contain assumptions of more or less relevant influence on the results:

- Allocation method:
  - Extraction of vacuum distillate completely charged on paraffin fraction.
  - The approach applied by Nieschalk [2003] concerning the production chain of PAO.
- Fuel substitution:
  - Presume a partial saturation of the secondary fuel management.
- Distribution distances:

7.3.1 Extraction of vacuum distillate completely allocated to paraffin fraction

Aromatic extracts are basically considered as by-products of base oil production with specific product utility. In section 6.1.2 it is discussed that the aromatic extracts tend more and more to be an undesired co-product. The market for a useful application (rubber industry or ink) is decreasing and several refineries now feed the extracts into a catalytic cracking unit (FCC). Realizing this, the efforts to separate paraffin from aromatics are to allocate solely to the paraffin fraction. The resulting changing in the inventory of base oil is calculated in Table 6-4. The specific burden of base oil will increase by 18 %.

Outcome: Slight movement of the results in favour of regeneration. Concerning global warming the advantage of direct combustion (substitution of a mix of coal, lignite, pet coke) is decreasing but not cleared out.

7.3.2 Alternative allocation approach concerning the production chain of PAO

The whole production chain from primary resource to PAO leads to a variety of by-products. So within nearly each production step allocation have to be done. ISO 14041 clearly gives priority allocation method based on physical relations. Such are considered in this assessment. Selecting an alternative method will be justified by the specific external conditions in case.

Nieschalk [2002] analysed the production chain of PAO and found out, how much process energy is necessary to produce 1 Mg of PAO. Due to the specific production situation, he defined an adapted allocation method. Identically with the approach applied by the author of this study, he divided energy consumption to the different by-products with reference to physical parameters (here: mass). The decisive difference between the two approaches is the linkage of the individual process steps (modules) to one chain by Nieschalk. He connects the individual process steps by considering real yield relations. While allocation strictly by mass always leads to a relation "1 Mg of product by 1 Mg of raw material" (material loss excluded) the problem of low yield ratios of specific products are systematically neglected. The approach by Nieschalk considers these yield ratios. Consequently 1 Mg of the specific product needs (much) more than 1 Mg raw material to be produced. In Figure 7-7 the way of calculation is shown.

In this case the specific burdens allocated to PAO are larger in order of magnitude. The factors between the impact category results of basis and alternative method range from 20 (GWP) to 110 (fossil resources).

Figure 7-6 shows the impact results in normalised units. The tremendously larger grade of magnitude becomes obvious. According to this approach, an amount of mineral oil resources equivalent to the consumption of more than 30 million of European inhabitants would be saved if 600,000 Mg of used oil are regenerated. Based on the current content of about 10 % of synthetics in used oil, the benefit would sustain the equivalent of 10 million inhabitants.

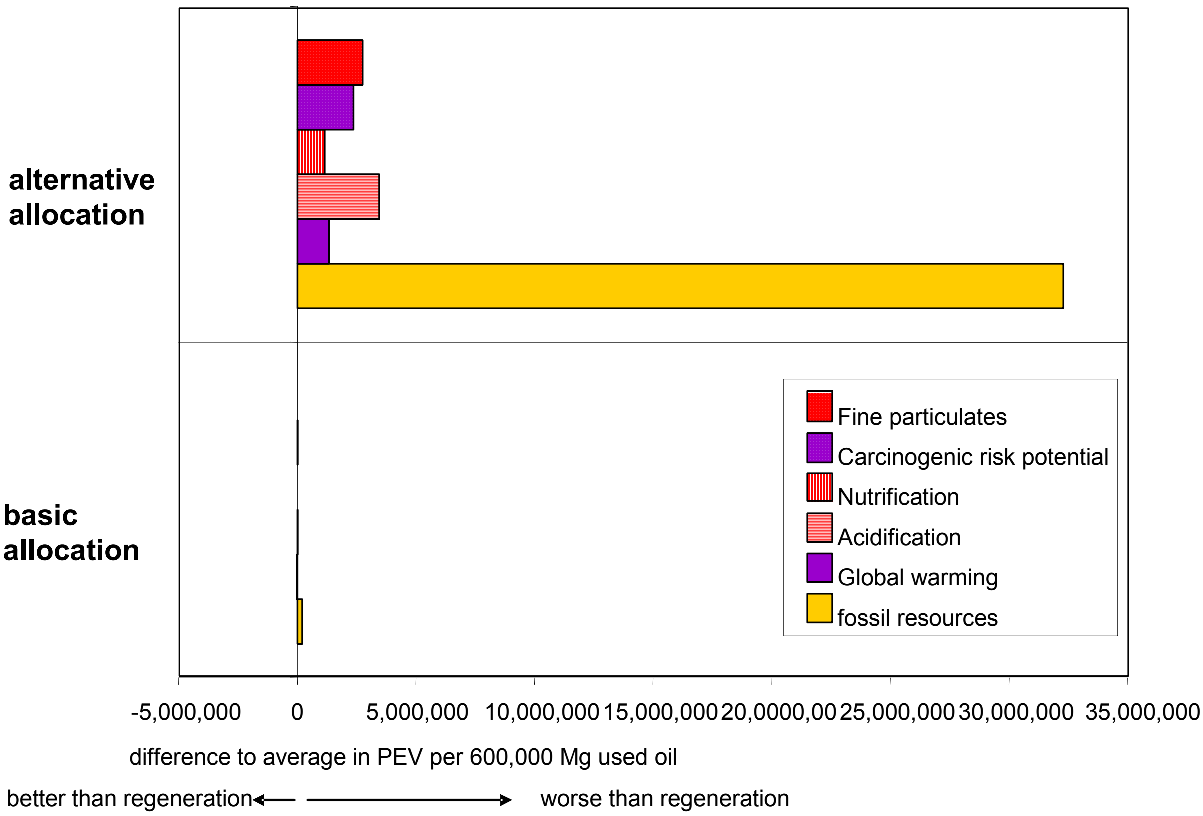

Figure 7-6 **Impact-related and normalized differences of combustion and average regeneration; basic allocation compared with an alternative approach (scenario 70 % base oil, 30 % PAO)**

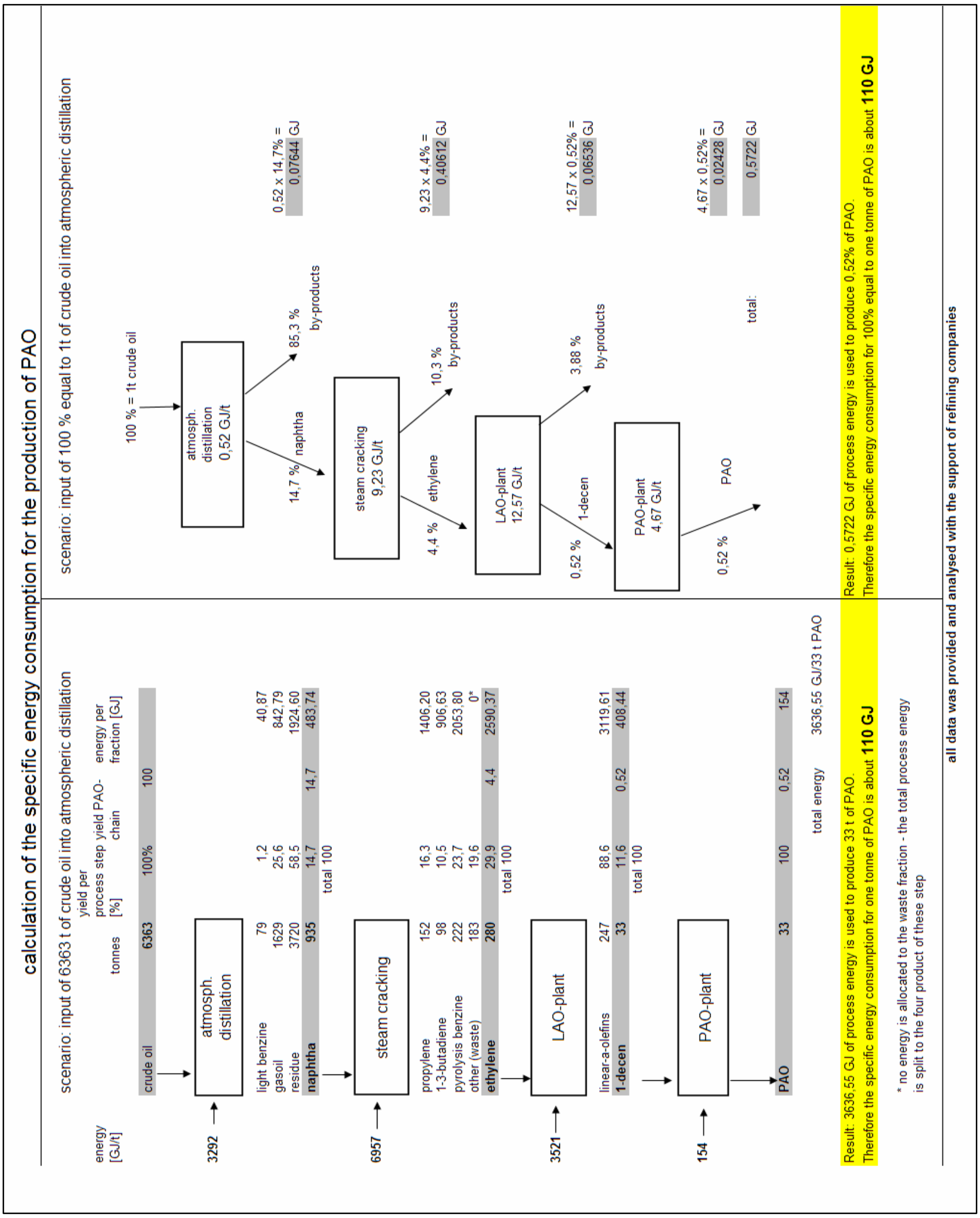

Figure 7-7 Alternative approach of allocating process energy and feedstock along the production chain of PAO; according to Nieschalk [2002]

7.3.3 Other fuels substituted - saturation of secondary fuel market

During the last years, energy recovery of high calorific waste has evolved strongly in some European countries. Especially in the Netherlands, Germany and France secondary fuels constitute high and increasing share. The kind of waste used is mostly a result of economic factors. Meanwhile some individual cement works have nearly reached 100 % substitution of primary fuel.

This development is presumed to lead to saturation of the secondary fuel market sooner or later. Eventually waste recovered fuels will compete with each other. Especially meat and bone meal, which is an often used secondary fuel, is presumed to vanish from fuel market within the next years. Plants using this material will be substituted with other wastes. At this point the relevance of waste/waste substitution shall be illustrated. Taking up an average quota of 17 % of waste as fuel in European cement works, the substituted fuel mix will be adapted:

	Coal (3/4 overseas)	**Lignite**	**Pet coke**	**Fuel oil**	**Natural gas**	**Waste**
Basic mix	44%	10%	40%	5%	1%	
Waste considered	36.5%	8.3%	33.2%	4.2%	0.8%	17%

As waste mix used tyres, used solvents and meat/bone meal (each by a third) are chosen for this exemplary analysis. Typical values concerning the elementary composition of these waste types are documented in Table 7-9.

Table 7-9 Composition of selective waste types used as secondary fuel

		Used tyres	**Used solvents**	**Meat and bone meal**
water	%		4	4.4
C fossil	%	50.1	76.8	
C renewable	%	19.9		43
S	%	1.5	2.8	0.38
Cl	%	0.075	2.8	0.42
Cd	mg/kg	8	0.24	0.27
Tl	mg/kg	0.25	0.1	1.15
Hg	mg/kg	0.17	0.024	0.1
Sb	mg/kg	0.7	1	2.9
As	mg/kg	20	1	0.93
Pb	mg/kg	410	14	2.7
Cr	mg/kg	97	10	2.3
Co	mg/kg	250	1	0.85
Cu	mg/kg	450	10	12
Mn	mg/kg	750	10	24
Ni	mg/kg	77	10	3.3
V	mg/kg	5	1	10
Sn	mg/kg	10	1	5
Lower heat value	MJ/kg	31	38.3	17

Figure 7-8 shows the effect of assumed 17 % waste shared in the substituted fuel mix. Compared to the basic results given in Figure 7-4 (100 % primary fuel substitution) a significant shift for the benefit of regeneration is clearly visible. With regard to 30 % PAO, regeneration measures up with combustion even in terms of global warming.

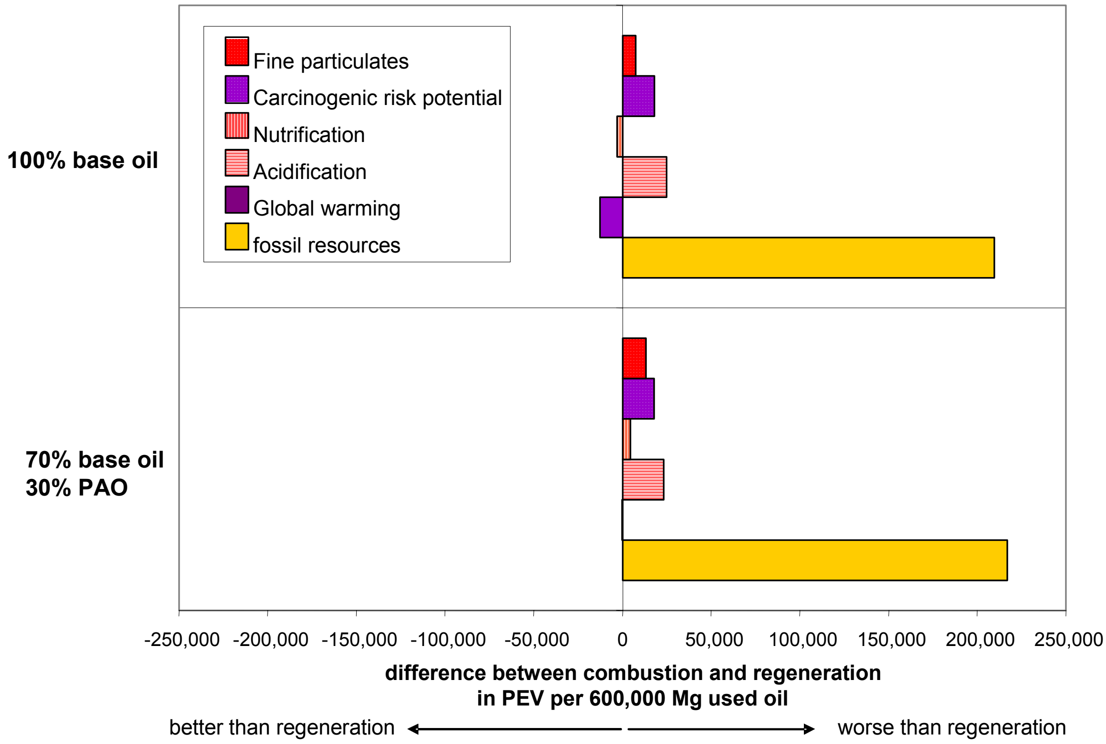

Figure 7-8 **Overview of impact-related and normalized differences between average regeneration and combustion (substitution of cement work fuel mix respecting 17 % secondary fuel)**

7.3.4 Distribution distances

As a basic assumption all ways of used oil recovery have been charged with a delivery distance of 100 km. There has been made no differentiation because of missing proof on influence of type of recovery on actual delivery distances. On the other hand re-refining plants are less densely dispersed than combusting sites. So longer distances from source to re-refining plant might be consequential. At this stage the influence of transport on the results and a change of the settings shall be analysed.

Table 7-10 provides a view on the relations between the specific contribution of delivery and total result of the regeneration system (transport + regeneration + up- and downstream processes) and the relation between delivery and "net" result (caused burden minus omitted burden).

Especially with regard on the influence on the net results it is obvious that varying distances is not a highly sensitive parameter. Nutrification is the only impact category taking more than 10 %. Doubling the distance from source to re-refining plant from 100 km to 200 km would decrease the environmental benefit concerning nutrification by 11 %. Even when the distance to combustion sites are kept constant, the worsening of the regeneration result wouldn't change significantly.

Table 7-10 Relative influence of delivery on impact results of re-refining

	Contribution of used oil delivery to impact result of re-refining			**Relation of impact of delivery to net result [a)]**
	minimum	maximum	average	
Fossil resources	5%	61%	23%	0.3%
Global warming	1%	2.9%	1.9%	2.2%
Acidification	6%	22%	12%	2%
Nutrification	17%	40%	27%	11%
carc. risk potential	3.3%	15%	9.2%	0.5%
Fine particulates	12.4%	29.5%	19%	4.3%

a) based on the 100% base oil scenario

8 Conclusion

The most striking conclusions offered by this assessment are:

1. All the five considered regeneration options lead, through substitution, to higher environmental release than the processes cause. This is apparent in all considered impact categories. So the basic request by the environmental action programme [EC 2001] – the ecological net benefit – is definitely proved.
2. A direct comparison of regeneration and primary base oil refining shows, in terms of energy demand, a high efficiency of the innovative re-refining techniques considered.
3. The change towards more and more synthetic or semi-synthetic compounds in lubricants is significantly reflected in environmental impacts that are increasingly omitted when used oil is regenerated. Primary production of 1 kg of PAO causes more than double CO_2 emission than production of 1 kg classical base oil. Semi-synthetic compounds (XHVI or HC oils) are found between this range.
4. A comparison with direct combustion is done presuming basically the average situation in European cement industry (mainly coal and pet coke as primary fuel) but also presuming other utilities substituting fuel oil by used oil.
   - In the first case, clear advantages concerning “fossil resources”, “acidification”, “toxic air pollutants” favour regeneration. Concerning “nutrification” the discrepancies between regeneration and combustion are low, with the higher ratio of synthetic compounds tipping the scales in favour of regeneration. With weight on a coal substitution by used oil combustion, the relieving effect concerning “global warming” is higher when combusted. But in comparison with the Arcadis/ifeu [2000] the edge of combustion has significantly diminished: from 1,070 kg CO_2-eq. per Mg used oil to 636 kg (without synthetics) respectively to 396 kg CO_2-eq. (30 % synthetics considered).
   - In the second case, the advantages are thoroughly in favour of regeneration or – concerning the scenario without synthetics – disadvantages (global warming and nutrification) are reduced to low significance in relation to the other categories.
5. The analysis of some sensitive parameters shows additional aspects developing in favour of regeneration, especially with regard to allocation method and when an increasing pool of secondary fuels starting to compete is taken into account.
6. The valuation given in the UBA study from 2000 has finalized with a tie between regeneration and combustion. The assessment at hand shows a trend strengthening the pros for re-refining and weakening the (unique) draw-back. Considering the necessarily subjective character of valuations, the total outcome is obviously more beneficial. With regard to increasing material quality and the vagueness of the substituted fuel type concerning combustion, the former parity is shifting gradually in favour of re-refining.

In summary, re-refining of used oil for recovery of base oils leads to significant resource preservation and relief from environmental burdens.

Most of the LCA studies performed in the past have concluded with an indifferent evaluation when re-refining was compared with the combustion option for used oil. This study shows that efficient regeneration technology, the future potential of the re-refining industry, and sensitive environmental aspects lead to conclusions favouring re-refining of used oils to recover base oil. This LCA is evidence of improved environmental benefits from re-refining: supporting the priority given it by EU policies.

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Critical Review of IFEU Life Cycle Assessment of Used Oil

'Ecological and energetic assessment of
re-refining used oils to base oils:
Substituion of primarily produced base oils
including semi-synthetic and synthetic
compounds'

for
GEIR – Groupement Europeen
de I'Industrie de la Regeneration

February 2005

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Contents

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1. Summary

The IFEU Life Cycle Analysis (LCA) examined in this critical review was carried out within the constraint of making a comparison with the results of an earlier LCA (Arcadis/IFEU 2000). This constraint inevitably reduced the scope for the authors of the LCA to change the methodology and analysis to take account of best practice introduced since 2000. Equally, the critical review panel was established after the study had been completed and we were therefore unable significantly to influence its structural elements. We were however given unrestricted access to the data and authors during the review process.

Section 7.1 of ISO 14040 defines the objectives of the critical review as being to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040 series;
- 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 interpretation reflects the limitations identified and the goal of the study;
- The study report is transparent and consistent.

We are satisfied that, within the constraints placed on the scope of this study and subject to a small number of reservations, the LCA has been conducted in a way that is consistent with ISO 14040 series. Our reservations are:

1. Updated data for re-refineries have been compared with data for conventional refineries that are assumed to be unchanged.
2. The same functional unit has been used to evaluate two distinctly different goals; the second goal (comparing re-refining with burning used oil in a cement kiln) may require a different functional unit from the one used.
3. No consideration has been given to the marginal impact on the management of existing conventional oil refineries when used oil is re-refined.

After detailed consideration and review we are satisfied that the methods used for allocation in the manufacture of polyalphaolefins (PAOs) comply with ISO requirements. We would welcome further comments on the allocation methodology from the oil refining industry.

We are satisfied that the LCA methods are scientifically and technically valid although we have expressed the following reservations:

1. The "best case" scenario in which PAO constitutes a 30% share of the lubricant market may be unrealistic. We acknowledge that in page 9 of the study the 30% market share includes synthetic and other high viscosity oils.
2. The exclusion of impact categories concerned with the aquatic environment, malodorous emissions and solid waste needs further justification. We acknowledge that malodorous emissions used to be an issue for old style re-refining technologies but are not considered significant for the five modern techniques used in this LCA.
3. The *marginal* fuel displaced in a cement kiln that accepts used oil should have been identified. The method used in the LCA based on an average-mix fuel is not correct. It is likely that the results would be more clearly in favour of re-refining if this had been done.

We are generally satisfied that the data used are appropriate and reasonable. We have suggested the following issues deserve closer attention:

1. The sampling of mass balance data for one of the re-refining techniques revealed some errors. The final version of the LCA has been corrected to take account of the minor errors discovered during the review.
2. There is no evidence that data provided by the re-refining operators and co-ordinated by the trade association has been subjected to an external validation process. We acknowledge that a method for data gathering was established and since all of the operators use quality management systems we do not consider this to be a major issue but one of detail and transparency.
3. The use of crude oil equivalents and the weighting attached to the various fossil fuels requires further justification for an international audience. The use of these weightings (based on estimates of reserves and current patterns of consumption) is especially sensitive in a study of used oil.

We are satisfied that the interpretation of the data is accurate within the limitations identified and the goals of the study.

We have made a number of minor recommendations to improve the transparency and consistency of the LCA:

The basis on which the five re-refinery operators provided comparative data needs further explanation. We understand that the data were from a yearly average and careful consideration was given to this issue before the study began.

1. We have identified a number of places in which operators of conventional oil refineries and cement kilns could be invited to comment on the data used. These are: the marginal impact on refineries when re-refining occurs, the allocation method for the manufacture of

PAO, and the identification of the marginal fuel displaced in cement kilns by used oil.

2. The transparency of the LCA was identified as a general weakness by the panel. The publication of this critical review alongside the LCA will largely compensate for this weakness.

2. Panel Membership

David Fitzsimons, Panel Chairman from Oakdene Hollins in the UK.
Professor Dr. Birgit Grahl, from Institut für integrierte Umweltforschung Heidekamp.
Professor Dr.-Ing. Günter Fleischer, from Technical University Berlin.

Joachim Küssner of PWC Corporate Finance department in Düsseldorf was a member of the panel for the first two weeks of the review and contributed significantly to the review of methodology. His position on the panel was taken by Professor Fleischer from 1st February 2005.

ISO 14040 section 7.3.3 encourages the involvement of "interested parties" in the critical review. Interested parties in this case could include cement kiln operators, oil refinery operators, lubricant manufacturers, non government organisations (NGOs) as well as various policy makers and advisors. For practical reasons explained in this report, the critical review process was carried out by the appointed panel members without more extensive involvement from other interested parties. However, at appropriate places in this critical review we have highlighted where further technical information from interested parties would be especially helpful.

2.1 Declaration of Independence

Members of the panel received financial compensation from GEIR for the time and expenses incurred during the review. Panel members were invited to declare whether as individuals or as employees they had a pecuniary interest in the used oil re-refining industry in general or in individual companies operating in the sector. On the 28th January 2005, the date on which the declaration was requested at a formal meeting of the panel in Frankfurt, each panel member confirmed that they had no such pecuniary interest. They each declared themselves to be wholly independent for the purposes of the critical review.

2.2 Methodology

ISO 14040 recommends that a critical review panel is established either at the start of the LCA project or alternatively at a later stage. It is usually more effective to establish a critical review panel at the start of a project. In this case, it was not until the LCA study was close to completion that a critical review panel was considered. David Fitzsimons travelled to IFEU in Heidelberg in November 2005 to review the study, but because of pressures of work it was not possible to constitute the review panel until January 2005.

By not establishing a critical review panel at the outset of the LCA project, the opportunity to influence the choice of basic parameters such as system boundaries was reduced. Nevertheless, a number of changes were made to the LCA as a result of the critical review. Where changes were made, and these changes comprehensively responded to the issues raised by the panel, we have not included a discussion of them in this report.

The procedure used for review was:

1. Each member of the panel independently read the draft LCA and raised queries.
2. Queries were grouped together as being related to either (a) methodology (b) data inventory (c) data analysis (d) interpretation of the analysis and the reliability of conclusions drawn from the interpretation.
3. A formal meeting of the panel was convened on 28th January 2005 in order to identify areas of particular concern and to give the author an opportunity to respond. Several issues were raised both in writing and verbally including three main issues that were subsequently investigated in greater depth. These were data quality assessment, allocation methodology for PAO, and the methodology used for the substitution of fuels in cement kilns. These and several other matters raised at the meeting and in exchanges between panel members are discussed in this report.
4. The author of the report was invited to make revisions to the LCA where appropriate.
5. The draft of this report was then circulated only to members of the critical review panel for comment and revision. Neither the GEIR nor the author were permitted to contribute to the final report.

Section 7.1 of ISO 14040 defines the objectives of the critical review as being to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040 series;
- 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 interpretation reflects the limitations identified and the goal of the study;
- The study report is transparent and consistent.

This report concludes by providing a comprehensive response to each of these objectives. For ease of reference, the critique section of this report is structured in the same way as the LCA study.

All errors and omissions in this report are the responsibility of the members of the critical review panel.

3. Critique

The structure used in this section largely reflects that employed in the LCA study.

3.1 Goal Definition

The goals for the LCA were defined by GEIR. We are not able to comment further on the suitability, completeness or otherwise of the goals.

3.2 Methods and Scope

One of the goals of the LCA is to update an earlier study (Arcadis/IFEU 2000). The new data provided by the five recently upgraded re-refining processes offered an opportunity to evaluate whether the results of that earlier study would be significantly altered by the new re-refining techniques. For this reason, the LCA closely follows the methods and scope of the earlier study.

This may not be ideal if the goals of the LCA are to be achieved. Comparability with the earlier study requires, as far as possible, the replication of the maximum number of elements from that study.

This decision could have implications for the methods and scope. Revised data have been used for the five re-refining processes but data for equivalent systems in oil refineries have not been updated. We have been assured that there has been no significant change to the performance of oil refineries in Western Europe and that the data used, dating from the mid 1990s, do not need to be updated. We would welcome comments from the oil industry on whether there have been significant changes to oil refineries since the mid 1990s, in particular to refinery processes using waxy distillate as a feedstock.

3.3 Functional Unit

Waste management LCAs present particular problems compared to product LCAs as waste is usually heterogeneous. Defining the functional unit inappropriately can embed assumptions that lead to inevitable conclusions and thereby undermine the purpose of preparing an LCA. For example, by defining the waste material in a way that assumes that all waste is presented for treatment as segregated and contaminant free. This is an especially sensitive issue when the goal of the LCA is to evaluate one treatment or disposal option with another. In this case, the LCA includes an analysis of the impact of using used oil in cement kilns.

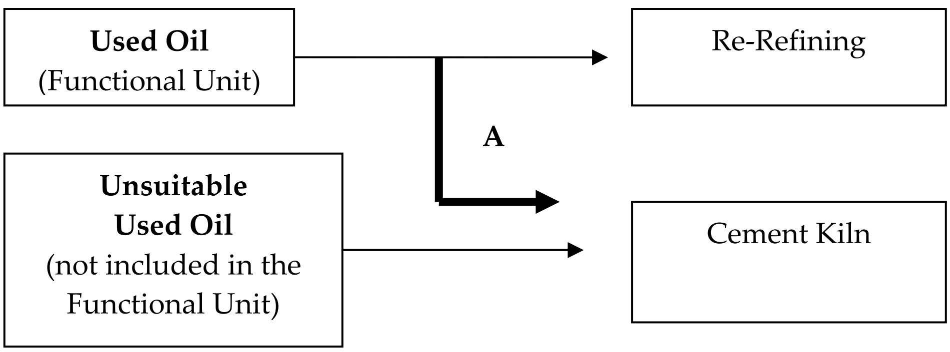
The International Expert Group on Life Cycle Assessment for Integrated Waste Management has considered this issue (Coleman T, Thomas B 2003). The advice being "it may or may not be sensible to impose constraints on the systems being considered and potentially therefore on the functional unit". ISO 14041 states: "in defining the scope of the LCA study, a clear statement on the specification of the function of the product (system) shall be made … the functional unit defines the quantification of these identified functions – considered within the goal and scope of the study".

This advice and definition encourages careful consideration of the functional unit. The critical review panel investigated this issue and its potential consequences for the results of the LCA.

The functional unit in this case has been defined as being the used oil presented to re-refining processors. The compositional analysis used through out the LCA is based on actual data provided by the re-refiners.

As re-refining places quality constraints on the types of used oil that are acceptable for re-refining such a definition is only acceptable if the LCA is comparing equivalent types of re-refining. It is less useful where the functional unit is to be burned in a cement kiln, since the constraints on cement kilns are considerably less than those on re-refineries. Route "A" is possible for the functional unit but there is no similar alternative option for unsuitable used oil (figure 1).

Figure 1. Comparison of actual and alternative functional units



This issue could be dismissed as trivial if either of the following is shown to be correct:

1. There is an insignificant amount of used oil presented for collection that is unsuitable for re-refining.
2. It is feasible to collect both types of used oil separately.

Information was provided to us on the Italian used oil collection market implying that approximately 10% of collected used oil was suitable only for energy recovery in a cement kiln. This figure excluded waste oil from the marine sector that is commonly contaminated with bunker fuels and water.

We were also told that used oil in Germany is typically only mixed with unsuitable used oils, fuels, solvents, paints etc by the used oil collector at his depot. This implies that used oil suitable for re-refining can be collected separately without much difficulty.

We enquired whether the definition of used oil in the European Waste Catalogue would be a more suitable definition for the functional unit. The main difficulty associated with using this as the functional unit is that compositional analysis of the additional and unsuitable used oils would not be available.

Our main concern became more tightly focused on the implications of ignoring used oil that is unsuitable for re-refining: specifically, whether the environmental burdens associated with separate collection might exceed any environmental advantages from re-refining compared to burning in a cement kiln (or other similar facilities such as steel works, lime kilns and power stations). Separate collection may for example require a greater number of depots, more road transport kilometres and an increased risk of inappropriate disposal. We acknowledge that water must be removed from used oil taken to steel works and minimised for use elsewhere. Although the transport issue is discussed under sensitivity analysis it is not done so comprehensively.

The two distinctly different goals set for the LCA place a constraint on the design of the functional unit. We concluded that the LCA had defined the functional unit appropriately for the first of these goals: that of comparing re-refining with conventional refining. However, it is much less appropriate to use the same functional unit for the second goal: that of comparing re-refining with energy recovery in cement kilns.

3.4 System Boundaries

There are two separate system boundaries. The first concerns the comparison of re-refining with conventional oil refineries. For the LCA to be a valid comparison, the choice of an equivalent system to that of re-refining used oil is necessary. In common with other LCAs for waste management, the choice of equivalency system is sensitive: it can become an artificial construct because no other comparable process manufactures base oil and a range of other mineral oil products from used oil.

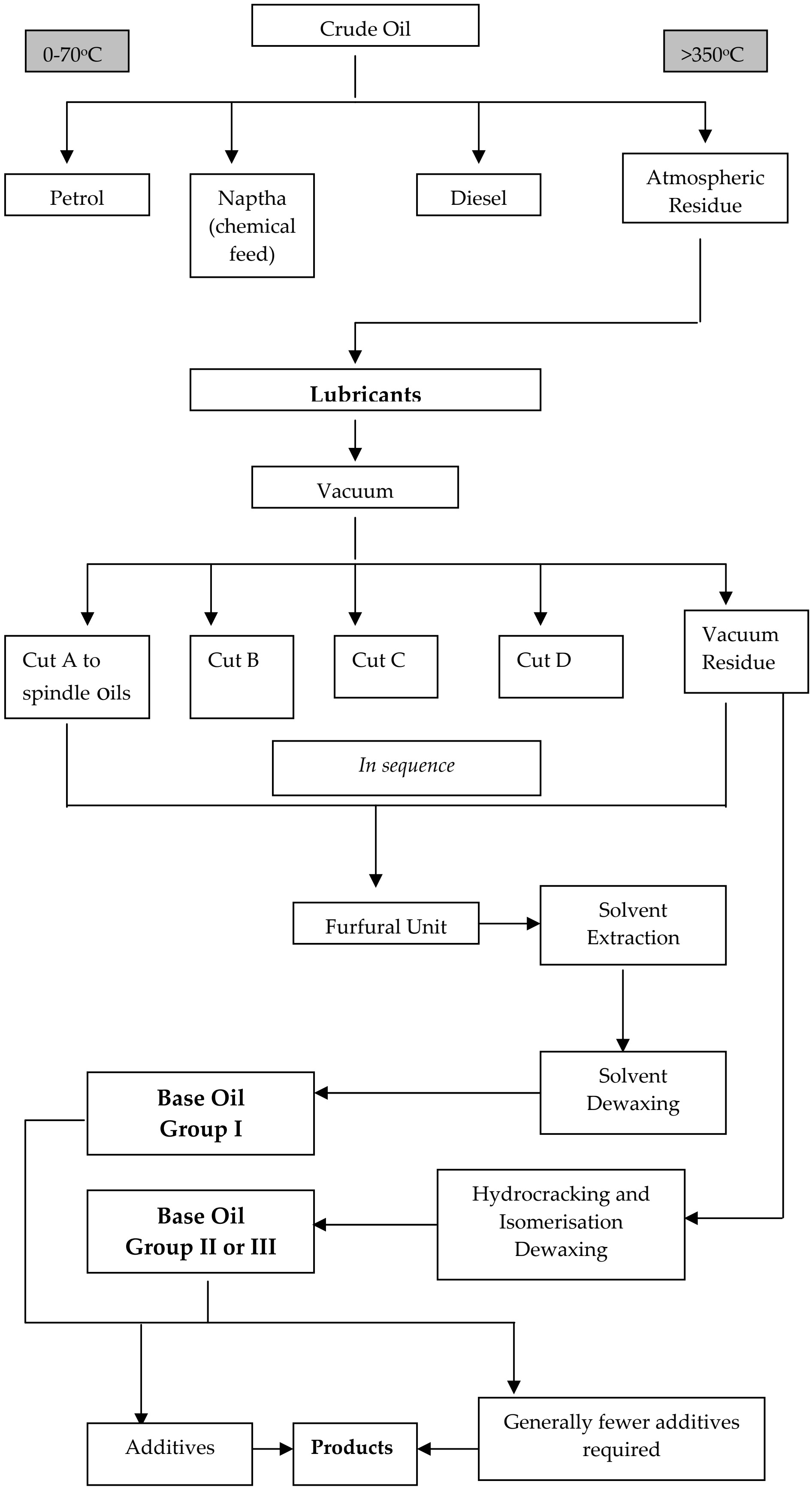
This choice is further complicated by the changing composition of the lubricant products from which used oil is derived. An increasing proportion of new lubricant is being manufactured using highly refined and chemically more stable oil. To achieve this higher quality oil, additional and highly resource-intensive processes are required within conventional refineries.

The equivalency system created for the purposes of the LCA is to assume that waxy distillate is the equivalent feedstock in a conventional refinery to used oil in a re-refinery. As the market share of more highly refined lubricants increases, the additional resources required to manufacture them are added to the burdens calculated for the refining of waxy distillate.

If a re-refinery manufactures base oils and other mineral oil based fuel products, the marginal impact on the conventional refinery system needs to be investigated. For example: are conventional refineries forced to return waxy distillate to a cracker unit to manufacture other products, or is it possible to reduce the quantity of waxy distillate that is manufactured?

Approximately 1.5% of crude oil supply is manufactured into lubricants, of which 60% can be recovered after use. As production of all the other products manufactured from crude oil will be unchanged by the re-refining of used oil, the way in which the refinery process is changed by not having to manufacture perhaps 35% of the previously manufactured base oil deserves careful consideration. A simplified schematic of the process of conversion is shown in figure 2.

Figure 2. Summary process flow for oil refining

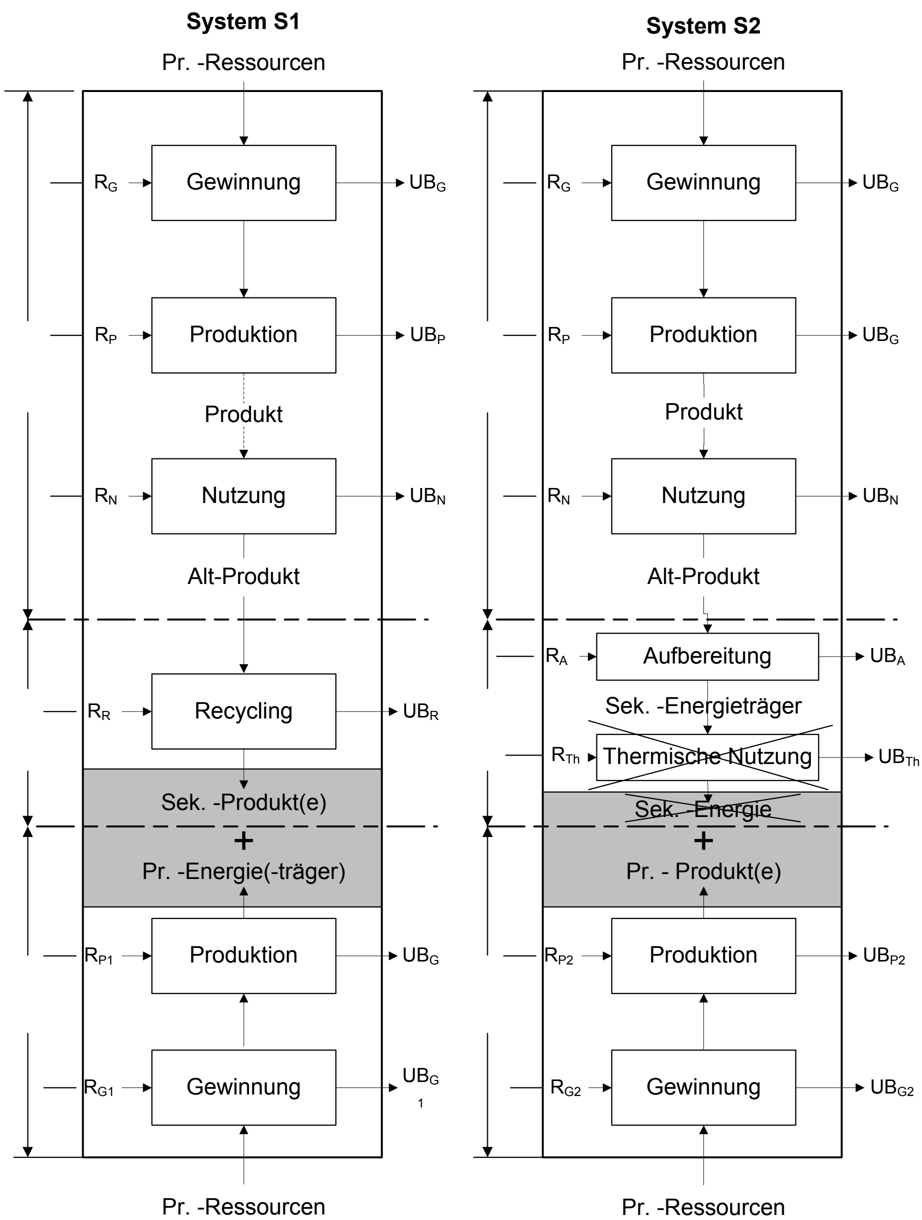


We raised this issue of the marginal impact on refineries and were assured that the impacts on refinery management would be negligible. This implies that refineries are capable of adjusting the portfolio of products manufactured from a range of feedstock at nil marginal environmental burdens. We would welcome comments from the oil refining industry on whether this is an accurate reflection of refinery management.

Having received the assurances, we concluded that the system boundaries are suitable for the comparison of re-refining with conventional refineries and comply with the requirements of ISO 14041.

The panel then discussed the suitability of the system boundaries for the second goal of comparing re-refining with energy recovery in a cement kiln. The main concern was that the two systems were not symmetrical; System 1 (re-refining) produced a range of mineral oil products whilst System 2 manufactured cement clinker for which only the heat value of the used oil was useful. This is shown in figure 3.

Figure 3. Summary of systems used for comparison



Source: Reworked by Fleischer

This issue of comparing recycling with systems that use the energy value in the waste feedstock is discussed in the literature (Ekvall T, Weidema, BP 2004). Recent methodological studies in the paper sector are also relevant (Frees et al 2004).

At issue is the equivalence of outputs from the two processes that are being compared. This is an LCA considering the benefits arising from using one system or the other. One produces base oils and various other fuels whereas the other produces cement clinker.

S. 11

It is of particular relevance in the case of used oil as the majority of crude oil is refined into fuels and it could be argued that used oil is equivalent to fuel oil.

If used oil is burned in a cement kiln, society needs to be supplied with base oil and other fuels from a conventional refinery. This information is provided in the LCA. Society will not have to supply as much fuel to the cement kiln in order to receive the same quantity of cement clinker. This information is provided in the LCA. However, the method used in the LCA to identify the *marginal* type of fuel displaced in the cement kiln is not correct.

We have concluded that the system boundaries used for the second goal comply with the requirements of ISO 14040. Although society receives different products from the two systems (base oil and cement clinker), the important marginal impacts concern the type of fuel displaced in the cement kiln. The LCA has not identified the marginal fuel appropriately.

3.4.1 Scenarios

Best and worst case scenarios are given. These are based on estimates of possible market shares for highly refined lubricants containing polyalphaolefins[a] (PAOs). The LCA uses scenarios based on the quality of lubricants because the resources required to manufacture these products is far greater than that required to manufacture classic Group I base oils. Consequently, the re-refining of these sophisticated used oils is likely to yield higher net benefits than the re-refining of classic Group I oils.

The choice of 0% and 30% market share is not clearly explained and the panel raised queries about this. The market share of the highest quality lubricants varies geographically and is correlated with the average age and sophistication of the car pool. In Germany, the market share is higher than it is in other European countries and is said to be at about 9% in 2005.

We were most concerned about whether a 30% market share for such sophisticated lubricants was a realistic scenario. Car owners may in practice only use the highest quality lubricants when the vehicle is under a manufacturer's warranty. When the vehicle is out of warranty and has been sold to a second owner, less sophisticated lubricants may be used in order to minimise the costs of maintenance. Since consumption of lubricant increases as the engine wears, it might be expected that the owners of older vehicles would represent a larger segment of the market for lubricants than

[a] PAO is manufactured from "gases" at the top of the distillation column by polymerisation and has low volatility and exceptionally high viscosity.

the owners of new vehicles. In these circumstances, it would seem unlikely that 30% of the market would switch to such high quality products.

We discussed trends in engine design, marketing efforts by the major lubricant manufacturers and increased uses for PAOs in other sectors such as aerospace and industry. We also discussed whether refining techniques for PAOs would have changed significantly by the time a market share of 30% was achieved. For example whether gas to liquid refining was undertaken, and the implications for re-refining.

We acknowledged that the LCA (page 9) does include other high viscosity oils including synthetics in the 30% market share "best case" scenario.

We concluded that the scenarios are helpful in establishing whether or not there are likely to be greater benefits from the re-refining of used oil containing a greater proportion of these more sophisticated oils.

3.5 Impact Assessment

Two issues were considered in detail: the choice of indicator and the characterisation factors.

3.5.1 Aquatic Impacts

The choice of indicators may have been driven more by a need to compare on a consistent basis the results of this LCA with those of the previous study (Arcadis/IFEU 2000).

Some other comparative LCAs of used oil (e.g. ADEME 2000) have included measures of aquatic toxicity and eutrophication. It is also shown from the compositional analysis of used oil that 5% to 8% of the feedstock is water. To exclude consideration of impacts on the aquatic environment may be reasonable on the grounds of symmetry with conventional refining but this is most unlikely. Some of the five re-refining plants included in the analysis operate sophisticated water treatment plants in-house whilst others do not and instead discharge waste water for treatment off-site. It would be helpful for reasons of transparency to provide an explanation as to why this factor was excluded.

We put these points to the author, Horst Fehrenbach. In this study more indicators have been used than in the previous study. He argued that the excluded indicators in this study were shown not to have been significant in the previous study. The 2000-CR (critical review) confirmed this. The main advantage from concentrating on the more significant indicators was that Prof. Dr. Hedden (for the refinery) and Dr. Möller (for the lubricants products) had more time to check data. In our view this improved the inventory documentation and the transparency of the impact assessment.

3.5.2 Malodorous Emissions

The audience for these studies might be expected to include local authorities with responsibility for development control. In the past, malodorous emissions were a problem at small scale re-refineries. The modern techniques considered in this LCA are considered to have over come these problems.

Local authorities might expect to understand if there are differences between the re-refining of used oil and the refining of waxy distillate in terms of the atmospheric discharge of malodorous substances such as mercaptans.

We have acknowledged that the equivalence between used oil feedstock and waxy distillate is reasonable. However, this is not the same as accepting that it is equivalent in all respects. Used oil typically contains a higher level of sulphur compounds due to the contamination of lubricant with fuel. It is contaminated with the post-combustion products of fuel while the lubricant is in an engine. This inevitable contamination requires re-refineries to pre-treat used oil comprehensively in order to remove the risk of unpleasant smells near such facilities. The five techniques considered in this study are thought to have sufficiently robust methods for pre-treating the used oils.

The trend toward lower sulphur fuels will tend to reduce this risk over time and the pre-treatment techniques used in all five modern re-refining processes are designed to reduce the risk further.

LCA methodology can be used to take account of such issues. The impact could be measured by requesting each of the re-refining plants and equivalent conventional refineries to reveal the number of occurrences of incidents involving the release of malodorous substances.

That it is neither discussed nor included reflects the confidence that the commissioning organisation has in the reliability of the modern re-refining technologies.

3.5.3 Solid Waste

Other LCAs on used oil have also investigated the generation and fate of solid wastes (ADEME 2000, N EPA 1995). Since re-refining accepts a feedstock that is more likely to contain elements that need to be removed and discarded compared to waxy distillate, the question arises as to what is the fate of these contaminants. This factor has been excluded possibly on grounds of *de minimis* as the composition analysis includes only 1% ash. If the functional unit had included a wider range of used oil, this factor would be more important.

3.5.4 Characterisation Factors

The characterisation factors used for resource depletion are derived from German Government sources and reflect the weighting given to four categories of fossil fuel resources. These are shown in table 1.

Table 1. Characterisation factors used for the "Resource Depletion" Impact Indicator

Category	Factor	Unit
Mineral Oil	1	Kg Crude Oil Eq./kg
Natural Gas	0.627	Kg Crude Oil Eq./kg
Coal	0.1836	Kg Crude Oil Eq./kg
Lignite	0.0409	Kg Crude Oil Eq./kg

The factors used are specific to Germany and reflect the current level of consumption and anticipated reserves for each category. Other countries would not necessarily accept these factors and it would generally aid transparency if the LCA highlighted these issues as they arise. The terms "mineral oil" and "crude oil" are interchangeable in this analysis and it is generally good practice to highlight this wherever possible.

In our view, the use of "crude oil equivalents" is not helpful to the accuracy and transparency of the LCA. Indeed, it may distort the results in favour of any process that recycles mineral oil. The weighting factor makes the conservation of one tonne of oil five times more important than the conservation of one tonne of coal. The basis of this weighting appears to be a calculation of the rate at which each resource is being depleted. For certain uses, for example as fuel in a power station or cement kiln, they are broadly interchangeable as substitute fuels for one another. Consequently, it might be more accurate to measure not in "crude oil equivalents" but in heat values.

On further investigation, we found that this measure was used because it had been used in the previous LCA (Arcadis/IFEU 2000) and is referred to as the “UBA” method. This is satisfactory from the point of view of consistency within the objectives set for the LCA but in our view should not be used in future LCA studies for used oil without careful consideration of the consequences for the results. It would be helpful if the differences could be shown in this study.

We concluded that the most significant impact categories had been selected although we have reservations over whether it was appropriate to ignore aquatic impacts and the possibility of malodorous emissions. We were concerned about the use of a weighting factor for various fossil fuels.

3.6 Inventory Analysis

The final version of the revised LCA is to include a section on inventory analysis. In the time available to the panel general queries were raised concerning the source and quality of the data provided by the five re-refining processes. Sample investigations were conducted on the CO_2 calculations and the basis on which these were made.

Our main focus was to investigate whether the data provided by the operators of the five re-refining plants was subjected to validation tests. The purpose of the LCA is to identify whether the improved re-refining techniques present advantages over those techniques analysed in 2000. Since provision of the data was coordinated by the trade association (GEIR) there is at least a risk that the data has been selected in order to present a positive case. We found no evidence of this but ISO 14040 requires that, where data for the inventory analysis are taken from individual operators, methods of validation are included.

We understand that data was for an average year and it would assist transparency if this were explained. These issues are not trivial as it needs to be clear whether the data provided cover a standard time period or whether there are seasonal factors that have been ignored. The data might represent only that achieved during ideal operating conditions.

In the case of used oil, seasonal factors might include a change in the composition of used oil due to the use of different oils during extreme weather conditions. Equally, different operating temperatures in lubricated equipment may present seasonal variations. The proportion of used oil that is contaminated with water may also be seasonal.

We understand that all five operators use quality assurance methods and it should be possible to provide evidence that the data have been provided on an equitable basis. It would be good practice to demonstrate this in the text, given that the data from the operators is such a key element of the LCA analysis.

We should emphasise that we found no evidence that data provided by the operators was incorrect. The only error found whilst sampling the spreadsheets for mass balance calculations was created during data analysis and was subsequently corrected. This is dealt with in the next section.

3.6.1 Sampling

Because of the complex data-sets used in the study from a variety of sources the panel carried out a sample test of the calculations made, as well as raising several queries over the consistency of data.

At the time of writing the critical review the detailed queries concerning the consistency of data were still being addressed. None of these are considered to have significant impacts on the results of the LCA. The detailed concerns included the assumption of 100% process efficiency for PAO manufacture, as 1 tonne of feedstock appeared to be processed into 1 tonne of product.

Sampling of the data analysis was carried out on the CO_2 calculations and found to be satisfactory.

We investigated the input-output balances (tables 5.1 to 5.5). ISO 14041 section 6.5.2 requires a mass balance approach that demonstrates the fate of all feedstock. This was a matter of some concern as differences were discovered in the mass balance. In one instance feedstock of 1.000 kg of used oil was found to produce outputs of 1.172 kg, implying that 100% of input material was converted to 117.2% of outputs. By itself this single error would not cause the results of the LCA to be wrong but, since we were using a sampling method, it implied that further errors may be present in the data. This particular error was investigated in detail and its cause discovered (rounding and O_2 use). The final version of the LCA has been corrected.

In view of the time constraints it was not possible to carry out a comprehensive check on the validity of the data as required by ISO 14041 section 4.3. Although we were able to investigate in detail the most sensitive data.

We concluded that we have reservations about the transparency of the data used. However, subject to the detailed queries being addressed and assurances over the scale and scope of any other mass balance errors, we found that the analysis of the data was satisfactory.

3.7 Sensitivity Parameters

We have queried whether a 30% "best case" scenario for PAO content in used oil is realistic. Equally important is the allocation method for the production of PAO, derived from Nieschalk (2003). Since PAO is manufactured from such a small component of the oil treated in distillation columns, only the most careful of allocation methods should be used.

When this issue was discussed at a meeting of the panel, the range of estimates for the marginal increase in energy required to manufacture PAO was very great.

Because of the sensitivity of the results to this allocation method, the panel investigated it in some detail. Using data provided in an Excel spreadsheet the allocation method was reworked and was found to be consistent with that used in the study (fuel: 27GJ/tonne of PAO).

Nevertheless, since the results of the LCA are sensitive to the accuracy of this allocation method, we would welcome comments from the oil refining industry. We are satisfied that in this study the allocation method has been carried out to the standards required to meet ISO 14040 series.

3.8 Other Significant Issues

3.8.1 Marginal Fuel in Cement Kilns

A workshop in 2001 (International Workshop on Integrated Waste Management) highlighted the relevance of substituted fuel choices (Finnveden G, Sundqvist J-O, Sundberg J 2001). Much work has been carried out on a methodology for identifying which fuels are displaced; there is now broad international consensus that practitioners should seek to identify the *marginal* activities that are displaced by recycling, reusing etc.

For example, where burning a waste material allows the generation of electricity it is the impact on the most expensive, least preferred or marginal source of electricity that should be used for comparison purposes.

In this case, the LCA uses an average-mix tonne of fuel in a cement kiln for comparison. This is not current best practice and has an important implication. The average-mix tonne is based on all the types of fuels that are used in a cement kiln. Consequently burning used oil in a cement kiln that uses a large proportion of coal or lignite is inevitably seen to result in an environmental benefit in terms of global warming potential (GWP).

The panel discussed the issue and asked: which of the several different types of fuels used in a cement kiln should be considered to be the marginal fuel? Put another way, which of the fuels would be displaced if one tonne of used oil were to be burned?

Although it was agreed that taking an average-mix tonne was certainly not the correct approach, there was no agreement as to the marginal fuel. One body of opinion favoured displacing other similar liquid wastes such as solvent wastes. This was rejected on the basis that solvent wastes are the least cost method of providing fuel. An alternative view was that coal usage in cement kilns is generally falling as the proportion of fuel supplied from wastes increases. This indicates that waste generally displaces coal. This was dismissed on the same grounds, that coal is not the most expensive fuel used in cement kilns. Although not unanimously accepted, the use of heavy fuel oil in cement kilns was thought to be the most expensive form of fuel used by cement kilns and displayed attributes that are more similar to used oil.

If heavy fuel oil were to be identified as the marginal fuel in cement kilns instead of the "average-mix fuel" used in this and the previous study, the results of the LCA would be more clearly in favour of re-refining compared to burning. There is no doubt that the average mix fuel is incorrect and that the conclusions drawn from analysis based on this assumption are unreliable.

We would welcome further comment from LCA practitioners and cement kiln operators on the most satisfactory method for identifying the marginal fuel displaced by used oil.

3.9 Study Conclusions

The conclusions drawn from the comparative analysis provided in the LCA are consistent with the results. However, in view of the reservations we have expressed in this critical review we feel that the conclusions are expressed too bluntly for the audience this LCA is addressing.

It would be more accurate to draw attention to the constraints under which the study was conducted. Specifically, that it is an updated version of the previous study (Arcadis/IFEU 2000) and that it has two distinctly different goals.

The degree of confidence that can be expressed about the results of the LCA is different for each of these goals. In our opinion, a higher level of confidence can be attributed to the results comparing re-refining with conventional refining. It is also possible to conclude with a higher level of confidence that the results of the LCA show a trend in favour of re-refining compared to the previous LCA.

However, a lower level of confidence should be expressed about the results attributed to the comparison between re-refining and burning in a cement kiln.

4. Conclusions

Section 7.1 of ISO 14040 defines the objectives of the critical review as being to ensure that:

- The methods used to carry out the LCA are consistent with ISO 14040 series;
- 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 interpretation reflects the limitations identified and the goal of the study;
- The study report is transparent and consistent.

We are satisfied that, within the constraints placed on the scope of this study and subject to a small number of reservations, the LCA has been conducted in a way that is consistent with ISO 14040 series. Our reservations are:

1. Updated data for re-refineries have been compared with data for conventional refineries that are assumed to be unchanged.
2. The same functional unit has been used to evaluate two distinctly different goals, the second of which may require a different functional unit from the one used.
3. No consideration has been given to the marginal impact on the management of existing conventional oil refineries when used oil is re-refined.

After detailed consideration and review we are satisfied that the methods used for allocation in the manufacture of PAO comply with ISO requirements. We would however welcome further comment on this aspect of the LCA from the oil refining industry.

We are satisfied that the LCA methods are scientifically and technically valid although we have expressed the following reservations:

1. The "best case" scenario in which PAO constitutes a 30% share of the lubricant market may be unrealistic. We acknowledge that the "best case" scenario of 30% includes not only PAO but other synthetics and high viscosity oils.
2. The exclusion of impact categories concerned with the aquatic environment, malodorous emissions and solid waste requires further justification. We acknowledge that malodorous emissions were a feature of old re-refining technologies not the modern techniques considered in this study.

3. The marginal fuel displaced in a cement kiln that accepts used oil should have been identified. The method used of an average-mix fuel displaced in a cement kiln by used oil is not correct. It is likely that the results of the LCA would have been more clearly in favour of re-refining had this been done.

We are generally satisfied that the data used are appropriate and reasonable and we have suggested the following issues that deserve closer attention:
1. The sampling of mass balance data for one of the re-refining techniques revealed some errors that were subsequently corrected.
2. There is no evidence that data provided by the re-refining operators and co-ordinated by the trade association have been subjected to an external validation process. We found no evidence of errors in this data and as all the operators use quality management systems this evidence should be available.
3. The use of crude oil equivalents and the weighting attached to the various fossil fuels requires further justification for an international audience. The use of these weightings (based on estimates of reserves and current patterns of consumption) is especially sensitive in a study of used oil.

We are satisfied that the interpretation of the data is accurate within the limitations identified and the goals of the study.

We have made a number of minor recommendations to improve the transparency and consistency of the LCA:
1. The basis on which the five re-refinery operators provided comparative data needs further explanation. We acknowledge that average year data was used but it would be helpful if the basis of the data is explained in the study to show whether the data are from a consistent operating period, whether they are based on ideal operating conditions or whether there are any seasonal issues.
2. We have identified a number of places in which operators of conventional oil refineries and cement kilns could be invited to comment on the data used. These are the marginal impact on refineries when re-refining occurs, the allocation method for the manufacture of PAO, and the identification of the marginal fuel displaced in cement kilns by used oil.
3. The transparency of the LCA was identified as a general weakness by the panel. The publication of this critical review alongside the LCA will largely compensate for this weakness.

Panel Members' Photos


Prof. Dr.-Ing. Gunter Fleischer


Joachim Küssner


Prof. Dr. Birgit Grahl


David Fitzsimons - Chairman

IFEU's comments to the Critical Review Report

The IFEU team expresses its thanks for a fair and effective review process by the review panel. The expertise of all three members of the review team is a guarantee for a solid synthesis of the LCA and the critical review report.

We appreciate the conclusion in the report that our LCA complies with the ISO 14040 series. Because an LCA is always a complex work product, it is always to be expected that open points are identified in a review that require clarification, discussion and potentially a revision on our side. This is particularly true for the issue of refining and re-refining that requires a large number of methodical assumptions. We accept the critique where it is justified and explain our differing point of view in some cases.

The areas requiring our comments to the critique are “disregarding marginal effects”, “fuel substitution” and “data of the re-refineries”.

1. The review concludes that marginal impact on the management of existing conventional oil refineries when used oil is re-refined were not considered by us. This is a valid critique. However, assessing the real marginal impact would be a very complex and time-consuming analysis if it could by carried out at all. The markets of mineral oil products are very fluctuant and the refineries are bound to adapt to developments all the time. While we agree that this is an important issue, we doubt that it is possible to properly measure the impact of re-refining on the base oil sector.

2. The review concludes that it is not correct to take an average fuel mix as the marginal type of fuel to be displaced in a cement kiln. While there may be alternative and possibly more precise and appropriate approaches to identify the “correct fuel”, alternative approaches will involve further complications and are subject to considerable uncertainties. In our opinion, simple parameters such as medium fuel prices are not the correct indicators. Each combustion plant derives its fuel mix based on a number of specific requirements, price not being the only criterion. Because the knowledge of which fuel exactly is replaced in each individual cement kiln, we feel confident that taking an average mix in account is the best approach under the circumstances. We would further like to point out that our report includes calculations for the option of the “correct fuel” from a marginal point of view. The results are reported in the LCA and reflected in our conclusions.

3. A further point of the review addressed the quality of the data regarding the re-refining techniques. The review claims that it is not equivalent to the data for standard refineries. We cannot provide a guarantee that each data point is exact because we have to trust the companies delivering such data. We have interviewed the persons that are responsible for the technical data and we have checked its plausibility. Likewise, the data concerning standard refineries was also derived from company information. Consequently, we cannot agree with the claim made by the review team.

Horst Fehrenbach

Statement of GEIR

The Groupement Européen de l'Industrie de la Régénération (GEIR) is glad to present this study to experts and interested audience. This study clarifies existing uncertainties and takes the advantages of modern re-refining into account.

Our special thanks are addressed to the re-refining operators from Europe and overseas who provided the necessary operating and quality data for the LCA. We are particularly grateful to Horst Fehrenbach, author of the LCA for his professional commitment to create this study and to coordinate a significant number of meetings and telephone conferences. We appreciate him being a competent expert. We would also like to thank the members of the Critical Review team Mr. David Fitzsimons, Prof. Dr. rer. nat. Birgit Grahl, Prof. Dr.-Ing. Günter Fleischer and Joachim Küssner for their work. The Critical Review went in great detail and encouraged vital discussions. Finally, the result of everybody's endeavours is a study which shows a number of aspects which have not been considered in other studies so far. The data of five up-to-date re-refining techniques have been considered. The focus has also been put to the use of new synthetic and semi-synthetic components.

We especially agree with the opinion of the Critical Review team that the study has given reliable proof of the advantages of re-refining in comparison with the virgin refineries. With choosing the "right" substitute fuel the re-refining would have an ever greater advantage in comparison to burning.

With the help of re-refining it is possible to improve significant environmental impacts and especially to avoid CO2 emissions.

The result clarifies the slightly ambiguous conclusions of former LCAs and critical reviews.

After stating the ecological advantages of re-refining experts will now apply also to the economic considerations. In the light of exploding prices of crude oil the re-refining as a "domestic source" will become more valuable again. The flexibility of the branch has led to an enormous increase of productivity. As soon as the existing problems regarding excise duty derogations for the burning are overcome a sustainable resource industry can be make a significant contribution to society.

The final scientific results, the achieved high level of re-refining technology and the provision of additional workplaces are sufficient to justify the priority of waste oil recycling in a more precise way.

Brussels, 25th February 2005

Hartmann

C. Hartmann
President