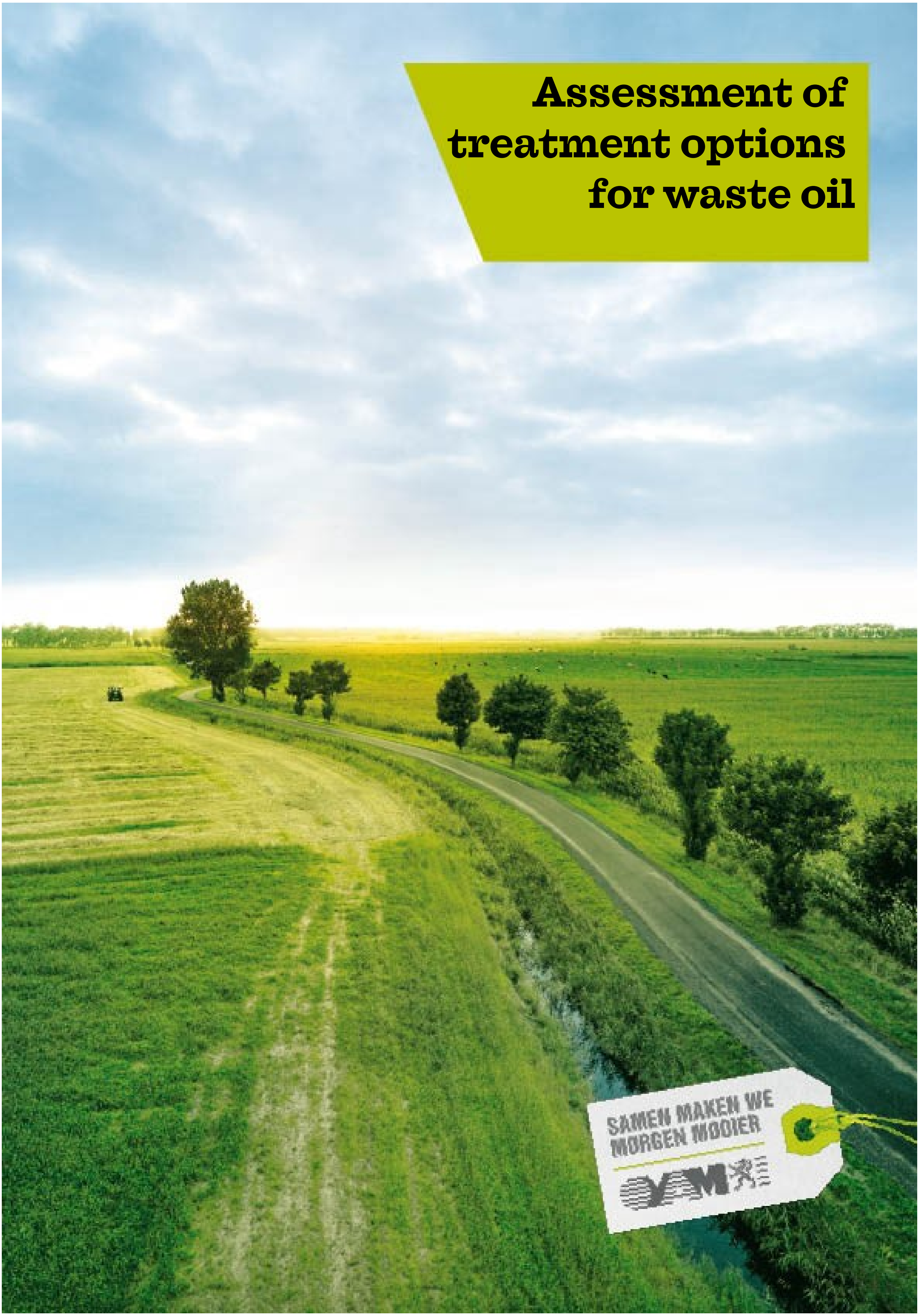
Assessment of treatment options for waste oil



Assessment of treatment options for Waste Oil

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Summary

In the present case study the Life Cycle Thinking (LCT) concept is applied to evaluate three different techniques that are currently used for treatment of Flemish waste oils covered by the corresponding Environmental Agreement (Milieubeleidsovereenkomst betreffende de aanvaardingsplicht voor afgewerkte olie), further referred to as MBO. The results of the comparison will be taken in account as technical background data for elaborating a new Environmental Agreement on waste oil that will be settled between the Flemish MBO-covered waste oil sector and the public authority. A comprehensive description of the methodological approach can be found in the parallel report “Methodology for applying Life Cycle Thinking” (OVAM, 2011).

In 2009 67.155 tons of lubricating and industrial oils was put on the market in Belgium.[ab] Approximately 69% hereof (or 46.337 tons) was assumed to be collectable. In 2009, operators under contract with Valorlub collected 43.354 tons, representing 93,6% of the potential collection rate. A total of 43.038 tons of Belgian waste oils was reported to have been received by waste oil processing installations. Flemish MBO-covered waste oil is subject to the following recovery operations:

- R1 Use principally as a fuel or other means to generate energy;
- R5 Recycling/reclamation of other inorganic materials (e.g. in asphalt);
- R9 Oil re-refining or other reuses of oil.

The largest output fraction resulting from treatment of Flemish waste oils consists of the main products of R9 operations, which include gasoil from thermal cracking, base oil from re-refining, cutting oil from the reclamation option and flux oil from other re-use options.

The different techniques that are assessed in the present case-study are:

- The use of waste oil as an auxiliary fuel to provide process heat in a rotary kiln (RK) designed for treating liquid and solid hazardous waste streams with organic content, equipped with a flue gas treatment system;
- The recycling of waste oil by thermal cracking into light distillate fuel oil. The process steps included are (at least) filtration, dewatering, thermal cracking, distillation and stabilization;
- The recycling of waste oil into base oil by re-refining. Lubricating oil is obtained by adding additives to the base oil that results from the re-refining process. Five different facilities and techniques were considered in the evaluation. (The final conversion of base oils into lubricating oils does not form part of the present assessment.)

The **characteristics** of the waste oil under study are within the ranges of the Flemish waste oils covered by the MBO, in force since August 29th of 2008. The **functional unit** used for modelling is the treatment of one metric ton of waste oil that is covered by the Flemish MBO. For the characterization of the environmental impacts the ReCiPe method was used.

The **environmental evaluation** revealed damage caused by climate change (both to human health and the ecosystem) and fossil fuel depletion to be the most relevant impact categories. This is a consequence of the fact that the treatment techniques are energy consuming and that the avoided useful outputs are in all cases petroleum-derived products. The relative impacts for the most relevant impact categories are presented in Figure 1. The results are relative to the technique that avoids the most impact.

[a] VALORLUB (2010). Jaarverslag 2009 tbv OVAM, conform de bepalingen van artikel 11 §4 van de Milieubeleidsovereenkomst, June 2010.
[b] OVAM (2010). Evaluatie milieubeleidsovereenkomst Afgewerkte olie Rapportering over 2009.

Figure 1 shows re-refining technique 3 as obtaining the best score for all impact categories. From the underlying figures it was concluded that this score is largely due to the maximisation of the (internal) re-use of energetic fractions rather than maximisation of base oil production. Even more, despite the fact that this technique has the best overall environmental performance, it does not comply with the criterion stated in the BREF Waste Treatment that re-refining processes of waste oil should achieve a yield higher than 65%. So, in this particular case, the minimization of environmental impacts was performed without applying Best Available Techniques.

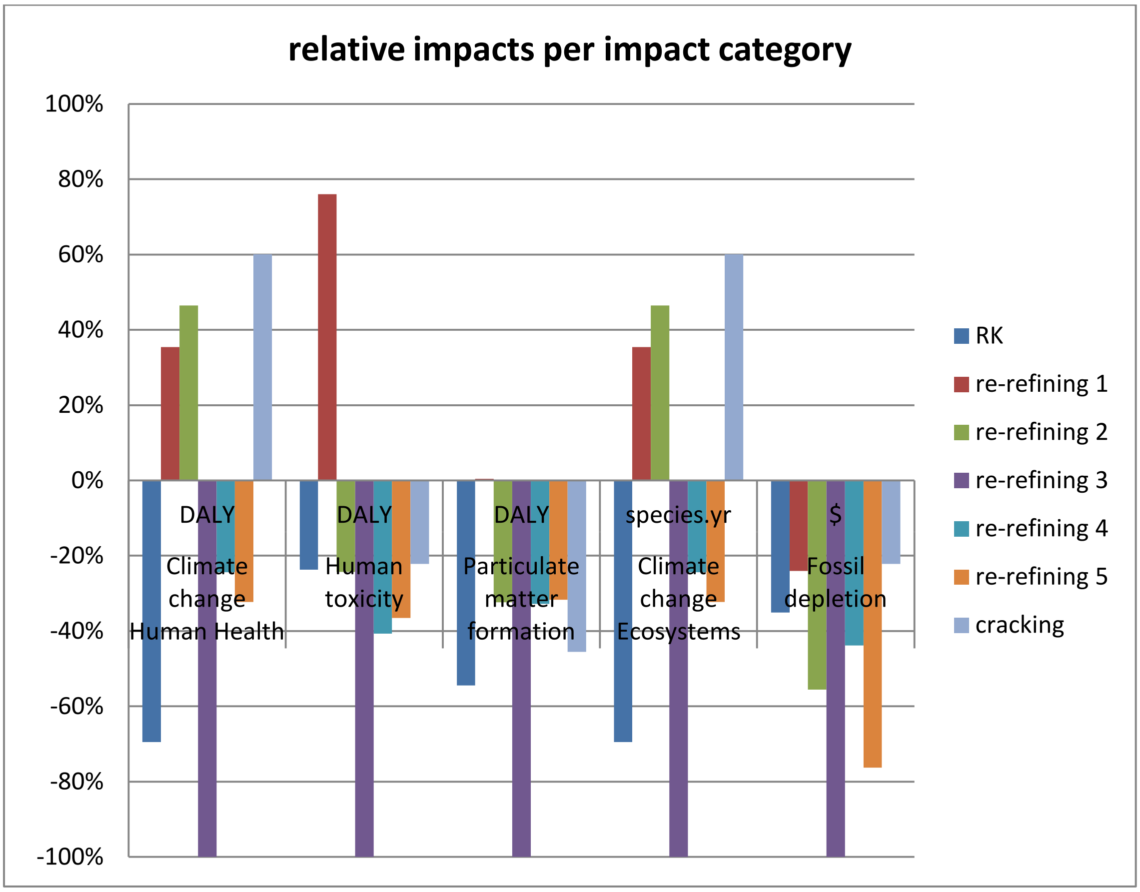

Figure 1: Relative impacts per impact category

Regarding the damage categories related to climate change (both to human health as on ecosystems) Figure 1 shows that the re-refining techniques 1 and 2 and cracking have a net impact. The relative differences between these two techniques are not significant. All other techniques avoid net impacts for this impact category. The relative differences between the re-refining options 4 and 5 are not significant. The same goes for the difference between the rotary kiln (RK) end re-refining technique 3.

For the impact categories damage to human health by toxic substances and particulate matter only re-refining technique 1 causes net impacts. The differences in impact between RK, re-refining options 2, 4, 5 and cracking are not significant.

All evaluated techniques avoid the depletion of fossil fuel.

Overall, the environmental profiles show that for none of the impact categories all re-refining options have significantly lower environmental impact scores than treatment in RK or cracking. Moreover, in every impact category there are one or more re-refining options with environmental impacts that exceed the RK score, and there can always be identified a re-refining option with an environmental impact score comparable or worse than for thermal cracking.
The significant differences among the re-refining options themselves make it inappropriate to define one hypothetical average re-refining technique. From the above, it can be concluded that

the resulting environmental impact scores for each of the assessed techniques, combined with a wide range of impact scores for a diversity of available re-refining techniques make it impossible to make a clear general prioritisation between rotary kiln, cracking and re-refining, based on the environmental impacts of each technique. Neither could one or two specific re-refining options be withheld, as all corresponding facilities are located abroad, and uncertainty exists on the quantities of Flemish MBO-covered waste oil that are actually processed through specific re-refining techniques, as well as on the quality of the corresponding outputs. The environmental impact scores of the use of MBO-covered waste oil as auxiliary fuel in a rotary kiln are comparable or lower than those of thermal cracking.

All the facilities where Flemish MBO-subject waste oil is treated are located in Belgium, Germany, France and the Netherlands. These countries integrate global organisations and networks that actively promote social and economical development and sustainability, and are all member states of the European Union, where common European regulations and standards regarding to socio-economic issues apply. In this context it is relatively safe to assume that no important differences exist between potential **social and socio-economical** indicators for the different subcategories. To corroborate this assumption, a detailed assessment with sector or installation specific data should be performed.

In the frame of the present case-study, five comparative waste oil treatment studies were reviewed. In general, the results from the actual case-study showed to be coherent with the conclusions from other, reviewed reports.

1 Introduction

A key aim of EU policies on resources and waste is to move to a more resource-efficient and sustainable future. EU policies and legislation on waste highlight the need for good waste management. The Waste Framework Directive establishes the waste hierarchy. This sets an order of priority, starting with the preferred option of waste prevention, followed by preparing waste for re-use, recycling and energy recovery, with disposal (such as landfill) as the last resort.

Following the waste hierarchy will generally lead to the most resource efficient and environmentally sound choice. However, in some cases refining decisions within the hierarchy or departing from it can lead to better environmental outcomes. The "best" choice is often influenced by specific local conditions and care needs to be taken not to simply shift environmental problems from one area to another. Decision-makers need to base their choices on firm factual evidence. Life Cycle Thinking and Assessment provide a scientifically sound approach to ensure that the best outcome for the environment can be identified and put in place.

From: http://lct.jrc.ec.europa.eu/pdf-directory/Making-Sust-Consumption.pdf

The Life Cycle Thinking (LCT) concept (and quantitative tools such as Life Cycle Assessment (LCA)) can provide an informed and science-based support to a more environmentally sustainable decision making in waste management.

Within this framework a global evaluation is made of several treatment techniques that currently are applied to Flemish waste oil covered by the corresponding Environmental Agreement (Milieubeleidsovereenkomst betreffende de aanvaardingsplicht voor afgewerkte olie).

The most relevant methodological aspects to apply LCT for the Flemish waste oil case are described in chapter 2 of the report. Subsequently, chapter 3 on the Flemish waste oil market focuses on the current volumes of collected and treated Flemish waste oils. Chapter 4 provides both a general description of waste oil treatment techniques and a detailed description of the treatment techniques that are assessed. Finally, the results of the assessment for environmental, social and economic aspects are presented in chapter 5.

2 Methodological aspects

2.1 Introduction

The general methodological approach used in the present case-study is described in a parallel report on different methodological aspects regarding to Life Cycle Thinking.

A general (conceptual) methodological framework for Life Cycle Assessment (LCA) is defined by ISO in its 14040 and 14044 standards (ISO, 2006) and in the ILCD Handbook (ILCD, 2010). his case-study adopts, the principles as defined by both ISO and the ILCD.

According to the ISO standards, LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (i.e. cradle-to-grave). (ISO, 2006)

The required steps when performing an LCA are::

- Goal and scope definition;
- Inventory Analysis;
- Impact Assessment;
- Interpretation.

The relation between the different phases is illustrated in Figure 2. The figure shows that the different phases are not independent of each other. It also shows that the scope, the boundaries and the level of detail of an LCA depend on the intended use of the study.

According to these guidelines an LCA must be performed in 4 steps:

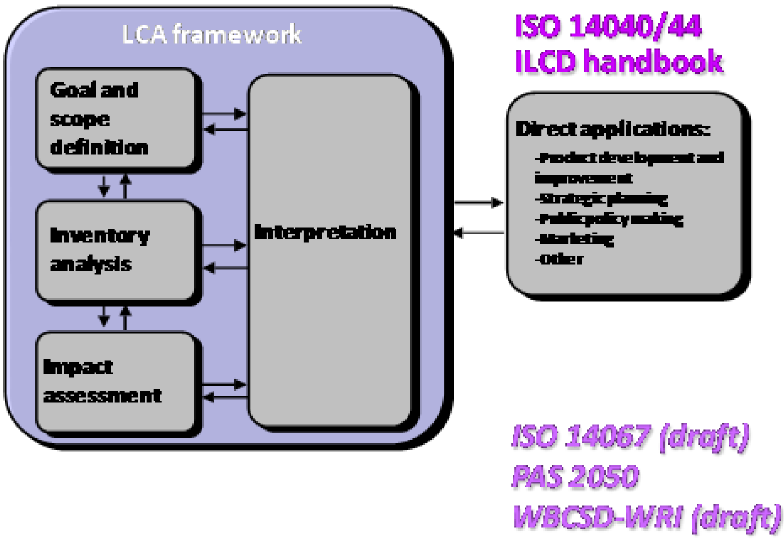

Figure 2: Methodological framework of an LCA (ISO, 2006)

2.2 Goal and scope

In the present case study, the overall environmental outcome of different waste oil treatment options will be determined by comparing alternative treatments. As different types of waste oils can be converted, through different processes, into different products or into mixes with different shares of similar products, comparisons that reflect real impacts of products and processes cannot be made readily and easily.

For this reason, it is necessary to clearly define, in a first step, what will be the subject of comparison:

> If we are to compare different treatment **techniques**, we would calculate the impact of different techniques processing one unit of product (e.g. 1 ton of a certain type of waste oil that is treated by each of the studied techniques). We can then assess the environmental impact of the techniques to treat that type of waste oil, irrespective of the resulting products. It is this approach that is followed for the present study.
>
> At the other hand, we could aim to detect how to produce a certain quantity of one **product** (e.g. base oil) with a minimal impact. This time, we can make a decision upon the environmentally best way to make base oil, whatever the input that is required.

Both approaches are equally valuable, but give answers to fundamentally different questions.

In this study, impacts of three different **techniques** to treat waste oil are compared. The techniques are replacement of auxiliary fuel in a waste incinerator, thermal cracking and re-refining. The characteristics of the waste oil under study are within the ranges of the Flemish used oils covered by the corresponding Environmental Agreement (Milieubeleidsovereenkomst betreffende de aanvaardingsplicht voor afgewerkte olie), further referred to as MBO, in force since August 29th of 2008. The results of comparison will be taken in account as technical background data for elaborating a new Environmental Agreement on waste oil that will be settled between the Flemish MBO-covered waste oil sector and the public authority.

It was decided by the authority that the new MBO will stick to the principles of Life Cycle Thinking (LCT). LCT seeks to identify possible improvements to goods and services in the form of lower environmental impacts and reduced use of resources across all life cycle stages. The key aim of Life Cycle Thinking is to avoid burden shifting. This means minimising impacts at one stage of the life cycle, or in a geographic region, or in a particular impact category, while helping to avoid increases elsewhere.[a]

The conclusions of the comparison of treatment options refer to waste oil for which actually alternative options for treatment exist, and do not apply for waste oils with characteristics that make that no other options are available but elimination as hazardous substances, which, in accordance with the currently best available techniques, are incinerated in a dedicated installation.

It is further noted the treatment options considered in the present study do not cover the complete variety of available and used techniques to treat MBO covered waste oil. This will be discussed in Chapter 3.

The study focuses on the (avoided) impacts of the treatment of one ton of waste oil that actually enters the process gate of a treatment installation as it is. Legal and technical constraints do not form part of the present assessment.

[a] http://lct.jrc.ec.europa.eu/index_jrc

2.3 Functional unit

The functional unit is a measure of the function of the studied system, and provides a reference to which all inputs and outputs will be related.

The functional unit used for the present modelling is the treatment of one metric ton of waste oil that is covered by the Flemish MBO.

2.4 System boundaries

In Life Cycle Thinking in a waste management context, the life cycle starts at the end of a products' life cycle, i.e. at the point that a product reaches a waste status. Generally, life cycle system boundaries will in such case extend from **gate to grave**. For this study, the entrance gate of the system corresponds to the first step of treatment in the waste processing facility, i.e. after the waste oil has been collected, transported, pre-treated (e.g. dewatered) and/or temporally stored in collectors' or treatment facilities. Eventual differences in transport distances, requirements of pre-treatment and storage-specific concerns are not taken into account; the focus is entirely on the treatment process itself. Previous studies indicated that the impact related to transport is of minor importance.

The studied life cycles of waste oil end with the delivery of a specific useful product. In fact, this delivery provides a new gate. However, the use of the (by)products of treatment does not form part of the studied system, e.g. the impacts of the use of fuel oil derived from thermal cracking of waste oil are produced outside the boundaries of the studied system.

Geographically, the study considers the impacts of the use of, or substitution by, the Belgian energy mix for electricity production for those treatment facilities located in Belgium, and an average regional European (UCTE) mix for installations abroad. All waste oils are assumed to be covered by the Flemish MBO and collected in Flanders.

2.5 Methodological approach

Within the frame of Life Cycle Thinking, the sustainability of goods and services can be assessed by determining their environmental, economic and social impacts. Different methods can be followed to integrate the three pillars of sustainable development.

For the present study, the environmental impact of each treatment alternative for waste oil was determined by means of a Life Cycle Inventory (LCI) analysis, that involved creating an inventory of flows from and to the system boundaries. To develop the inventory, a model of each treatment process was constructed by using available data on inputs and outputs. For this modeling different methodological approaches are available.

An **attributional** approach focuses on describing the environmentally relevant physical flows to and from a product or process, while **consequential** assessment describes how relevant environmental flows will change in response to possible decisions. In the present case study, an attributional assessment was made to support the elaboration of a new MBO on waste oils. In a next step the impact of one or several MBO proposals on the existing flows could be analysed through consequential modelling.

In an attributional approach average data are used (i.e., data representing the average environmental burden of the treatment of a unit of waste oil in the system), and the focus is (largely) just on historical impacts over a products entire life, so it can be determined what part of the global environmental exchanges can be attributed to a specific activity that takes place in the world as it is. We can thus, for instance, calculate the environmental impacts attributable to a particular treatment of one ton of waste oil. To quantify the share of different impact categories, average data obtained from currently existing and applied treatments are used.

As it was not possible to tie a specific pre-defined quality waste oil input to a fixed quantity and quality of outputs (see 3.3), no theoretical standard (or average) waste oil input could be used to model environmental impacts of - also standardized - processes. Instead, installation specific input and output data were used for all treatments, **as they are**. It is however important to keep in mind that the different treatments cannot substitute each other in a perfect way for any of the qualities of MBO categorized waste oil, while at the same time treatments and installations might face different legal, process and permit related limitations for receiving and processing waste oil. Therefore, by using data from real processes in the present study, real actual impacts were determined, in the “world as it is”. Over time, shifts in MBO waste oil quality, technology and consumer demand might provoke changes in the calculated impacts.

Regarding the social and socio-economic impacts, only the relevance of potential differences between the waste oil treatments was briefly discussed.

Finally, some basic economic figures on the different treatments were summarized for comparison.

2.6 System modelling and solving multifunctionality

Within the systems that are studied in an attributional approach, multifunctionality can be solved by subdivision of multifunctional black box unit processes to mono-functional single operation unit processes. Nevertheless, when (further) subdivision is not possible, not required functions are **allocated** for.

ISO 14040/44 (par.4.3.4)**:**

The LCA shall identify the processes shared with other product systems and deal with them according to the stepwise procedure:

- Step 1: Wherever possible, allocation should be avoided or minimized. This can be done by detailing multiple processes into two or more sub-processes, some of which can be located outside the system boundaries. It can also be done by expanding the system boundaries so that inputs/outputs remain inside the system.
- Step 2: Where allocation cannot be avoided, it should preferentially be based on **causal relationships** between the system inputs and outputs. These causal relationships between the flows into and out of the system may be based on ***physical parameters***.
- Step 3: Where causal relationships cannot be established, allocation to different products may be based on their ***economic value***.

ILCD: Allocation is done by a two-step procedure according to ISO 14044:2006:

- Wherever possible, allocation should be avoided or minimized…
- As first criterion, the “determining **physical causal relationships**” between each non-functional flow and the co-functions of the process shall be identified and used as allocation criterion. This causal ***physical relationship*** (and implicitly also covered: chemical and biological – relationship) is the one that determines the way in which quantitative changes of the products or functions delivered by the system change the other inputs and outputs.
- Second criterion "market price". When it is not possible to find clear common physical causal relationships between the co-functions, the allocation is done according to a second, general allocation criterion. This is *the* ***market value*** of the co-functions in the specific condition and at the point they leave the process (or enter it as e.g. in case of waste and end-of-life treatment services).
- In many cases the co-products are not directly traded but further processed internally e.g. compressed, purified, packaged etc. first. Hence the market price of the resulting product that is sold is to be adjusted (i.e. reduced) for these additional steps, before using it as allocation key. Some interim co-products are not at all or at least seldom traded externally (e.g. refinery gas); market price information is to be approximated in such cases.

However, as the goal of the study is to compare waste treatment techniques, we are also interested to include existing interactions with other systems, particularly the credits for avoided primary production of products and services. In such case, **substitution** may also be applied in attributional modelling.

The present study considers waste oil that is treated in different processes, each of which delivers a series of different outputs, ranging from heat to distillate products. Nevertheless, the scope of the study does not include the quantification and analysis of the impacts of the use of the outputs of the techniques, yet the resulting products (e.g. fuel oil, base oil and naphtha) can be used in a wide range of applications that may produce highly varied environmental impacts. It is however assumed that these possible uses do not differ from the uses that would have been given to the corresponding equivalent primary products. We will thus include the interaction of the treatment technique with the systems that produce the equivalent primary products, in a way to account for the environmental burdens of the production and use of all of the outputs that are generated by the different treatments. This is done by substituting the functions of the generated products by an alternative way of providing them, based on physical and functional relationships. The life cycle inventories of the superseded products are then subtracted from those of the analysed systems (they are credited for). This way, the avoided impact of the primary production of the outputs generated by the waste oil treatment, is subtracted from the total treatment impact.

After this subtraction, a comparison can be made of the impacts of the three different techniques to treat one ton of a well defined type of waste oil, where the impact of the production of the different outputs is substituted by the environmental burdens of their primary production. An avoided environmental burden that is bigger than the treatment impact itself, will result in a negative environmental impact, or a net benefit, of treating the waste oil.

In one of the treatment options, namely the replacement of auxiliary fuel in a waste incinerator, the calorific value of waste oil is used as an input material to maintain optimal process conditions for the incineration of hazardous wastes, substituting the functionality of auxiliary fossil fuel by delivering process heat. This way, the environmental impacts of the use of waste oil will be limited to the net effects of the replacement. If auxiliary fuel is replaced partially or totally by waste oil, not only the avoided production of part (or all) of the auxiliary fuel will be subtracted from the system, but also the not realised benefits, i.e. the corresponding energy production. Likewise, the emissions and wastes originated by the replaced auxiliary fuel are avoided, but at the same time the replacing waste oil also causes a certain amount of emissions. The modelled system is represented in Figure 3.

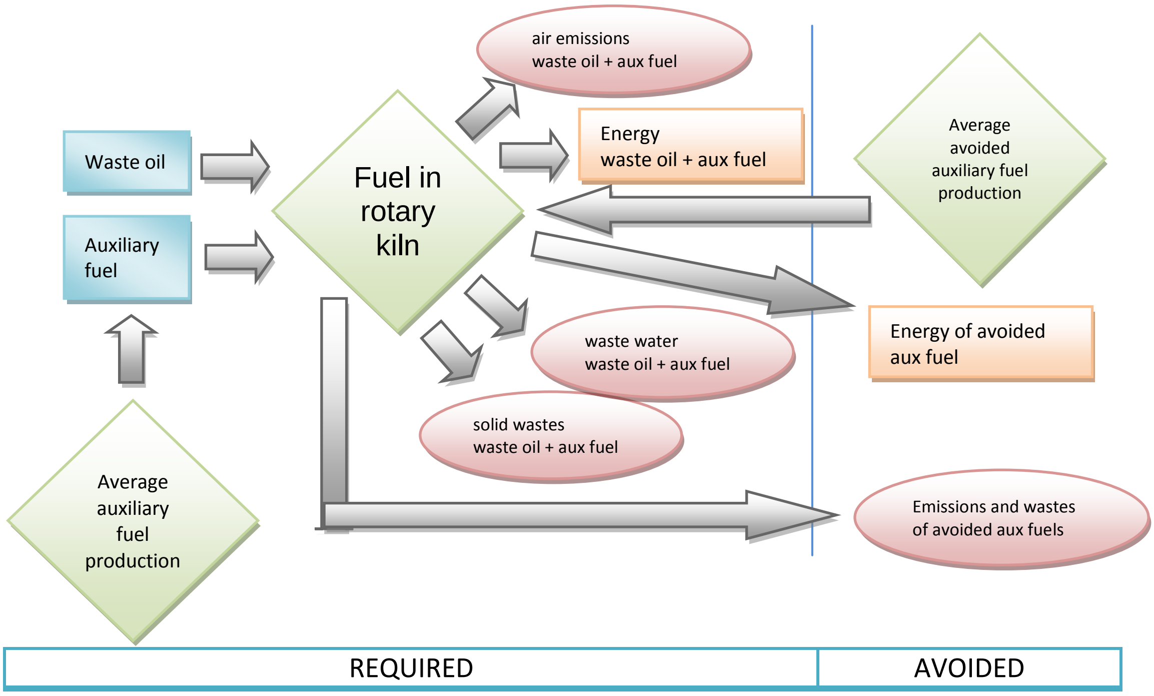

Figure 3: System of waste oil used as auxiliary fuel

The environmental impacts of the employment of waste oil in a rotary kiln are thus limited to the net effects of the substitution. These include higher metal, halogen and sulphur emissions, for which has to be accounted for, and, on the benefit side, the avoided production of the substituted auxiliary fossil fuel. However, this functionality cedes when the need for auxiliary fuel is completely satisfied by burning waste oil. Every ton of waste oil that is used behind this point, will have to be considered as hazardous waste that is offered to be incinerated with recovery of energy, a treatment option with different environmental (avoided) impacts that is not assessed in the present study.

Nevertheless, as the waste oil under study actually possesses an economic value (the operator of the incineration plant actually pays for it), it is most unlikely that the quantity of burned MBO-subject waste oil, would exceed the auxiliary fuel requirement. In an economically optimized system where enough waste oil is available, the operator will tend to replace all required auxiliary fuel by waste oil[a], as long as the latter is cheaper and the associated emissions do not provoke exceeding of the emission limit values.

For modelling, it is assumed that the energy contents of the auxiliary fuel and the waste oil are identical, so the replacement does not lead to a net gain or loss in energy production.

A simplified graph with the system boundaries and substituted functions for the three treatment options is presented in the next figure.

[a] It is noted that auxiliary fossil fuel will still be needed for installation start-up and shut-down, i.e. when normal operation temperatures are not reached.

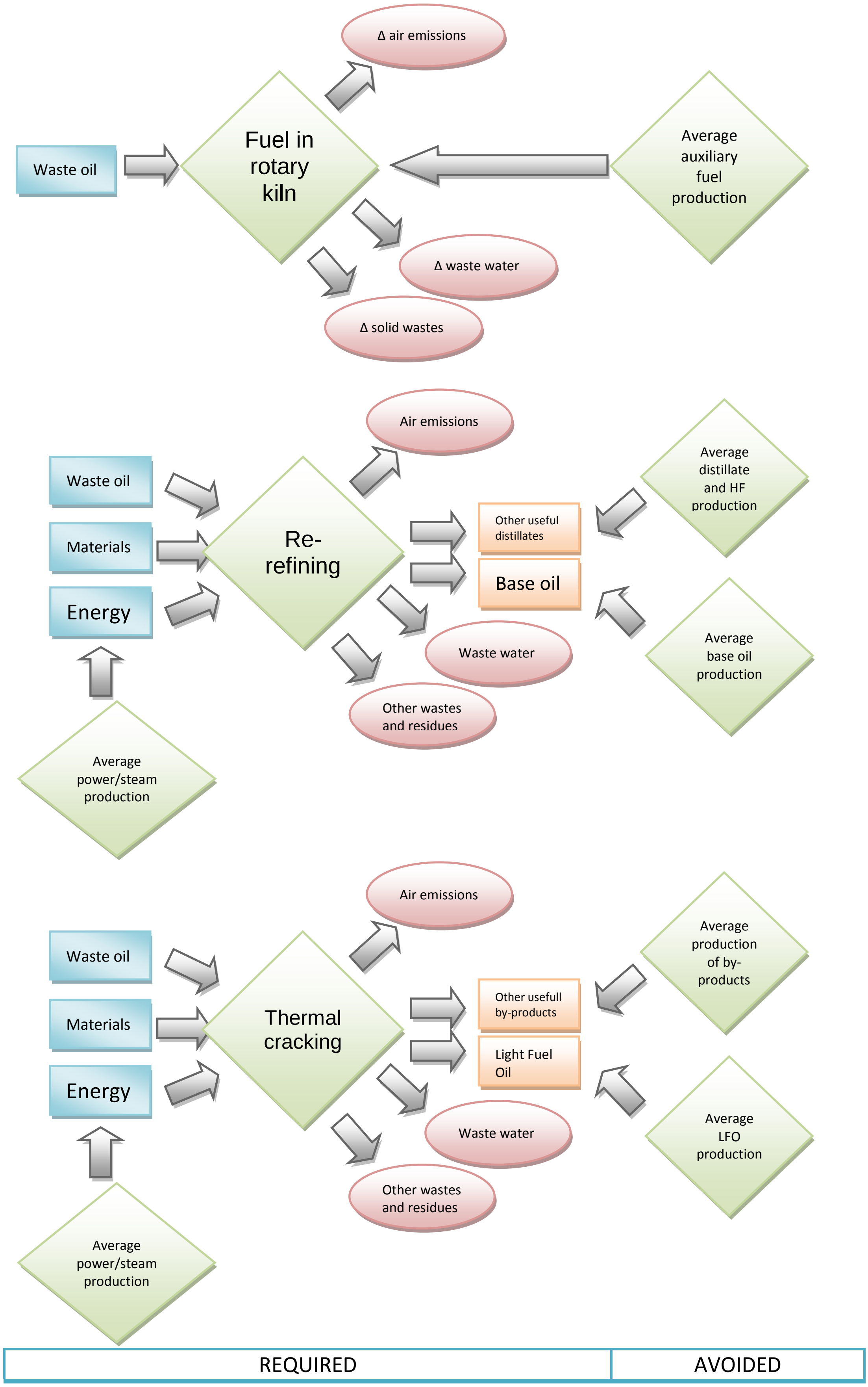

Figure 4: Simplified system of the studied waste treatment options

3 Waste oil market

3.1 Market supply of clean oils that may give rise to waste oils included in the Environmental Agreement (MBO)

It was calculated that in 2009 67.154.757 kilo of lubricating and industrial oils was put on the market in Belgium.[ab] Not all lubricating oils that are sold are collectible, as part of the oil will be lost during use (combustion, evaporation, residues left in containers), and part will be spilt, illegally burned or dumped. In 2008, Valorlub had adopted a potential collection rate determined by a French study commissioned by ADEME, of 69% or 46.336.782 kilo. In 2009, operators under contract with Valorlub collected 43.354.000 kilo, which represented 93,6% of the potential collection rate. At the other hand, it is reported that collectors collected 42.623.466 kilo, whilst installations received 42.311.660 kilo for processing. Finally, the sum of separate inputs of waste oil processing installations totaled 43.037.842 kilo. The differences can be explained, at least partly, by the fact that not all types of waste oils are included in the Environmental Agreement (Milieubeleidsovereenkomst or MBO), so collectors and installations might collect or receive other waste oil or waste oil/water mixtures together with MBO-subject oils. It is assumed that figures provided by collectors authorized by Valorlub only include quantities of (dewatered) used oils that derive from fuels and lubricants that were intended to give rise to waste oils included in the Environmental Agreement.

It is estimated by Valorlub that 63,9% or approximately 46.337.000 kilo of the Belgian lubricating and industrial oils is put on the Flemish market.

3.2 Volumes of collected and treated waste oils in Flanders

In Flanders, in 2009, 29.109.448 kilo of MBO-subject waste oil was reported to have been collected and 29.033.805 kilo was processed. Waste oil also recovered from collected emulsions. For Flanders, 10.035.706 kilo of collected emulsions was reported, with a approximate oil share of 5% or 501.785 kilo.

3.3 Actual treatment options of Belgian and Flemish waste oils

In Figure 5, an overview is given of the destinations of in Belgium collected waste oil. One of the cement ovens, the facility for thermal cracking and the rotary kiln are located in Belgium. All other installations that receive Belgian MBO-covered waste oil are located in neighbouring countries.

[a] VALORLUB (2010). Jaarverslag 2009 tbv OVAM, conform de bepalingen van artikel 11 §4 van de Milieubeleidsovereenkomst, June 2010.
[b] OVAM (2010). Evaluatie milieubeleidsovereenkomst Afgewerkte olie Rapportering over 2009.

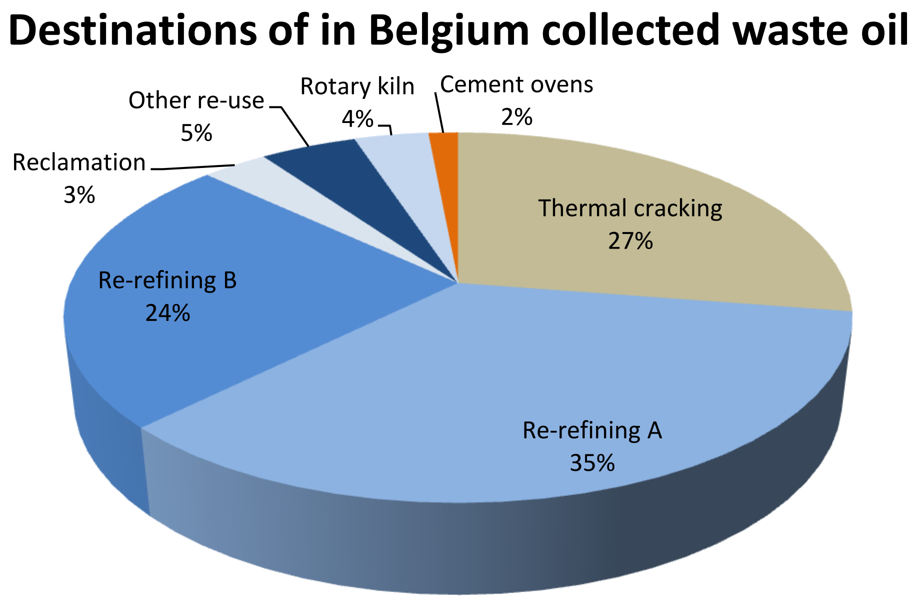

Figure 5: Overview of destinations of in Belgium collected waste oil

- Re-refining option A corresponds to re-refining companies[a], where similar waste oil treatment processes are used (TFE + clay finishing), with comparable outputs (75% base oil, 10% gasoil, 10% asphalt and 5% water). Base oil is used again for the production of lubricating oils.
- In re-refining option B multi-step distillation and solvent extraction is performed (TFE + solvent extraction), with the main output being base oil (65 to 70% of the input).
- In the reclamation option[b] only clear used oils are treated, excluding automotive waste oils. Process steps include dehydration, centrifugation, filtration, discoloring and adding of additives. The main output is cutting oil.
- The option "other re-use" considers the production of mainly flux oil. In 2008 one of the corresponding companies built a new unit to start base oil production from waste oil in early 2009, using a technology developed by Meinken Engineering.

All the installations that receive Belgian waste oil for re-refining and other re-uses that include a distillation step are located in Germany and the Netherlands. The share of this received waste oil that effectively is re-refined into base oil is not known, as the involved companies may offer a wider range of services, treatments and products, and might redirect (part of) rejected or processed (e.g. after filtering and distillation) MBO-covered waste oils to other facilities[c].

[a] One of the re-refineries corresponding to re-refining option A, that produced re-refined API Group I equivalent oils, was shut down in March 2009. Waste oil feedstock that was processed in this re-refinery is now received in a new plant, that uses the newer Hylube technology and catalyst, to produce higher quality re-refined API Group II equivalent oils. (Sullivan, T. (2009). German Rerefinery Shuttered. Lube Report, Volume 9, issue 14. LNG Publishing Co., Inc., April 2009)

[b] It is noted that the techniques that are used in this option are not equivalent to re-refining, and that the main product is not base oil.

[c] As illustrated in "Kennisgeving grensoverschrijdende overbrenging van afvalstoffen, Kennisgevingsnummer NL205739", available at http://www.senternovem.nl/mmfiles/NL205739_tcm24-350146.pdf

Furthermore, the inclusion of flux oil production generated a sharp discussion on the fact whether the production of **flux oil** should be considered as regeneration or not[a].

In conclusion, it is observed that in 2009, almost 90% of the collected waste oils in Belgium are sent to destinations that can process the oils by a technique that is considered in the present study.

No separate figures were available on the destinations for Flemish waste oil. Nevertheless, from the figures on the aggregated output of the treatment facilities it can be observed that proportionally less Flemish than Belgian waste oil is treated by thermal cracking, while more Flemish waste oil goes to the other options. The relative shares of the different outputs generated by Belgian and Flemish waste oils are however very similar, as is shown in Table 1. No significant differences (> 1% of total output) are reported between shares of Belgian and Flemish outputs of emulsions.

Output	**% of total outputs Flemish waste oils**	**% of total outputs Belgian waste oils**
Water	5	5
Sediment	1	1
Main output R9	69	68
Main output R1	4	3
Gasoil	8	7
Asphalt	4	4
Heavy fuel oil	6	8
Naphtha	3	4
Total	100	100

Source: Valorlub (2010)[a]

Table 1: Comparison of relative share of outputs Flemish vs. Belgian waste oils (2009)

3.4 Capacity of the treatment facilities

The share of Belgian waste oils in the existing treatment capacities of the installations where the about 29.000 tons of Flemish MBO-covered waste oils was calculated, using confidential figures informed by Valorlub.

It was concluded that for the option of thermal cracking, Belgian MBO-covered waste oils occupy a relevant part (30%) of the existing treatment capacity, while at the same time an important part (27%) of Belgian waste oils are treated in this facility. WOS Hautrage is the only

[a] "As regards the substantive question whether the production of flux oil should be regarded as regeneration, the Ombudsman noted that Article 3(1) of Directive 75/439 defines the term "regeneration" as leading to the production of "base oils". However, the Commission and the complainant did not agree on a definition of the term "base oils" and the directive does not contain a definition of this term." "The exclusion of flux oils from the definition of the term "regeneration" in the German legislation, which appeared to be the argument on which the complainant constructed the allegation concerning its supposed punishment, was in full conformity with Directive 75/439" (From: Complaint Case 1528/2006/(GG)(WP)VL, June 2010. Available at http://www.ombudsman.europa.eu/en/cases/decision.faces/en/4949/html.bookmark)
"Moreover, it is to be noted that flux oil is a petroleum distillate used to produce a long-term reduction in the viscosity of bitumen. Waste flux oils are not collected for regeneration. Article 1, 4th indent of the Waste Oils Directive defines 'regeneration' as 'any process, whereby base oils can be produced by refining waste oils, in particular by removing the contaminants, oxidation products and additives contained in such oils'. The processing of waste oils into flux oils does not remove the contaminants, oxidation products and additives in the waste oils. Furthermore, it does not permit the re-use of waste oils for the use for which they have been originally intended (in particular in the case of used combustion engine oils and gearbox oils, and also mineral lubricating oils, oils for turbines and hydraulic oils)." (From Parliamentary questions, 19 August 2005, Answer given by Mr. Dimas on behalf of the Commission, E-2112/2005, August 2005. Available at http://www.europarl.europa.eu/sides/getAllAnswers.do?reference=E-2005-2112&language=ES

installation where Flemish waste oil is thermally cracked to produce fuels as main products. No other plants for this treatment exist in Belgium nor in the neighbouring countries.

At the same time, Belgian waste oils fill in less than 10% of the capacity of the receiving re-refining installations (including flux oil producing facilities), all located abroad. Several other re-refining facilities that actually are not a destiny for Belgian waste oils, also might have available capacity for treating Belgian waste oils.

The use of the energy content of Belgian waste oils to deliver process heat, is principally realized in an incineration facility located in Flanders, where these oils are assumed to substitute near to 100% of the needs for auxiliary fuels under normal operation conditions (i.e. excluding installation start-up and shut-down).

Existing limitations regarding treatment capacity, as well as other market related factors, will play a role in the results that are obtained by policies that pretend to impact the order of preference of waste oil destinies.

3.5 Outputs of the treatment facilities

In all processes, except for incineration without previous treatment, eventually present **water** is removed. Only dewatering and other treatments that take place after reception of the waste oil at the installation for re-refining or thermal cracking are included within the system boundaries (see 2.4). The water is adequately treated before being discharged. Waste oils also contain sediments that have to be disposed. The shares of water and sediments in collected waste oils were estimated from the results of analysis performed by stakeholder facilities, and account for 5 and 1% respectively.

The re-refining options as well as thermal cracking include a **distillation step** where different marketable hydrocarbon fractions are obtained, from light non condensable gases to heavy distillate residues. Some of these fractions are used internally to provide energy for the different processes. The heavier fractions can be used in the asphalt, steel or cement industry.

More clean and clearer waste oils can be treated without cracking or distillation steps, by laundering or reclamation. Reclamation is used especially for hydraulic waste oils, which are simply centrifuged and/or filtered and then used, for instance, as mould release oil or base oil for the production of chain saw oil.

Treatment processes as re-refining and thermal cracking can be steered according to the quality of incoming waste oils, and the quantity and characteristics of the different fractions can be optimized in relation to specific needs of producers and clients, which may vary over time. Hence, it is not possible to tie a specific pre-defined quality waste oil input to a fixed quantity and quality of outputs. For this reason, installation specific input and output data were used for all treatments, as they are.

Waste oil is burned in a rotary kiln for waste incineration in Flanders, and in two cement ovens. The emissions of incineration, and their impacts, are reduced by high process temperatures[a] and flue gas treatment. Part of the waste oil energy content is recovered as process heat (cement oven and rotary kiln when the waste oil replaces auxiliary fuel to maintain the process conditions) or for the production of steam and electricity (rotary kiln when the waste oil is treated like any other hazardous waste (and does not replace auxiliary fuel)).

Waste related activities are classed as recovery (R) or disposal (D) as defined in the Waste Framework Directive. Flemish MBO-covered waste oil is subject to the following recovery operations[b]:

[a] As defined by Article 50, Chapter IV, of the Richtlijn Europees Parlement en Raad E.G. van 24 november 2010 Richtlijn 2010/75/EU van 24 november 2010 van het Europees Parlement en de Raad inzake industriële emissies (geïntegreerde preventie en bestrijding van verontreiniging)
[b] OVAM (2010). Evaluatie Milieubeleidsovereenkomst Afgewerkte olie Rapportering over 2009.

- R1 Use principally as a fuel or other means to generate energy (e.g. in rotary kiln, cement oven)[a];
- R5 Recycling/reclamation of other inorganic materials (e.g. in asphalt);
- R9 Oil re-refining or other reuses of oil.

Water and sediments are disposed of by the following disposal operations[b]:

- D1 Deposit into or onto land (e.g. landfill of sediments)
- D6 Release into a water body, except seas/oceans (e.g. water fraction after treatment), after:
    - D8 Biological treatment not specified elsewhere in this list which results in final compounds or mixtures which are discarded by means of any of the operations in this list
    - D9 Physico-chemical treatment not specified elsewhere in this list which results in final compounds or mixtures which are discarded by means of any of the operations in this list (e.g. evaporation, drying, calcination, etc.)
- D10 Incineration on land (e.g. incineration of sediments)

Figure 6 gives an overview of the different fractions that result from: recycling and reuse (R5 and R9); the waste oil used for energy recovery (R1); and the residues that are disposed (D). The largest fraction consists of the main products of R9 operations. These should include **gasoil** from thermal cracking; **base oil** from re-refining options A and B; **cutting oil** from the reclamation option; and **flux oil** from the other re-use option.

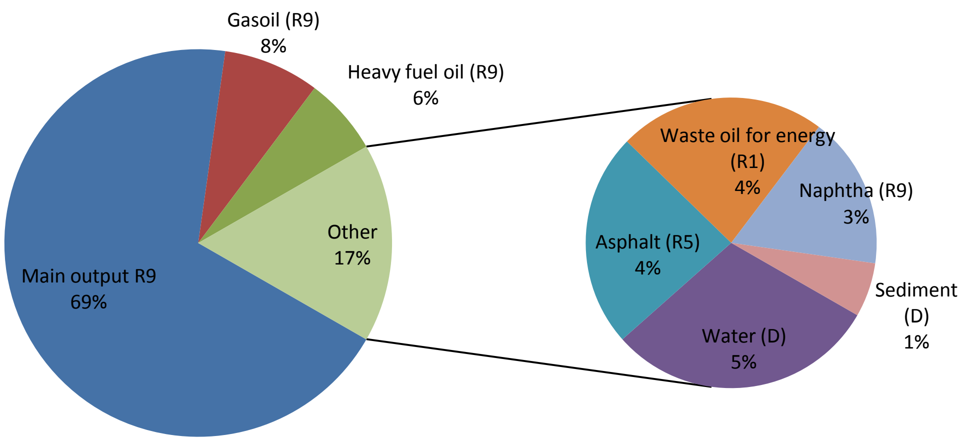

Figure 6: Fractions resulting from treatment of collected waste oils

Figure 7 gives an overview of the output from treatment of emulsions collected in Flanders. Approximately 20% of the oil fraction of MBO-subject emulsions is reused (R9), while 80% is used by the cement industry for the recovery of energy (R1).

[a] Incineration in a rotary kiln of waste oil that does not replace auxiliary fuel would be considered as a D10 disposal operation.

[b] OVAM informed that for water D6 is only used after D8 and D9, and that sediments are also treated by D10. (OVAM, 2011, pers. comm.)

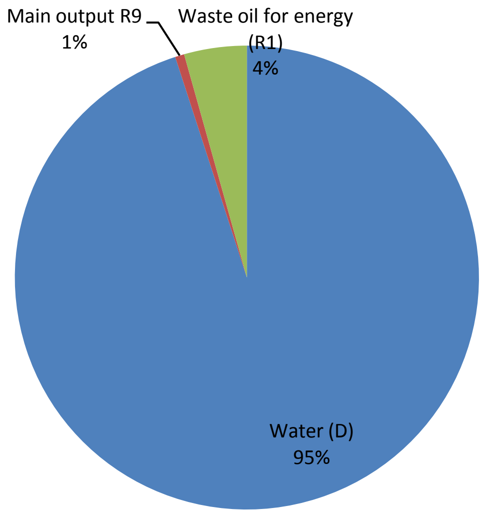

Figure 7: Output from treatment of emulsions collected in Flanders

3.6 Comments on waste oil codes and product qualities

The Environmental Agreement (MBO) on the acceptance obligation of waste oils[a], is only applicable on waste oils that are accepted under the following codes of the List of Wastes in Annex 1.2.1 B of the VLAREA:

08 03 19* Disperse oil.
12 01 06* mineral-based machining oils containing halogens (except emulsions and solutions)
12 01 07* mineral-based machining oils free of halogens (except emulsions and solutions)
12 01 08* machining emulsions and solutions containing halogens
12 01 09* machining emulsions and solutions free of halogens
12 01 10* synthetic machining oils
12 01 19* readily biodegradable machining oil
13 01 04* chlorinated emulsions
13 01 05* non-chlorinated emulsions
13 01 09* mineral-based chlorinated hydraulic oils
13 01 10* mineral based non-chlorinated hydraulic oils
13 01 11* synthetic hydraulic oils
13 01 12* readily biodegradable hydraulic oils
13 01 13* other hydraulic oils
13 02 04* mineral-based chlorinated engine, gear and lubricating oils
13 02 05* mineral-based non-chlorinated engine, gear and lubricating oils
13 02 06* synthetic engine, gear and lubricating oils
13 02 07* readily biodegradable engine, gear and lubricating oils
13 02 08* other engine, gear and lubricating oils
13 03 06* mineral-based chlorinated insulating and heat transmission oils other than those mentioned in 13 03 01
13 03 07* mineral-based non-chlorinated insulating and heat transmission oils
13 03 08* synthetic insulating and heat transmission oils
13 03 09* readily biodegradable insulating and heat transmission oils
13 03 10* other insulating and heat transmission oils
13 08 02* other emulsions
13 08 99* wastes not otherwise specified
20 01 26* oil and fat other than those mentioned in 20 01 25

In 2007, all exported MBO-subject waste oil was classified under the 13 02 05 code for mineral-based non-chlorinated engine, gear and lubricating oils. As no re-refining installations are located in Belgium, it can be concluded that only Flemish waste oils with code 13 02 05 were processed in re-refining installations.

An Ökopol (2005) study[b] estimated that approximately 80% of the collected waste oils are suitable for re-refining. In the Netherlands, bulk collectors of waste oil from categories I and II[c] are permitted according to the Enactment on the collection of wastes.[d e] Both categories are primarily intended to be regenerated into base oil, however when regeneration due to technical reasons or market developments is not economically feasible, category II oil could be reprocessed into gas oil or equivalent fuel. For the collection of waste oils from households no permit is required.[f] Figures on the quantity of waste oil, based on a monthly survey of bulk waste collectors in the Netherlands, indicate that in 2009, 3.471.702 liters of category I and II waste oil were collected per million inhabitants[g]. Flanders had 6.208.877 inhabitants in 2009[a],

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[a] Milieubeleidsovereenkomst betreffende de aanvaardingsplicht voor afgewerkte olie, Belgisch Staatsblad, 29.08.2008, Ed. 2, 45315.
[b] Ökopol (2005): Stoffstrom- und Marktanalyse zur Sicherung der Altölentsorgung, Study by the German Federal Environmental Agency (UBA, FKZ 20431 32), Hamburg 2006
[c] The categorization of waste oils that is made by the Dutch legislator has no relation whatsoever with the API base oil quality categories.
[d] Besluit van 19 maart 2004, houdende regels met betrekking tot het inzamelen van bedrijfsafvalstoffen of gevaarlijke afvalstoffen (Besluit inzamelen afvalstoffen)
[e] Landelijk Afvalbeheerplan 2009-2021. Available at: www.lap2.nl
[f] Regeling afgewerkte olie, 27 maart 2002, DGM/SAS2002026862. Centrale Directie Juridische Zaken Afdeling Wetgeving.
[g] Centrale Bewerkingseenheid N.V., Personal communication, 2011

which potentially would lead to 21.555.371 liters of non-household Flemish waste oil suitable for re-refining, assuming that waste oil collecting and generating sectors are comparable in both countries. Actually, 27.707.649 liters of non-household waste oil were collected in Flanders in 2009. Based on these figures, and presuming the above mentioned similarities between Flanders and the Netherlands, 78% of the collected non-household waste oil in Flanders would be suitable for re-refining, figure that comes very close to the Ökopol (2005) estimate of 80%.

Waste oil characteristics obviously vary **between** different waste codes, but also **within** a certain category different qualities for treatment can be observed. For instance, within the 13 02 04 code of chlorinated engine, gear and lubricating oils, higher chlorine contents could affect the suitability for thermal cracking, while chlorine contents in the lower range would not impose any restriction for that specific treatment. Similarly, an increase of the share of synthetic lubricants based upon esters within the 13 02 06 code, could influence the suitability for re-refining, since esters are s suitable to regeneration because they tend to be less stable in the presence of caustic (often used by regeneration processes) and less stable to the hydro-finishing step.[b]

The quality of outputs, even in the same product category, that are obtained by the available waste oil treatments also varies considerably, as output characteristics depend on the input quality, client requirements, process characteristics and technical or regulatory constraints. To determine an adequate substitute for re-refined base oil, as is required for modeling the re-refining treatment, the quality of this base oil needs to be plotted against virgin base stock quality. Typically, solvent extracted base stocks fall into API Group I and hydrotreated base stocks into Group II, while hydrocracked VHVI base stocks are normally categorized as Group III.[c] European vendors of re-refined stock maintain that the technical qualities of re-refined stock are no different from Group I base oil. An Ökopol (2008) study however notes that only about 580.000 t/a (compared to a total used oil capacity in EU 27 re-refineries of 1.600.000 t/a in 2006) are base oil capacities from modern re-refining plants able to produce base oil quality with a market price close to primary base oils (API I/API II).[d]

Since the outputs of waste oil treatment operations are put on the market as substitutes for primary resources, as is presented in Figure 8, quality differences are relevant. As a substitute, certain minimum quality properties have to be met. As the waste oil market is well-established and mature, the economic return of waste oil derived products will vary with the price of the substituted primary product and the quality of the corresponding waste oil derived product.

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[a] Belgisch Staatsblad, March 4th, 2011.

[b] Taylor Nelson Sofres Consulting (2001).Critical review of Existing Studies and Life Cycle Analysis of the Regeneration and Incineration of WO. 20 AW 83-5, December 2001.

[c] Scottish Environment Protection Agency, National Best Practice Project: Mineral Oil Wastes, Final Phase 1 Report, November 2005. Available at http://www.sepa.org.u

[d] Ökopol (2008). Increasing world market prices - driver for high level recycling!? Discussion paper on the challenges & perspectives from the changing resource situation on recycling decisions, Final version, Ökopol-Institut für Ökologie und Politik GmbH, Hamburg, Mai 2008

Source: Based on Ökopol (2008)

Figure 8: Key quality properties of waste oil treatment outputs per substituted product category

In the frame of the present study, it is important to note that the relation between the secondary product and the primary substituted product is not only relevant from an economic point of view, but also plays a major role when dimensioning environmental impacts. Yet, the calculated impacts of the avoided primary production of the substituted products are subtracted from the impacts of the recovery and regeneration processes. For this reason, when a lower quality waste oil derived product is considered to substitute a higher quality primary product (that required more energy and inputs and caused more emissions to obtain such higher quality), the calculated net impact of the secondary product will be unfairly low. At the contrary, when compared with a lower quality primary product, the net environmental impact of producing a secondary product from waste oil could be an overestimation.

Regarding the re-refined base oil quality, the study “Global Used Oil 2009: Market Analysis and Opportunities” from global consulting and research firm Kline & Company finds the following key drivers for growth in the re-refining industry: [a]

- Growing virgin base stock prices due to high costs of crude oil have increased interest in re-refined base stocks.
- Improvements in re-refining technology have dramatically improved the quality of re-refined base stocks, allowing them to be used in blending of a growing range of lubricants.
- Regulation in Europe, and increasingly in North America, favors re-refining.

However, the researchers states that: “To achieve its potential, the re-refining industry will have to deal with a number of challenges. Chief among these are negative customer perceptions. Awareness of the quality of re-refined lubricants is spreading among a growing band of end-users; however, this perception is not nearly universal and customer hesitance due to perceptions of poor quality and inconsistent supply still prevents a larger-scale industry growth.” This statement might equally apply on the quality of secondary fuels obtained by thermal cracking of waste oils.

[a] Press release available on http://www.klinegroup.com/news/re-refined_basestocks9-21-10.asp

4 Treatment options

4.1 General

A wide variety of treatment options for waste oil exists. Table 2 summarizes different theoretical options for the treatment of waste oils. It is important to note that not all qualities of waste oil can be treated by all types of treatments, and that different treatments may lead to different products. In some treatment processes operational conditions can be adapted to prioritize between several possible end products, or to maintain a certain product quality with variable feed.

Waste oil	**Type of treatment**	**Products**
Clean waste oil	re-use	Hydraulic or cutting oil • electricity companies • shipping industry • major engineering companies Mould release oil or base oil for the production of chain saw oil
Engine waste oil + clean waste oil	regeneration or re-refining	Lubricant base oil
All types of waste oil Including synthetic oils	thermal cracking	Distillate gas oil products • gas oil (also called heating oil, diesel oil, furnace oil...) • de-metallised fuel oil • marine gasoil (MGO) • re-refined light base oil
Mixed wastes*	gasification	Synthetic gas • hydrogen • methanol
All types of waste oil but especially heavy polluted ones	severe re-processing	De-metallised fuel oil (or heavy distillate) • marine diesel oil (MDO) • fuel for heating plants…
	mild re-processing, then burning	Replacement fuel oil (RFO) • road stone plants, cement kilns, large marine engines, pulverised coal power stations...
	direct burning	Energy Replacement auxiliary fuel

** E.g. waste oil + original plastic container*

Source: Adapted from Critical Review of existing Studies and Life Cycle Analysis on the Regeneration and Incineration of Waste Oils, Final Report, December 2001, European Commission DG Environment, A2- Sustainable Resources- Consumption and Waste

Table 2: Waste oil treatment options and products

The Waste Framework Directive indicates that waste policies should aim at reducing the use of resources, and favour the practical application of the waste hierarchy.

According to the waste hierarchy concept re-refining would be preferable to use after reprocessing, and both options are situated on a higher level than incineration (with or without energy recovery). Nevertheless, Art. 4(2) of the Waste Framework Directive states that Member States shall take measures to encourage the options that deliver the best overall environmental outcome, which may require specific waste streams departing from the hierarchy where this is justified by **life-cycle thinking** on the overall impacts of the generation and management of such waste.

4.2 Options evaluated in this study

The present study is limited to the evaluation of treatment options for waste oils that are covered by the Environmental Policy Agreement on used oil (MBO afgewerkte olie). This Agreement includes a list of oils for which the agreement applies. Oils that are excluded from the Environmental Policy Agreement, and that are therefore not covered by this study, are:

- frying oil and frying fats or other nutritional oils;
- polychlorinated biphenyls (PCB's) and polychlorinated triphenyls (PCT’s), solvents, cleaning products, cleansing agents, antifreeze, brake fluids, hydraulic fluids based on water and/or glycol, other fuels or oil waste that has not been mentioned elsewhere;
- oil from oil/water dividers, bilge oil, oil originating from tank cleaning, oil for ocean shipping.

The full list of types of oils that are included is presented in 3.3.

The three treatment options for waste oil that are evaluated are summarized in Table 3.

Option 1	Use of waste oil as **auxiliary fuel** to provide process heat in a rotary kiln designed for treating liquid and solid hazardous waste streams with organic content, equipped with a flue gas treatment system. (cf. Indaver RK1&2, commissioned in 1989 and 1991)
Option 2	**Recycling** of waste oil by **thermal cracking** into light distillate fuel oil. The process steps are (at least) filtration, dewatering, thermal cracking, distillation and stabilization. (cf. WOS Hautrage, fully operational since early 2004)
Option 3	**Recycling** of waste oil into base oil by **re-refining**. **Lubricating oil** is obtained by adding additives to the base oil that results from the re-refining process. (different facilities and techniques)

Table 3: Studied treatment options for waste oil

4.2.1 Auxiliary fuel in a rotary kiln

4.2.1.1 Process

In Flanders there are two rotary kilns for the incineration of hazardous waste, both at the Antwerp plant of INDAVER. Rotary kilns are widely applied for the incineration of hazardous waste. The operating temperatures of rotary kilns used for the incineration of waste range from around 500°C (used as a gasifier) till 1450°C (used as a high temperature ash melting kiln). When used for conventional oxidative combustion of hazardous waste, the temperature is generally in the range of 900 – 1200 °C. In the case of Indaver >950°C.

A rotary kiln consists of a cylindrical vessel slightly inclined on its horizontal axis. The vessel is usually located on rollers, allowing the kiln to rotate or oscillate around its axis. The waste is conveyed through the kiln by gravity and its rotations.

In the energy recovery unit the energy content of the treated waste is recovered. This unit consists of a tubular water boiler. The steam or hot water is generally produced in tube bundles in the flue-gas path. The steam that is produced has a pressure between 13 and 40 bar with a temperature between 200 and 385 °C depending on the installation. At the INDAVER plant the steam parameters are 20 bar at 215 °C. The thermal efficiency of hazardous waste incineration installations is between 70 and 80%. A range of factors influence the efficiency of the steam generators that are used in hazardous waste incinerators, such as the composition of the gas and the potential for deposition on the heat-exchange surfaces. This has a significant influence on the construction materials that are used and on the design, as well as on the operational life time and performance of the equipment.

The used oil is treated in the installation during normal operation of the installation. It is not used during start up or shut down.

The flue gas cleaning installation of the RK includes the following systems:

- a deNOx installation (SNCR)
- a particle removing system (an electro-filter)
- an SOx and halogens removing systems (four stage wet system)
- a dioxin removing system (dioxin filter).

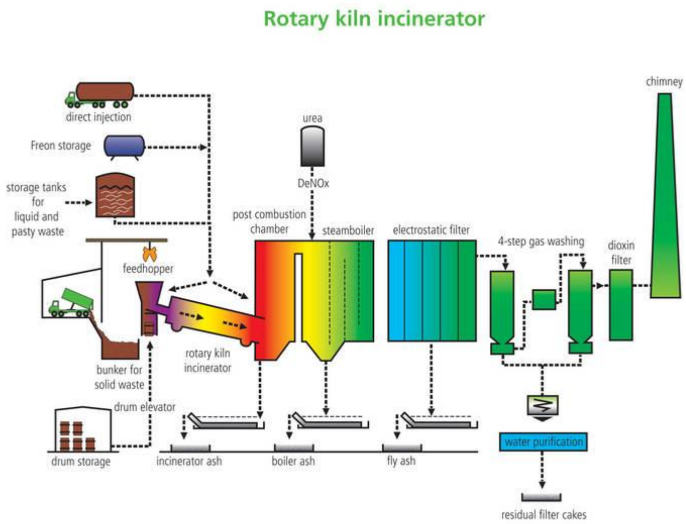

Figure 9 : scheme rotary kiln incinerator (INDAVER)

The installation of INDAVER has no limitation concerning the composition of the waste oils they accept to be treated in the installation, although a higher water content will result in a lower net heating value.

4.2.1.2 Acceptance criteria

The installation of INDAVER accepts mainly two types of waste oil. The first type, mainly delivered to the installation under Eural code 13 02 08, falls under the MBO. It is a waste stream which is quite stable. This waste oil is used to control the incineration process during normal operation (use as auxiliary fuel). The second type of waste oil, Eural code 13 03 01[a] does not fall under the MBO. The composition and calorific value of this waste stream varies per batch.

4.2.1.3 Average input

Following table (Table 4) gives an overview of the average composition of waste as taken into account to calculate the impacts related to the treatment of waste oil in the RK as an auxiliary fuel. This average composition is based on measured data delivered by INDAVER, supplemented by data found in literature.

		Average composition
heating value	MJ/kg	42
carbon	wt%	80
sulphur	wt%	0,51
chlorine	wt%	0,04
fluorine	mg/kg	0,06
arsenic	mg/kg	0,5
lead	mg/kg	45
cadmium	mg/kg	2
chromium	mg/kg	5
cobalt	mg/kg	5
copper	mg/kg	40
manganese	mg/kg	15
nickel	mg/kg	5
mercury	mg/kg	0,05
thallium	mg/kg	0,1
vanadium	mg/kg	0,5
tin	mg/kg	1 - 35
zinc	mg/kg	900

Table 4: average input into the RK taken into account for this study

4.2.1.4 Mass balance

Table 5 gives an overview of the average inputs and outputs of the RK plant of INDAVER related to the incineration of one ton of waste oil. These data refer to waste oil with an average composition of the waste oil as given in Table 5.

INPUTS		**Per ton of waste oil**
Additives FGC		
Quicklime	ton	0,028
Lime Stone	ton	0,092
NaOH	ton	0,059
deNOx reagens	ton	0,011

Table 5 : overview of the inputs in the RK related to the incineration of 1 ton of waste oil

[a] Insulating or heat transmission oils containing PCBs

The inputs (additives and use of water) as given above (in Table 5) are modelled based on data from the RK, allocated to the used waste oil based on the calorific value of the waste oil.

The outputs of the RK are given in Table 6. These outputs consist of emissions to air, and energy under the form of electricity and steam.

The **emissions to air** are calculated based on the average composition of the waste oil as given in Table 4. For the process related emissions (NO_x, dust, TOC, dioxins) the calculations are based on the actual emissions of the installation, allocated to the calorific value of the treated waste oil. For the fuel related emissions (CO_2, SO_2, Cl, F and the heavy metals) the emissions are based on the average composition of the waste oil (given in Table 6).These calculations are based on theoretical data. These calculations result in an overestimation of the actual emissions that occur during the incineration of waste oil.

The **energy production** is calculated based on the actual energy production of the RK, allocated to the calorific value of the waste oil.

OUTPUTS		**Per ton of waste oil**
Emissions to air		
carbon (as CO_2)	kg	2933
nitrogen (as NO_2)	g	3130
sulphur (as SO_2)	g	510
CO	g	259
TOC	g	15
Dust	g	9
chlorine	g	4
fluorine	mg	1
arsenic	mg	5
cadmium	mg	20
chromium	mg	50
cobalt	mg	50
coper	mg	400
lead	mg	450
manganese	mg	150
nickel	mg	50
mercury	mg	0,5
thallium	mg	1
zinc	mg	9000
Energy production		
process steam	GJ	7,61
Electricity	MWh	0,66

Table 6 : overview of the outputs of the RK related to the incineration of 1 ton of waste oil

4.2.1.5 Avoided products and/or processes

When using waste oil in a rotary kiln as auxiliary fuel to maintain a temperature of 1100 °C for 2 seconds[a], the input of virgin light fuel oil is avoided. To model this avoided production following data record was used.

- *Light fuel oil, at refinery* from the Ecoinvent 2.2 database. All processes on the refinery site are included (waste water treatment, process emissions). Emissions to water (direct discharges to rivers) were removed from the record because emissions to water are not taken into account. Because of streamlining, for all studied waste oil treatment options, the extraction of crude oil and the subsequent desalting process are left out of the inventory analysis, and are considered to take place outside the boundaries of the studied system. It is thus assumed that the impacts of crude oil extraction avoided oil products. The emissions from combustion facilities are not taken into account in this record. The multi-output-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated (based on mass) to the different products. Assumptions are for the European average.

To model the impacts that are related to this use of waste oil instead of virgin light fuel, the extra impacts that occur because of this use need to be taken into account. In this case this means that only the net emissions to air (the extra emissions that arise because of the use of waste oil instead of virgin fuel) have to be taken into account. Following table (Table 7) gives an overview of the net emissions that are taken into account in the evaluation.

Emissions to air		
sulphur (as SO2)	g	410
chlorine	g	4
fluorine	mg	1
arsenic	mg	5
cadmium	mg	20
chromium	mg	50
cobalt	mg	50
coper	mg	400
lead	mg	450
manganese	mg	150
nickel	mg	50
mercury	mg	0,5
thallium	mg	1
zinc	mg	9000

Table 7 : overview of the net emissions to air related to the treatment of waste oil

Because a rise in the emissions related to the composition of the waste oil (compared to virgin fuel oil) is assumed, no net additive use is taken into account in the flue gas cleaning system.

Since the average energy content of the waste oil is in the same range as light fuel oil, the use of waste oil does not produce extra energy. Consequently no net energy production is taken into account related to the use of waste fuel.

4.2.2 Thermal Cracking

4.2.2.1 Process

[a] As stated in directive (2000/76/EC) on the incineration of waste

Thermal cracking uses heat to break down long-chain hydrocarbon molecules into shorter ones. The process steps are typically filtration, dewatering, thermal cracking, distillation and stabilization.
Several processes exist today, such as:

- the Springs Oil Conversion (SOC),
- the Great Northern Processing Inc. (GNP) used oil thermal cracking process.

The Springs Oil Conversion is developed by Silver Springs Oil Recovery Inc, Canada. Two variants are available:

- SOC1: the de-watering is followed by the thermal cracking performed in fired heater coils with soaking drums or heated kettles. This process is suitable for small plants, in the 6 kt to 15 kt/yr range, but it is limited in the variability and/or quality of the feed.
- SOC2: the de-watering is followed by the thermal cracking performed in an indirectly fired rotary kiln. It is suitable to large capacities and can process also oils more refractory to thermal cracking (such as synthetic oils) and higher carbon residues (bunker fuels…).

The GNP technology is a thermal cracking of WO, utilising 'refinery calibre' systems and equipment. The installation of WOS uses this technology. The process consists of a screening and de-watering section, followed by a thermal cracking section, then a separation or distillation depending on the product slate desired and finally a purification and stabilisation stage. This technology is characterised by a large operational and product flexibility and adaptability to the changing market values of products. It can also be manipulated to maintain product quality with feed variability. As a matter of fact, the process operational conditions (temperature, pressure, residence time…) can be varied to produce a primary product (be it heavy fuel oil, gasoil or base oil) to be maximised and secondary product streams (consumed in the process for calorific value or sold) to be minimised. (BREF, 2005)

A typical cracking plant operates at a high temperature (420 °C) and low pressure. The light fraction (gasoil, naphtha and off gasses) is then distilled to separate the gasoil-fraction. The lighter fraction (naphtha and off gasses) can be further treated to separate the naphtha fraction and the off gasses. Thermally cracked gasoil is unstable if not further processed. It can discolour rapidly and precipitate gums and tars. A stabilisation and purification operation supplementing the thermal cracking can produce a gasoil which is not odorous, meets regulatory and consumer colour criteria, minimises the formation of gums and tars during storage and which is not highly acidic (BREF, 2005). For this, several methods are available:

- the 'Robysth' process
- chemical stabilisation (clay absorption, solvent extraction)
- hydrotreatment. Except for a standalone WO thermal cracking plant, this treatment might not be feasible due to the very high capital costs and the requirement for hydrogen gas.

Thermal cracking needs a limited amount of external energy input, mainly during start up.
The typical yield for thermal cracking lies between 60 (based on measurements and literature) and 70% (based on the partial yields of the different sub-processes: dewatering (95%); thermal cracking (90%), distillation (83%), purification/stabilization (99,5%)).   (BREF, 2005; OVAM, 2010)

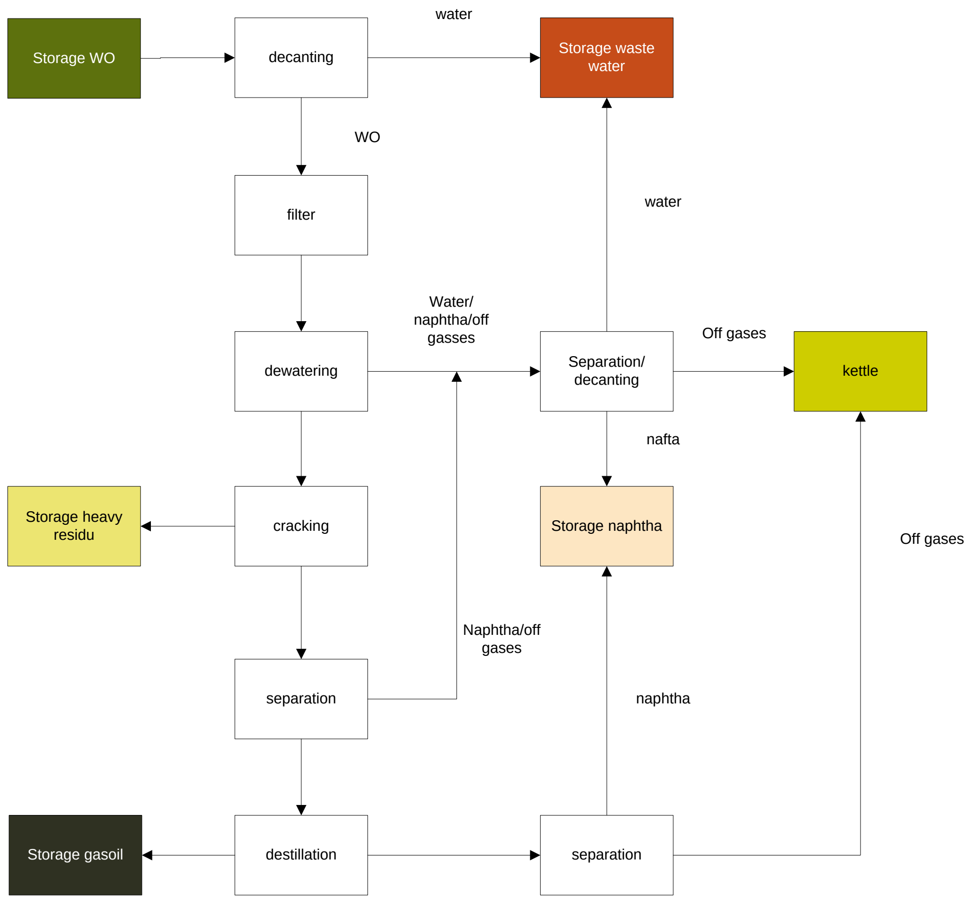

Figure 10 : scheme thermal cracking, based on the installation of WOS

4.2.2.2 Acceptance criteria

Used oil for thermal cracking has to meet several criteria before it can be accepted to be treated in the installation. These criteria are based on:

- limitations that are included in the permit of the installation,
- limitations to protect the treatment facility,
- limitations driven by the output of the installation.

The different parameters for which there are acceptance criteria are given below.

- Flash point,
- Chlorine,
- Sulphur,
- PCB,
- Water content,
- Content of heavy metals (Cd, Cu, Cr, Ni, Pb, V),
- TAN,
- MCR.

The installation of WOS mainly uses used oil that originates from garages (lubricating oils) and industry (hydraulic oils, cutting oils). Additionally the installation has a permit to accept and treat more types of waste oil than those covered by the MBO, such as:

- bilge oils (13.04),
- oil from oil/water separators (13.05.06),
- oily water from oil/water separators (13.05.07),

- wastes of liquid fuels (13.07).

4.2.2.3 Average input in the installation

The average composition of the waste oil delivered to the thermal cracking installation of WOS is given in Table 8.

		Average composition
water	wt%	6 à 10
heating value	MJ/kg	45
sulphur	wt%	0,35
chlorine	wt%	0,05
lead	mg/kg	25
cadmium	mg/kg	2
chromium	mg/kg	6 à 20
cobalt	mg/kg	2
copper	mg/kg	35
nickel	mg/kg	6 à 10
vanadium	mg/kg	2 à 3
zinc	mg/kg	600 à 900
PCB	mg/kg	<10

Table 8 : average composition of the waste oil delivered to the installation of WOS

4.2.2.4 Mass balance

During the treatment of waste oil in the thermal cracking unit of WOS additives and energy carriers are used. Table 9 gives an overview of the average input of additives and energy carriers used for the treatment of one ton of waste oil.

inputs	Per ton of waste oil		
additives	**Min.**	**Max.**	
Anti foulant	0,3	0,35	kg
corrosion inhibitor	0,075		kg
Energy carriers			
electricity	90	95	kWh
Natural gas	444,42	493,8	MJ

Table 9 : average input of additives and energy carriers related to the treatment of one ton of waste oil in the thermal cracking

The average output of the thermal cracker related to the treatment of one ton of waste oil is given in
Table 10.

outputs	Per ton of waste oil	
products		

process gas & naphtha	0,12	ton
gasoil	0,67	ton
heavy fraction	0,14	ton
residue		
water	*0,070*	*ton*
sediment residue	0,002	ton

Table 10 : average output of products and residues related to the treatment of one ton of waste oil in the thermal cracking

During thermal cracking, heavy metals in the waste oil will end up mainly in the residual fraction (sediment residue). During the assessment of the thermal cracking technique we did not take into account any additional dispersion or leaching of heavy metals during application of this residual fraction.

4.2.2.5 Avoided products and/or processes

During the treatment of waste oil in the thermal cracking plant different co-products are produced:

- Naphtha & process gas;
- Gasoil;
- Heavy fraction;
- Sediment residue

For this study we assume that the produced products can be used internal or external and that they replace products that otherwise would be produced based on crude oil. Because of streamlining, for all studied waste oil treatment options, the extraction of crude oil and the subsequent desalting process are left out of the inventory analysis, and are considered to take place outside the boundaries of the studied system. It is thus assumed that the impacts of crude oil extraction are equal for all avoided oil products.

The produced **naphtha and process gas** are used internally. The emissions that are generated because of this incineration are calculated based on the assumption that the calorific value of this gas stream is 37 MJ/kg. The CO_2 emission coefficient related to this fraction is assumed to be 73 kg/GJ. Therefore the CO_2 emissions that are generated because of the incineration of this fraction are assumed to be 320 kg.

For the produced **gasoil** the study on end-of-waste criteria for waste oils (OVAM, 2010) concluded that this fraction can be used (after meeting the criteria concerning the input into the installation, the treatment process and the final product) for specific applications in agriculture, inland shipping and the maritime sector. Therefore the production of gasoil trough cracking of waste oil avoids the production of virgin gasoil.

- Gasoil

  To model this avoided production the adapted data record, *Light fuel oil, at refinery* from the eco-invent 2.2 database is used. All process emissions on the refinery site are included. Emissions to water (direct discharges to rivers and waste water treatment were removed from the record because emissions to water are not taken into account. The emissions from combustion facilities are not taken into account in this record. The multi-output-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated to the different products (based on mass). Assumption for the European average.

The produced **heavy fraction** replaces the production of heavy fuel oil. Therefore the production of this fraction replaces the virgin production of heavy fuel oil.

- Heavy fuel oil

  To model this avoided production the adapted data record *heavy fuel oil, at refinery/kg/RER* from the Ecoinvent 2.2 database is used. All processes on the refinery site including process emissions. The emissions from combustion facilities, waste water treatment and direct discharges to rivers are excluded. Description of all flows of materials and energy due to the throughput of 1kg crude oil in the refinery. The multi-output-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated to the different products (based on mass). Assumption for the European average.

The **sediment residue** substitutes a combustible fraction. We assumed the replacement of virgin bitumen.

- Bitumen :

  To model the avoided production of Bitumen, the adapted data *record Bitumen from refinery Europe ETH* from the ETH/ESU database is used. Oil refineries are complex facilities. Several processes, such as distillation, vacuum distillation, or steam reforming are required to produce a large variety of oil products such as gasoline, light fuel oil or bitumen. Energy and material flows of a modern European refinery were analyzed. The analysis lead to product specific allocation factors for energy and catalysts. Furthermore working material consumption, additive requirements, production waste, and infrastructure are included. Emission factors for the Swiss and for the average Western European refinery are used. Energy consumption figures for Swiss, Western European and Russian refineries are distinguished. Airborne emissions comprise CO, CO_2, SO_2, NO_X, particulate matter, hydrocarbons (specified), acids and heavy metals (specified). Different production waste and their further treatment are distinguished. In addition to that land use and water consumption are recorded.

4.2.3 Re-refining

4.2.3.1 Process

This section details the different re-refining treatments that are applied to waste oils. These treatment processes exist (or are currently under development) in Europe. There are currently no re-refining installations in Belgium.

Re-refining processes involve the removal of impurities, defects and any leftover products from its old use. Generally, this type of process removes all impurities and additives and only base oil remains. Subsequently, lubricant producers add substances to attain the specifications of a virgin product.

Depending on the technology used re-refining treatments may differ for one or several of the following operations: **pre-treatment, cleaning, fractionation and finishing**. Not every plant applies all operations described. In practice, most plants only use a few of the processes shown, and usually there are two or more parallel streams from each process.

First a **pre-treatment step** is used to dewater (removal of water), de-fuel (removal of light ends and fuel traces such as naphtha, etc.) and remove sediments from the waste oil.
The main techniques used for this pre-treatment are settling, sedimentation, filtering and centrifuging.

In a second step (**cleaning**) the waste oils is de-asphalted and asphaltic residues such as heavy metals, polymers, additives, other degradation compounds are removed. This is done by distillation and the addition of acids. By using distillation the waste oil is separated in different fractions using their different boiling temperatures. By using acids, additives, polymers, oxidation and degradation products are removed by contact with sulphuric acid or precipitated as sulphates (e.g. metals). Sometimes clay cleaning is also considered, where the clarified oil is mixed with clay by absorption to remove any polar and undesirable compounds still present.

A third step involves the **fractionation** of waste oil to produce different distillation fractions. This is often done by vacuum distillation. These units can range in complexity from a simple splitting column to a full fractional distillation column, as used in mineral oil refineries.

A final step (**finishing**) consist of a final cleaning of the different cuts (distillation fractions) to achieve products with specific properties or according to relevant specifications (e.g. improve colour, smell, thermal and oxidation stability, viscosity, etc.). This finishing may also include the removal of PAHs in the case of a severe (high temperature and high pressure) hydrofinishing or solvent extraction (low temperature and low pressure). Following table gives an overview of the different options that are used for final cleaning of the distillation fractions. (BREF, 2005; Monier & Labouze, 2001)

Technique	**Principle of operation**	**Feed and output streams**
Alkali treatment	KOH or NaOH are added.	Colour properties are enhanced.
Bleaching earth	This treatment is used to remove the black colour from the oil (caused by the carbon breakdown from the additives), so it can visually be compared with virgin base oil.	The new goals, set up by the implementation of upcoming specifications for passenger car motor oils, cannot be achieved. In particular, the colour of the produced oils is darker than required.
Clay polishing	This is a process similar to the acid/clay process but acid is not used. Bentonite is the clay typically used. The clay is then separated from the oil using a filter press.	Generally, clay polishing does not produce the high quality base oils of solvent extraction
Hydrotreatment	Chlorine and sulphur are removed from the waste oil fraction at a high temperature under a hydrogen atmosphere and in contact with a catalyst, being converted into HCl and H_2S. Phosphorus, lead and zinc are also removed in this process. PAHs can be removed by severe hydrofinishing (high temperature and with hydrogen under high pressure).	The quality of the distillates is very high and the petroleum fractions are immediately marketable. Hydrogen is needed for the process. Hydrogen sulphide is formed, which can later be reduced to sulphur.
Solvent cleaning	PAHs are removed from the base oils by extracting them into the solvent (into ppb range). The solvent extraction also improves the colour and viscosity index.	The feed into the extraction must be a good quality base oil with all heavy metals etc. removed and already fractioned into wanted cuts. The products are a high quality base oil, the used solvent which is regenerated, and a small stream of base oil (c. 3 % of the total base oil stream) with a high PAH concentration, which is used as a fuel product

Table 11 : overview final cleaning options for waste oils

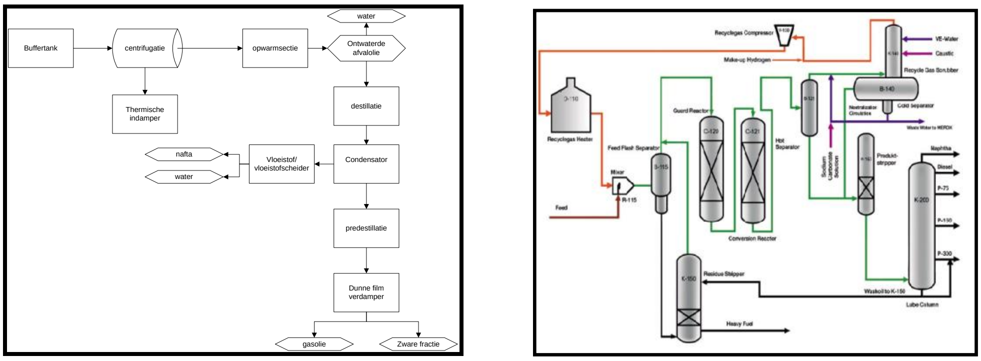

Figure 11 : process schemes of two different re-refining processes in Europe

The different possibilities to combine these different processes lead to different types and grades of base oil.

In the BREF waste treatment (BREF, 2005) is indicated that distillation combined with clay processes has a high adverse environmental impact, due to the large quantity of oily clay to be disposed of. The lubricating oil yield of these techniques is expected to lie in the region of 50% on a dry basis. Further the product quality achieved with these techniques is poor.

The techniques evaluated in this study are based on either hydrogenation or extraction technology as a finishing step.

4.2.3.2 Acceptance criteria

The BREF waste treatment (BREF, 2005) indicates that waste oils that are suitable to be re-refined are:

- Engine oil, which have homogeneous characteristic and are sought by re-refining plants
- Black industrial oils are potentially suitable for regeneration but due to the content of additives and other substances these oils are not typically preferred by re-refining plants,
- Light industrial oils, which are relatively clean. They can either be re-refined or re-used for other purposes. Their market is very specific an independent from the classical supply routes of recycling.

The feedstock quality has a severe influence on the environmental performance of an installation, as well as on the quality of the product. Segregated used lubricants can have a higher recovery value.

Experts consider the following waste oil to be re-refinable:

- Mineral-based non-chlorinated engine, gear and lubricating oils (130205)
- Mineral-based non-chlorinated hydraulic oils 130110)
- Mineral-based chlorinated insulating and heat transmission oils other than those mentioned in 13 03 01 (130306)
- Mineral-based chlorinated engine, gear and lubricating oils (130204), although only under certain conditions (i.e. limitation of chlorine or PCB content)
- Hydraulic oils with PCB (130101), although only under certain conditions (i.e. limitation of chlorine or PCB content)
- Hydraulic oils with chlorine (130109), although only under certain conditions (i.e. limitation of chlorine or PCB content)

According to the German Altölverordnung waste oils included in category 1 of Appendix 1 are suitable for reprocessing. This category 1 consists of following types of waste oils:

- mineral-based non-chlorinated hydraulic oils (130110)
- mineral-based non-chlorinated engine, gear and lubricating oils (130205)
- synthetic engine, gear and lubricating oils (130206)
- other engine, gear and lubricating oils (130208)
- mineral-based non-chlorinated insulating and heat transmission oils (130307)

Waste oils of different collection categories pursuant to Appendix 1 of the Altölverordnung may not be mixed.

As mentioned in §3.6 Flanders exported only waste oil with code 130205.

4.2.3.3 Average input

Following table shows the typical average composition of waste oil handled by the re-refining companies as evaluated in this study.

		1	**2**	**3**	**4**	**5**
water	wt%	5	6 - 8	6	8	6
heating value	MJ/kg		39,8	39,8	42,6	
ash	vol%			< 3		0,4
carbon	wt%					
sulphur	wt%	0,6	0,5 - 0,7	0,7	0,8	0,23
chlorine	wt%	0,07	< 0,09	0,04	0,1	0,1
fluorine	mg/kg			< 0,02		
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
cadmium	mg/kg			< 0,2	<1	0 - 5
chromium	mg/kg	2	5	5	5	
cobalt	mg/kg			< 0,5	1,3	
coper	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	
mercury	mg/kg		<0,1	<0,1	0,05	
thallium	mg/kg		<0,1	<0,1	29	
vanadium	mg/kg	<1	2	<1	< 1	
tin	mg/kg	<1	3	4	33	
zinc	mg/kg	500	800	760	700	
PCB	mg/kg	20	<3		10 - 11	< 2
PAH	mg/kg			0,022	4	

Source : IFEU, 2005

Table 12 : average physical properties and content of used oil according to the five re-refining companies

Based on these data, reference values are calculated and given Table 13. These values are used in the assessment to evaluate the re-refining techniques.

		average
water	wt%	6
heating value	MJ/kg	40
ash	vol%	1
carbon	wt%	80
sulphur	wt%	0,7
chlorine	wt%	0,07
fluorine	mg/kg	0,1
arsenic	mg/kg	0,5
lead	mg/kg	40
cadmium	mg/kg	0,2
chromium	mg/kg	5
cobalt	mg/kg	0,7
coper	mg/kg	30
manganese	mg/kg	10
nickel	mg/kg	5
mercury	mg/kg	0,05
thallium	mg/kg	0,1
vanadium	mg/kg	0,5
tin	mg/kg	15
zinc	mg/kg	700
PCB	mg/kg	10
PAH	mg/kg	1

Source : IFEU, 2005

Table 13 : reference values for waste oil as used in this study for the re-refining techniques

Table 14 gives an overview of a selection of quality data of re-refined base oil compared to virgin base oil as provided by the re-refining companies that are evaluated in this study. More information concerning the quality of base oil can be found in §0.

	Unit	**Typical quality**		**Method**
		Re-refined base oil (SN 150)	Virgin base oil (SN 150)	
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
Sulphur	ppm	10 – 2000	2000 – 6000	ASTM D-4294/DIN EN ISO 8754/ASTM D-5453
Total Acid No.	Mg KOH/g	< 0.003	< 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	< 0.1	IP-346
Benzo(a)pyrene	ppm	< 0.3	Not available	Grimmer (GC)/ICP

Source : IFEU, 2005

Table 14 : quality data of re-refined base oil

4.2.3.4 Mass balance

Different re-refining installations exist today. IFEU (IFEU, 2005) analyzed five different re-refining installations. This study gives excessive information concerning these different treatment options. Because Flemish waste oil is treated in more re-refining installations we modeled the five installations that were described in the IFEU-study. Four of these installations are based on hydrogenation, one on extraction technology. The installations that are analyzed are: Cyclone; Evergreen, Hylube, Minerlöl-Raffinerie Dollbergen and Viscolube. To grant anonymity to the different technologies the different companies are given a number. The order in the table does not fit the order as given above.

Input, per ton of waste oil	**1**	**2**	**3**	**4**	**5**	
auxiliaries						
caustic soda	4,67	10		0,71	2,69	kg
potassium hydroxide			0,06			kg
hydogen	5,16	4,32		2,02	0,3	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 [a]	2360 [c]	1630	617	216 [a]	MJ
process water	374				360	kg

[a] process heat and steam is produced by a natural gas fired furnace resp. boiler

[b] after combustion of light ends and covering partly the Gross demand on process heat there rest a net demand. This is normally covered by by-products of other refining sites of the company. For this balancing however natural gas firing is applied to avoid additional complications due to allocation.

[c] steam is produced also by by-products, however here also natural gas firing is presumed

Source : IFEU, 2005

Table 15 : average input in five different re-refining techniques per ton of waste oil

Process heat and steam are produced by a natural gas fired furnace respectively boiler.

output , per ton of waste oil	**1**	**2**	**3**	**4**	**5**	
base oil	770,8	694,9	544,5	725,2	695,6	kg
naphtha	37,6					kg
ligth ends		47[c]	25[e]	14,2 [e]	141 [f]	kg
extracts			78 [e]			kg
light fuel oil	75,2[a]			99,2 [e]		kg

gasoil		68,6 [a]			37,6[g]	kg
flux oil			29,3[f]	82,2 [f]		kg
heavy oil	56,4[b]		137,3[e]		65,8[h]	kg
bitumen additive		134,8[d]				kg
residue			123,6 [b]			kg
used process water	433,8	60	59,7	79	420	kg
net energy deliverance process heat			7500 [i]	707[i]		MJ

[a] gas oil (diesel quality) is applied as a fuel off the regeneration site but within the system boundary, the incineration of this fraction is assumed
[b] heavy oil and residues are applied as reduction material within a blast furnace, the equivalency process is the production of heavy fuel oil with pre chain.
[c] light ends (naphtha quality) are applied as a fuel on the regeneration site and cover partly the process heat demand.
[d] residues are applied within the manufacturing of bitumen layers, the equivalency process is the production of bitumen
[e] light ends, extracts and fuel oil are applies as a fuel on the regeneration site, they cover the process heat and steam demand and leave a 'net energy deliverance'
[f]flux oil, residues and light ends are applied as additive to bitumen. Equivalency processes are heavy fuel production and natural gas respectively
[g] diesel quality, equivalency process is the production of gasoil
[h] heavy oil is applied on-site as a fuel and covers partly the process heat demand
[i] after combustion of light ends, extracts, light fuel oil and heavy oil and covering the process demand on heat and steam there is a 'net energy deliverance'. The equivalency process is a light fuel oil combustion process with pre-chain.

Source : IFEU, 2005

Table 16 : average output of five different re-refining techniques per ton of waste oil

During re-refining, heavy metals in the waste oil will end up mainly in the heavy or residual fraction. During the assessment of the re-refining technique we did not take into account any additional dispersion or leaching of heavy metals during application of this heavy or residual fraction.

4.2.3.5 Avoided products and/or processes

During the treatment of waste oil in a re-refining installation, different co-products are produced:

- Base-oil
- Gaseous fraction (light ends, naphtha, extracts)
- Gasoil fraction (light fuel oil, gasoil,)
- Heavy fraction (heavy oil, flux oil, bitumen additive, residue).

For this study we assume that the produced products can be used internal or external.

Base-oil is used to produce lubricants. It is assumed that it replaces the virgin production of base oil.

- Base oil
  The production of base-oil avoids the virgin production of base oil. Base oils are used to produce lubricants. Different lubricant properties can be obtained by blending different grades of base oils and special additives. Base oil is a speciality product and

consequently not all crudes are suitable. Heavy crudes are frequently used as feedstock to conventional base oil complexes.

A conventional base oil complex is very labour intensive mainly due to its batch operation, the many grades of base oil normally produced and the associated intensive product handling operations.

In 1990 the American Petroleum Institute (API) established a base oil classification system that uses physical and chemical parameters to divide all base stocks (oils) into five groups as listed in table below[a]:

Group	Viscosity Index	Saturates	Sulphur in %	Description
I	80-120	< 90%	> 0.03%	Conventional (solvent extraction)
II	80-120	≥ 90%	≤ 0.03%	Requires hydroprocessing
III	>120	≥ 90%	≤ 0.03%	Requires severe hydroprocessing, often special feedstocks
IV			---	PolyAlphaOlefins (PAO), obtained by chemical reactions
V			---	All other base stocks not in Group I – IV including other synthetics

The lubricant industry commonly extends this group terminology to include:

- Group I+ with a Viscosity Index of 103–108
- Group II+ with a Viscosity Index of 113–119
- Group III+ with a Viscosity Index of at least 140

Group I base oils are the least refined of all the groups. They are usually a mix of different hydrocarbon chains with little or no uniformity. While some automotive oils on the market use Group I stocks, they are generally used in less demanding applications. They are manufactured by solvent extraction, solvent or catalytic dewaxing, and hydro-finishing processes, and are normally low in natural viscosity index, although some oil fields produce better grades than others. They have 20 to 30% aromatics, high nitrogen and sulphur. Common Group I base oil are 150SN (solvent neutral), 500SN, and 150BS (brightstock). Group I base oils are also used for blending with superior base oils.

Modern catalytic processes give products that are clearly differentiated from conventional solvent-refined base oils. The resulting base oils have characteristics which are superior to anything that could be made by conventional solvent-refining technology relying on physical separation processes. Through catalytic hydrogenation, a clean, stable base oil can be obtained from which almost all aromatics, sulphur, and nitrogen are eliminated. Under the more severe conditions (higher pressures and temperatures), nitrogen and sulphur are converted to NH_3 and H_2S respectively, while aromatics are saturated.

On the other hand, the more severe and extensive the processes are, the higher the energy consumption and the lower the overall yield. Energy use will vary between refineries, but consumptions as high as 0,4 tonnes fuel oil equivalent per tonne of base oil product are not uncommon.[b]

The overall energy consumption of a refinery is normally dominated by a few processes. Atmospheric and vacuum distillation accounts for 35 - 40 % of the total process energy consumption, followed by hydrotreating with approx. 18 - 20 %. (BREF Mineral Oil and Gas Refineries, 2003)

[a] http://www.baseoilmarket.com/oil.php
[b] Mortier, Roy M.; Fox, Malcolm F.; Orszulik, Stefan T. (Eds.) (2010). Chemistry and Technology of Lubricants 3rd ed., 2010, XIII, 547 p.

To model this avoided production these impacts were modeled using data from (IFEU, 2005) and (IPPC, 2001) because there were no data available in the Ecoinvent 2.2 database.

Figure 12 shows a full production process for base oil production based on desalted crude oil. The data given in this scheme are further used to model base oil production.

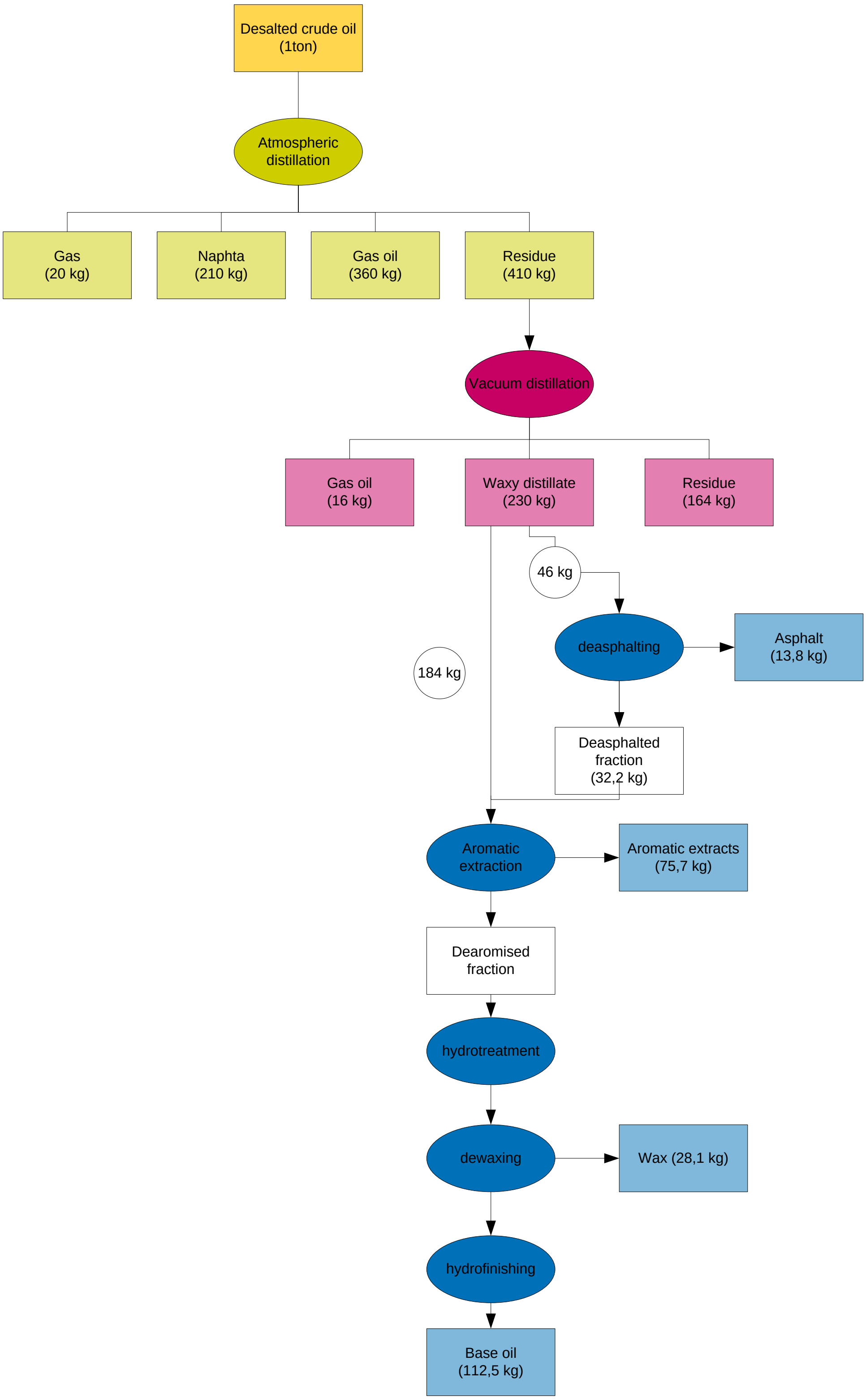

Figure 12 : overview of the production process of base oil from crude desalted oil

As for the other studied waste oil treatment options, here again the extraction of crude oil and the subsequent desalting process are left out of the inventory analysis, and are considered to take place outside the boundaries of the studied system. It is thus assumed that the impacts of crude oil extraction are equal for all avoided oil products.

The utility requirements per ton of feedstock, of each of the process steps of base oil production from desalted crude oil, are summarized in Table 17 and Table 19. Table 18, Table 20 and Table 21 define the co-product yields of these processes. These yields are necessary to be able to allocate the different energy and auxiliary consumptions to the different co-products according to physical relationships.

Atmospheric distillation (input is one ton of desalted crude oil)			
Electricity		MJ	18
Process heat		MJ	540
Process steam		MJ	81,125
Cooling water		kg	4000
Vacuum distillation (input is one ton of atmospheric residue)			
Electricity		MJ	10,8
Process heat		MJ	600
Process steam		MJ	118
Cooling water		kg	4000

Source: BREF, 2001; IFEU, 2005

Table 17: Utility requirements of a mineral oil refinery per ton of feedstock

Product yields by the primary refining			
gas			2,00%
naphtha			21,00%
gas oil (atmospheric)			36%
gas oil (vacuum)			1,64%
waxy distillate			22,96%
residue			16,40%

Source: BREF, 2001; IFEU, 2005

Table 18 : product yields of the primary refining steps

De-asphalting		
Electricity	MJ	60
Process heat	MJ	0,51
Process steam	MJ	1,57
Aromatic extraction		
Electricity	MJ	21
Process heat	MJ	1004
Process steam	MJ	234 (8 m3)

Furfurole	kg	0,5
NMP	kg	0,3
Process water	kg	49
Cooling water	kg	14560
Effluent	kg	65
High pressure hydrotreatment		
Electricity	MJ	0,09
Process heat	MJ	0,46
Process steam	MJ	590
Cooling water	kg	110
Dewaxing		
Electricity	MJ	375
Process heat	MJ	288
Process steam	MJ	1599
Di-Me	kg	0,6
MEK	kg	0,4
Process water	kg	169
Cooling water	kg	4940
Effluent	kg	182
Hydro finishing		
Electricity	MJ	115
Process heat	MJ	425
Process steam	MJ	369
Process water	kg	73
Cooling water	kg	10000

Source: BREF, 2001; IFEU, 2005

Table 19 : energy and auxiliary requirements of a base oil production unit per ton of feedstock, as used in this study

	yield per process step		**percentage of absolute input**
De-asphalting			
Input into process step			20%
De-asphalted fraction	70%		14%
Asphalt fraction	30%		6%
Aromatic extraction			
Input into process step			94%
De-aromatized Fraction	65%		61,10%
Aromatic extracts	35%		32,90%
hydrotreatment			
Input into process step			61,10%
hydrotreated fraction	100%		61,10%
Dewaxing			

Input into process step			61,10%
Dewaxed Fraction	80%		48,90%
Wax	20%		12,20%

Source: BREF, 2001; IFEU, 2005

Table 20 : yields of the different process steps of a base oil refining as used in this study

Total product yields by the base oil refinery chain		
Base oil		48,90%
Asphalt		6,00%
Aromatic extracts		32,90%
Wax		12,20%

Source: BREF, 2001; IFEU, 2005

Table 21 : product yields of a base oil refinery

Following table shows stepwise the allocation for the use of electricity for the different co-products, per process step for the base oil production chain.

electricity in MJ per ton waxy distillate input					
	Base oil	**Asphalt**	**Aromatic extracts**	**Wax**	**total**
	48,90%	6,00%	32,90%	12,20%	100,00%
De-asphalting	5,84	0,72	3,93	1,46	11,95
Aromatic extraction	10,25		6,90	2,56	19,71
High pressure Hydrotreatment	0,05			0,01	0,06
Dewaxing	183,39			45,75	229,15
Hydro finishing	56,24				56,24
sum	255,77	0,72	10,83	49,78	317,10

Source: BREF, 2001; IFEU, 2005

Table 22 : example for allocation of electricity in the base oil production chain to the co-products

All re-refining processes produce a lighter fraction (naphtha, light ends and extracts). If this fraction is internally used for the production of energy (heat or steam) they generate the emission of CO_2. These emissions are calculated based on the assumption that the calorific value of this gas stream is 37 MJ/kg. The CO_2 emission coefficient related to this fraction is assumed to be 73 kg/GJ. If these fractions are a net output of the process (they are delivered as a product to a third party) the assumption was made that they avoid the production of natural gas.

– Natural gas

  To model this avoided production the record, *Natural gas, high pressure, at consumer/RER* from the eco-invent 2.2 database, is used. This dataset describes the average production of natural gas, the energy requirements and the emissions of the high pressure distribution network in Europe. Total network losses are based on assumptions, repartition of losses on high and low pressure network on calculations with data for other countries. The energy requirement is based on the environmental report of Italian company. Total leakages are assumed for Europe, HD-leakages are calculated out of the total with German data.

Furthermore 4 out of the 5 re-refining processes produce a light fuel oil (or gas oil) fraction. If this fraction is internally used for the production of energy (heat or steam) they generate the emission of CO2. These emissions are calculated based on the assumption that the calorific value of this gas stream is 40 MJ/kg. The CO_2 emission coefficient related to this fraction is assumed to be 75 kg/GJ. If this fraction is a net output of the process, the assumption was made that they avoid the production of virgin light fuel oil.

– Gasoil

    The production of gasoil avoids the production of virgin gasoil. To model this avoided production the data record, *Light fuel oil, at refinery* from the Ecoinvent 2.2 database is used. All processes on the refinery site are included (waste water treatment, process emissions and direct discharges to rivers) except the emissions from combustion facilities. Crude oil production was removed from the record for consistency purposes. The multi-output-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated to the different products (based on mass). Assumption for the European average.

Some of the re-refining processes produce a heavy fraction (flux oil, heavy oil, residue). If this fraction is incinerated internally for the production of process heat or steam, they generate emissions of CO_2. These emissions are calculated based on the assumption that the calorific value of this gas stream is 42 MJ/kg. The CO_2 emission coefficient related to this fraction is assumed to be 75 kg/GJ. If these fractions are delivered to a third party the assumption was made that they avoid the production of virgin heavy fuel oil.

– Heavy fraction

    To model this avoided production the adapted data record heavy fuel oil, *at refinery/kg/RER* from the eco-invent 2.2 database is used. All processes on the refinery site including process emissions. The emissions from combustion facilities, waste water treatment and direct discharges to rivers are excluded. This record gives a description of all flows of materials and energy due to the throughput of 1 kg crude oil in the refinery. The multi-output-process 'crude oil, in refinery' delivers the co-products petrol, unleaded, bitumen, diesel, light fuel oil, heavy fuel oil, kerosene, naphtha, propane/ butane, refinery gas, secondary sulphur and electricity. The impacts of processing are allocated to the different products. Assumption for the European average.

Finally one of the re-refining processes produce a residual fraction (bitumen additive). This fraction is delivered to a third party and replaces bitumen. Therefore this fraction replaces the production of virgin bitumen.

– Bitumen

    To model the avoided production of Bitumen, the adapted data *record Bitumen from refinery Europe ETH* from the ETH/ESU database is used. Oil refineries are complex facilities. Several processes, such as distillation, vacuum distillation, or steam reforming are required to produce a large variety of oil products such as gasoline, light fuel oil or bitumen. Energy and material flows of a modern European refinery were analyzed. The analysis lead to product specific allocation factors for energy and catalysts. Furthermore working material consumption, additive requirements, production waste, and infrastructure are included. Emission factors for the Swiss and for the average Western European refinery are used. Energy consumption figures for Swiss, Western European and Russian refineries are distinguished. Airborne emissions comprise CO, CO_2, SO_2, NOx, particulate matter, hydrocarbons (specified), acids and heavy metals (specified). Different production waste and their further treatment are distinguished. In addition to that land use and water consumption are recorded.

5 Assessment

5.1 Environmental impacts

5.1.1 Method

For the characterization of the environmental impacts we used the ReCiPe method. This method can be seen as an updated successor of the “eco indicator’99’ method.

The ReCiPe method was created by RIVM, CML, PRé Consultants, Radboud Universiteit Nijmegen and CE Delft. In ReCiPe you can choose to use midpoint indicators or endpoint indicators. Each method has been created for three different perspectives: individualist (I), hierarchist (H) and egalitarian (E).

ReCiPe uses an environmental mechanism as the basis for the modeling. An environmental mechanism can be seen as a series of effects that together can create a certain level of damage to for instance, human health or ecosystems. For instance, for climate change we know that a number of substances, increases the radiative forcing, this means heat is prevented from being radiated from the earth to space. As a result, more energy is trapped on earth, and temperature increases. As a result of this we can expect changes in habitats for living organisms, and as a result of this species may go extinct. From this example it is clear that the longer one makes this environmental mechanism the higher the uncertainties get. So the obvious benefit of taking only the first step is the relatively low uncertainty.

In ReCiPe eighteen of such midpoint indicators and three much more uncertain endpoint indicators are calculated. The motivation to calculate the endpoint indicators is that the large amount of midpoint indicators are very difficult to interpret, partially as there are too many, partially because they have a very abstract meaning.

The idea is that each user can choose at which level it wants to have the result:

- At the midpoint level there are eighteen robust midpoint indicator, that are relatively robust, but not easy to interpret
    - climate change (CC)
    - ozone depletion (OD)
    - terrestrial acidification (TA)
    - freshwater eutrophication (FE)
    - marine eutrophication (ME)
    - human toxicity (HT)
    - photochemical oxidant formation (POF)
    - particulate matter formation (PMF)
    - terrestrial ecotoxicity (TET)
    - freshwater ecotoxicity (FET)
    - marine ecotoxicity (MET)
    - ionizing radiation (IR)
    - agricultural land occupation (ALO)
    - urban land occupation (ULO)
    - natural land transformation (NLT)
    - water depletion (WD)
    - mineral resource depletion (MRD)
    - fossil fuel depletion (FD)

- At the endpoint level, most of these midpoint impact categories are further converted and aggregated into the following three endpoint categories. These three categories are easy to understand, but they are more uncertain :

    - Damage to Human health (HH)
    - Damage to ecosystems (ED)
    - Damage to resource availability (RA)

The user can thus choose between uncertainty in the indicators, and uncertainty on the correct interpretation of indicators.

Figure 13 gives an overview of the relationship between the LCI-parameters, the midpoint indicators and the end point indicators.

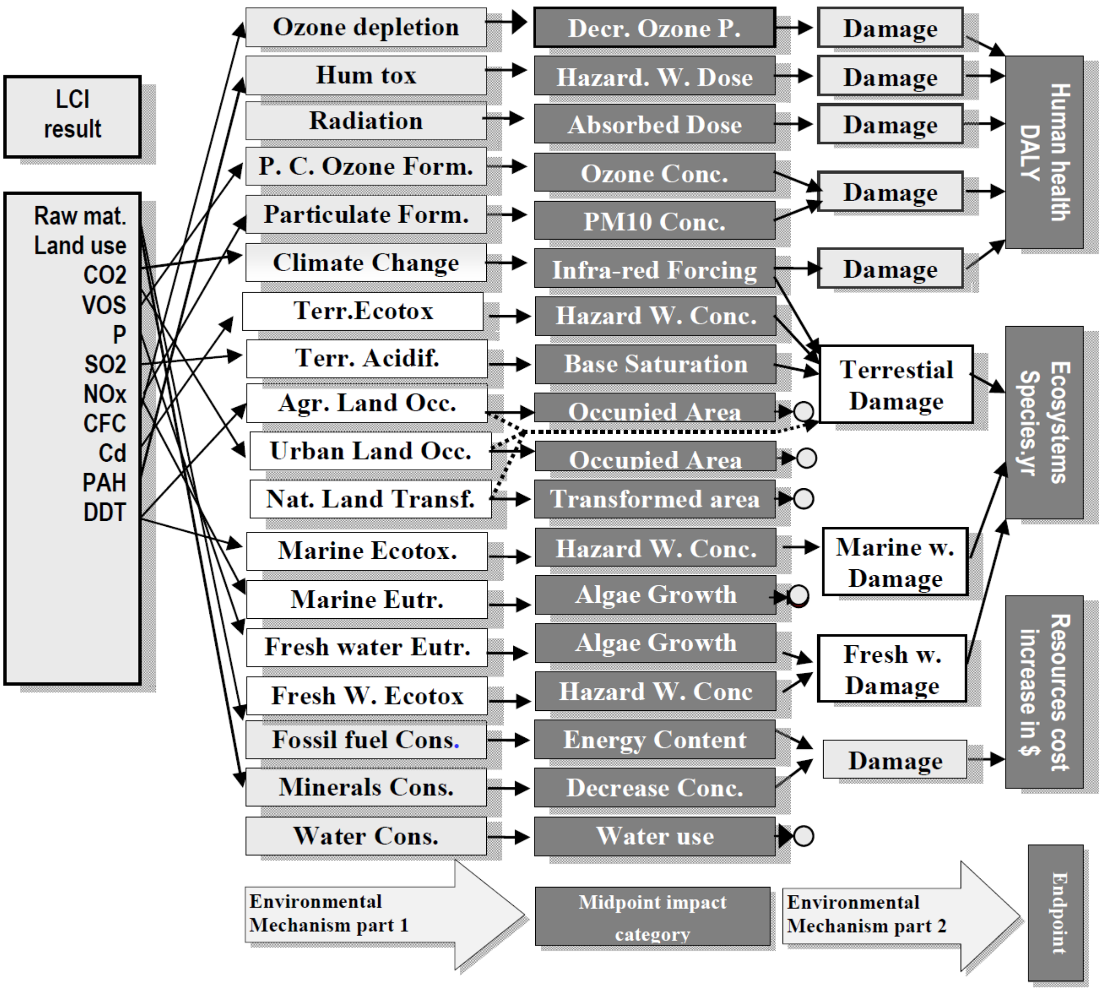

Figure 13 : relationship between LCI parameters (left), midpoint indicator (middle), and end point indicator (right)

Damage to human health is uses the concept of 'disability-adjusted life years' (DALY). The DALY of a disease is derived from human health statistics on life years both lost and disabled.

To calculate damage to ecosystems the loss of species during a certain time in a certain area was modelled in the ReCiPe-model as the basis for the endpoint indicator. In the Eco-indicator

99 method, ecosystem quality was expressed as the potentially disappeared fraction of species (PDF) integrated over area and time. As long as only terrestrial ecosystem damage is determined, the ‘area’ can be expressed as surface area in square metres. In ReCiPe, there is also a characterisation factor for aquatic eutrophication (both for freshwater and marine water), and the unit of this indicator is (PDF ×) m3×yr, which involves an integration over volume instead of area.

In the ReCiPe-model resource depletion is modelled based on the geological distribution of mineral and fossil resources. The use of these resources causes marginal changes in the efforts to extract future resources. The model is based on the marginal increase in costs due to the extraction of a resource. To this end, a function was developed that reflects the marginal increase of the extraction cost due to the effects that result from continuing extraction. In terms of minerals, the effect of extraction is that the average grade of the ore declines, while for fossil resources, the effect is that not only conventional fossil fuels but also less conventional fuels need to be exploited, as the conventional fossil fuels cannot cope with the increasing demand.

A full description of the model can be found in (ReCiPe, 2008)

5.1.2 Analysis of the results

The most important reasons for using the ReCiPe methodology are that this methodology is recognized as one of the scientifically sound and accepted method. The framework proposed by ISO 14040/44 and followed by the ReCiPe method consists of the following elements:

- selection of impact categories, category indicators and characterization models;
- classification: assignment of inventory data to impact categories;
- characterization: calculation of category indicator results.

The damage categories considered in this study are presented in Figure 14. We use the LCA software package “SimaPro 7” for performing the impact analysis and generating the environmental profiles.

When comparing the environmental profiles of the different treatment options with each other, we use the following rules of thumb of the evaluated techniques for defining a significant difference on the net result:

- 20%: for the well-defined impact categories such as depletion of fossil fuels and climate change;
- 30% for the impact categories where the methodology is less well-founded or incomplete, being human toxicity, particulate matter formation.

If the net results of the treatment techniques differ less than 20 or 30% (depending on the impact category) the assumption has to be made that there is no difference between these techniques for the impact category that is analyzed[a].

[a] These rules of thumb were applied to the net results of the environmental assessment. If however these rules would be applied to the absolute values of the environmental assessment this would lead to a larger interval. This could lead to the conclusion that there are more techniques for which the differences between the results are not significant.

5.1.3 Results

The results of the environmental assessment indicate that for the end-point category ‘damage to human health’ the categories ‘climate change, human health’, ‘human toxicity’ and ‘particulate matter formation’ are the most relevant impact-categories. The end-point category ‘damage to ecosystems’ is dominated by impact-category ‘climate change ecosystems’, the mid-point impact category ‘natural land transformation’ can be seen in the results, but this impact category is of minor importance. Finally for the end-point category ‘depletion’ the results show that this impact is dominated by the impacts caused by the ‘depletion of fossil fuels’.
The results at endpoint level indicate which impact categories are the most important ones. A full overview of the results, both at midpoint and endpoint level, is presented in annex.

A first overview of the results for the most relevant impact categories is given in a relative order. So the results of the installation that avoids the most impacts were set on 100%. The impacts of the other installations are given relatively to this avoided impact of 100%. The result of this analysis is given in Figure 14.

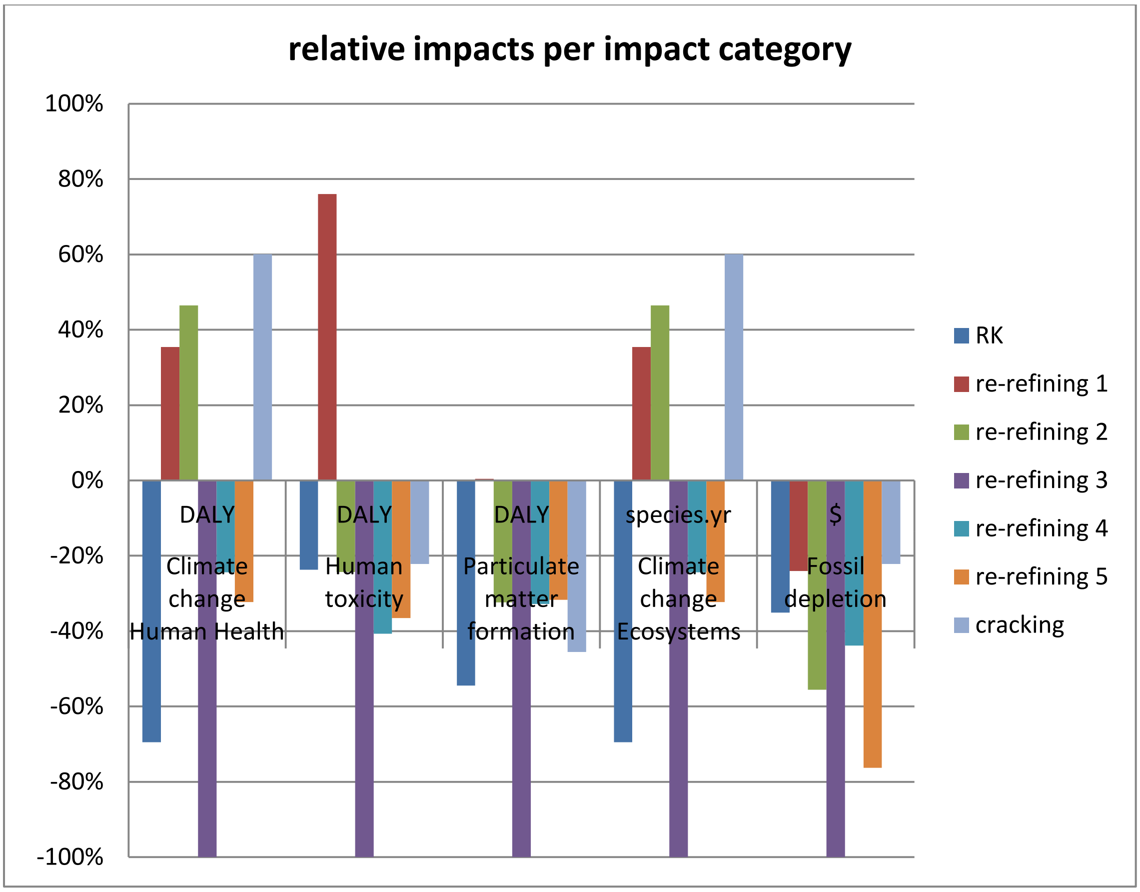

Figure 14 : overview of the relative impacts for the relevant impact categories

Figure 14 shows that re-refining technique 3 obtains the best score for all impact categories and that the environmental impact scores of the use of MBO-covered waste oil as auxiliary fuel in a rotary kiln are comparable or lower than those of thermal cracking.

5.1.3.1 Damage to human health

The end point indicator ‘damage to human health’ consists of three midpoint indicators that have a relevant impact for this indicator. In what follows we describe more in detail on the reasons for this impact (or avoided impact) per relevant midpoint indicator.

– Damage to human health by climate change

As can be seen in Figure 15 four of the evaluated techniques avoid impacts for damage to human health by climate change. For the re-refining 4 and 5 this is mainly because of the avoided production of base oil. The difference between these two techniques is not significant. For re-refining 3 the avoided impact is caused by a combination of the avoided production of base oil and the avoided production of heat. These avoided impacts are larger than the impacts caused by the re-refining technique itself, resulting in an overall net avoided impact. For the RK the avoided impact is entirely caused by the avoided production of fuel oil. The difference between the latter and re-refining 3 is not significant.

Three techniques cause net impact for this impact category. This is due to the fact that the installations themselves and the used energy carriers in these installations have a larger impact than the impact that is avoided by the production of the useful outputs. The differences between these techniques are not significant.

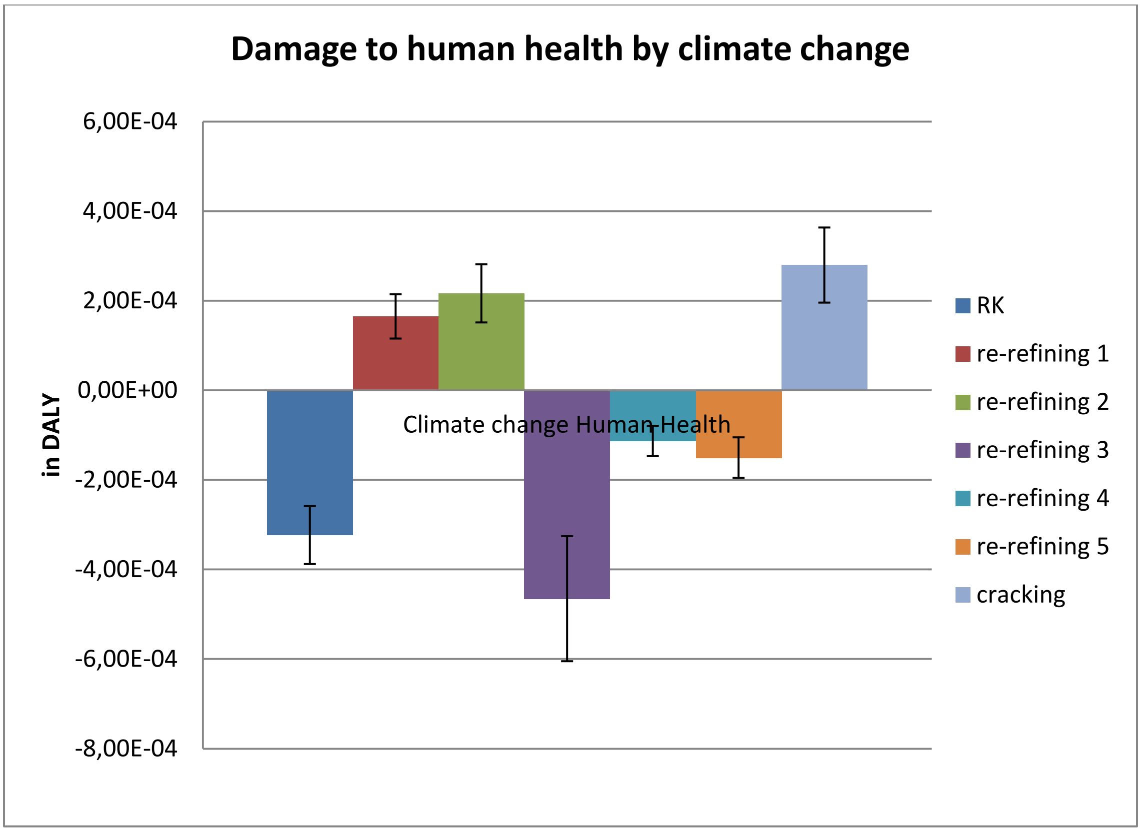

Figure 15 : damage to human health caused by climate change

– Damage to human health by toxic substances

Figure 16 gives an overview of the damage to human health by toxic substances that is caused or avoided by the different treatment options. Only re-refining 1 causes a net impact for this impact category, mainly because of the use of electricity by this technique. The impact that is caused is not compensated by the avoided impact related to the production of base oil. The other techniques all avoid damage to human health by toxic substances. For re-refining 2, 3, 4 and 5 and cracking the impacts are caused by the use of electricity. This impact is however compensated by the production of the use full outputs. In the RK the impact is caused by the net emissions to air caused by the use of waste oil. This impact is however compensated by the avoided production of light fuel oil.

The differences between RK, re-refining 2, 4, 5 and cracking are not significant.

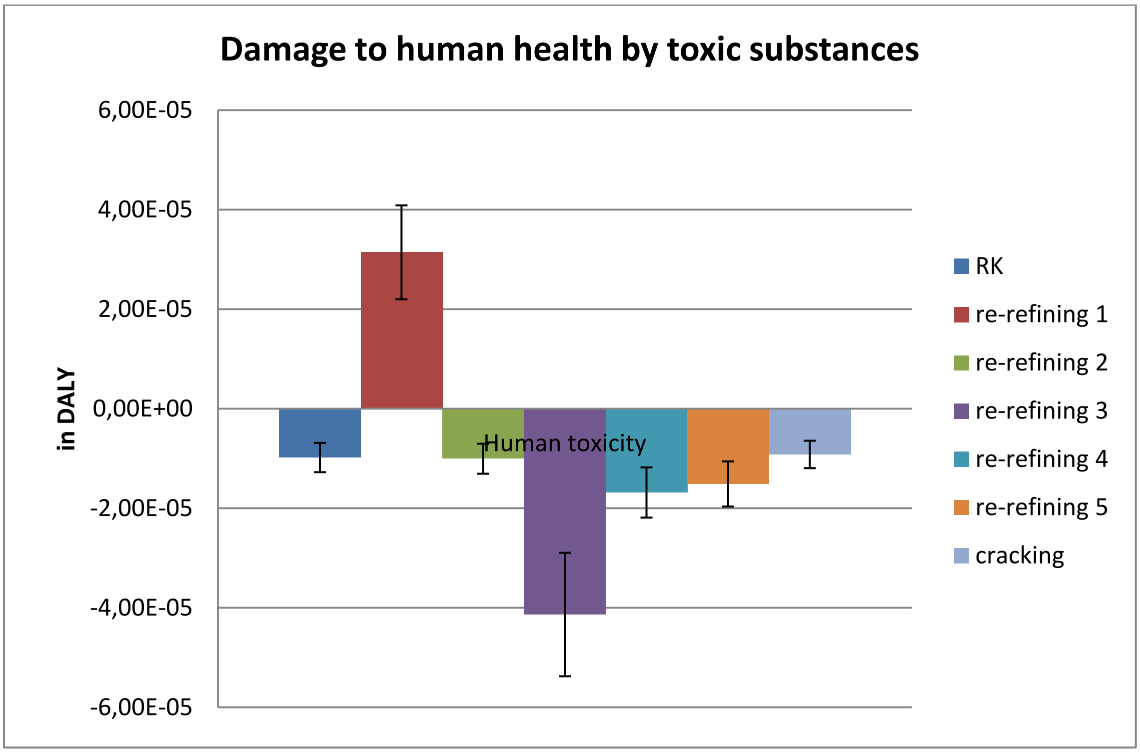

Figure 16 : damage to human health caused by toxic substances

– Damage to human health by particulate matter formation

Figure 17 gives an overview of the damage caused to human health by particulate matter formation. Re-refining 1 causes a small net impact for this impact category (7,40E-07). The impact caused by this technique is mainly due to the use of electricity. This impact is not entirely compensated by the avoided production of base oil.

The other techniques all avoid impact for this category. The impacts caused by the use of electricity (re-refining techniques 2, 3, 4 and 5) and cracking are compensated by the production of useful outputs. For the RK the impact caused by the net emissions related to the use of waste oil, are compensated by the avoided production of light fuel oil.
The differences in impact between RK, re-refining 2, 4, 5 and cracking are not significant. Also the difference between RK and re-refining 3 is not significant.

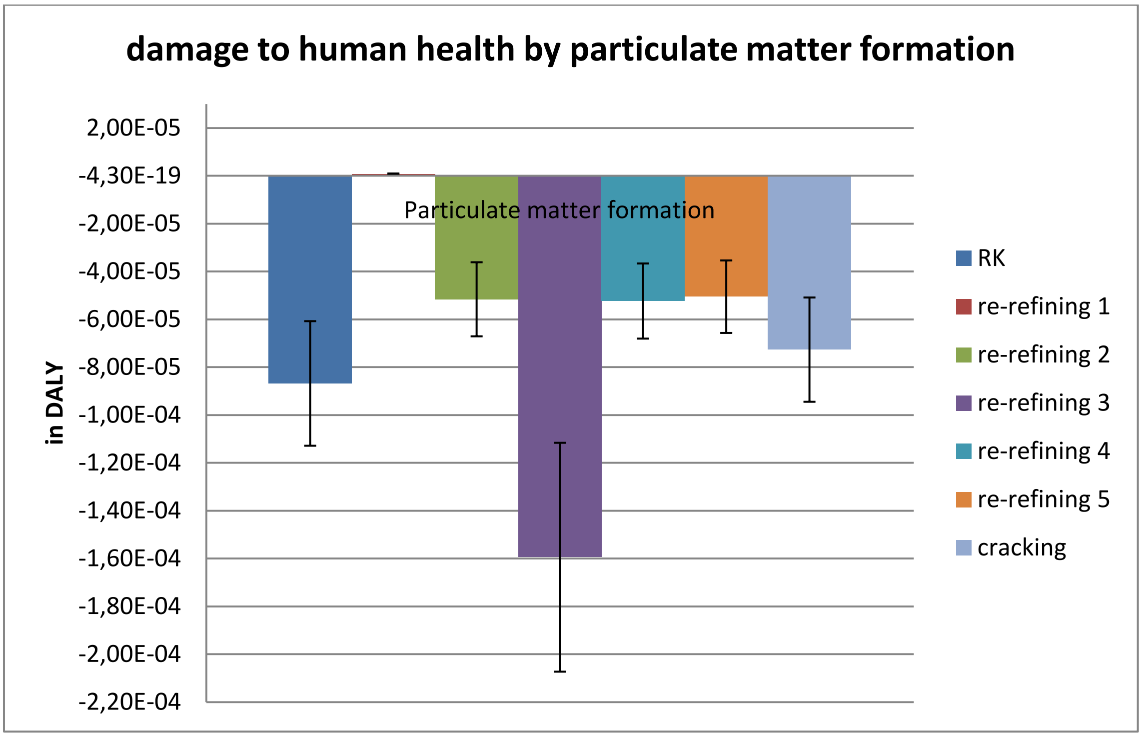

Figure 17 : damage to human health caused by particulate matter formation

5.1.3.2 Damage to ecosystems

For the end point indicator 'damage to ecosystems' there is only one impact category that has a relevant influence, namely the damage caused by climate change.

– Damage to ecosystems by climate change

Figure 18 has the same structure as Figure 15, because these impact categories are both impacts caused by climate change. For this impact category the same conclusions can be drawn: three techniques cause a net impact for this category. The impacts caused by these techniques (re-refining 1 and 2 and cracking) are related to the treatment facilities and the energy carriers they use to treat the waste oil. These impacts are not compensated by the avoided impact related to the use full outputs that are produced by these techniques. The differences in impacts caused by these techniques are not significant.

For re-refining 3 the avoided impact is caused by a combination of the avoided production of base oil and the avoided production of heat. These avoided impacts related to the production of these use full outputs are higher than the impacts caused by the technique itself. For the RK the avoided impact is entirely caused by the avoided production of fuel oil. The difference between the RK end re-refining 3 is not significant.

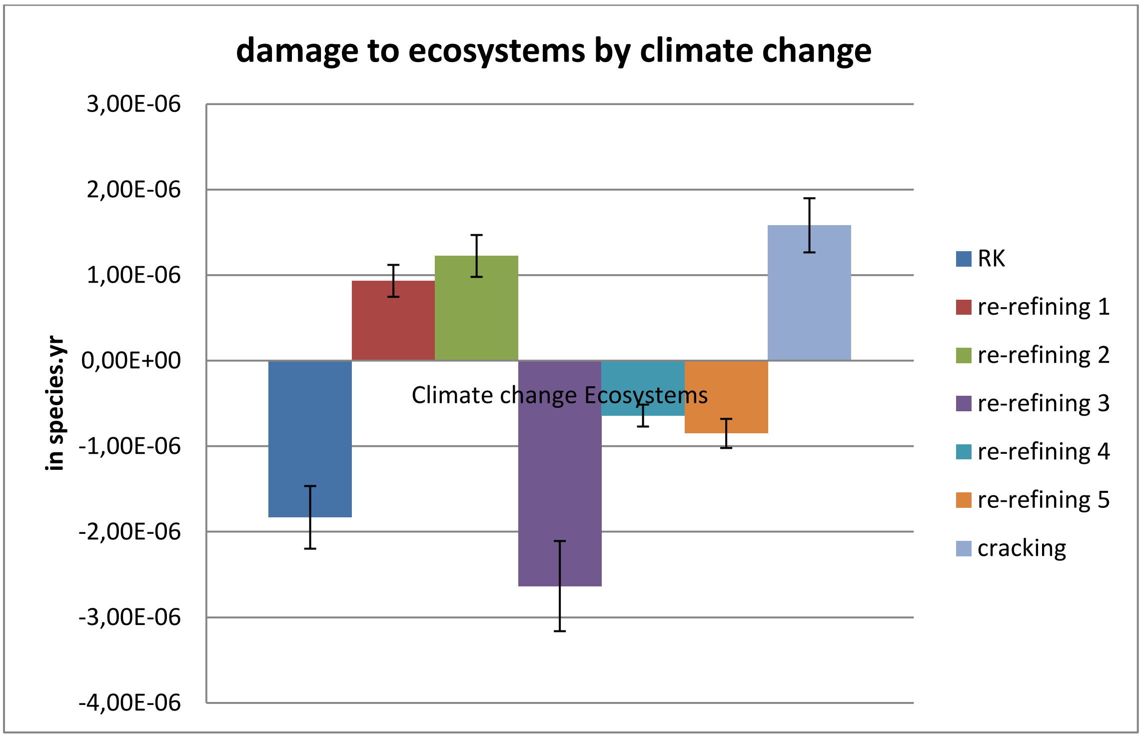

Figure 18 : damage to ecosystems by climate change

5.1.3.3 Damage to resource availability

For the end point indicator 'damage to resource availability' only the midpoint impact category fossil fuel depletion is relevant.

– Fossil fuel depletion

All evaluated techniques avoid the depletion of fossil fuel. The difference between cracking and re-refining 1 is not significant. This is also the case for the RK and re-refining 1, and for the RK and re-refining 2 and 3. Furthermore the differences between re-refining 2 and 5 are not significant. Finally the differences between re-refining 3 and 5 are also not significant.

For re-refining 3 a large part of the avoided impacts are related to the avoided production of base oil, but an almost even large part originates from the efficient use of energetic by-products.

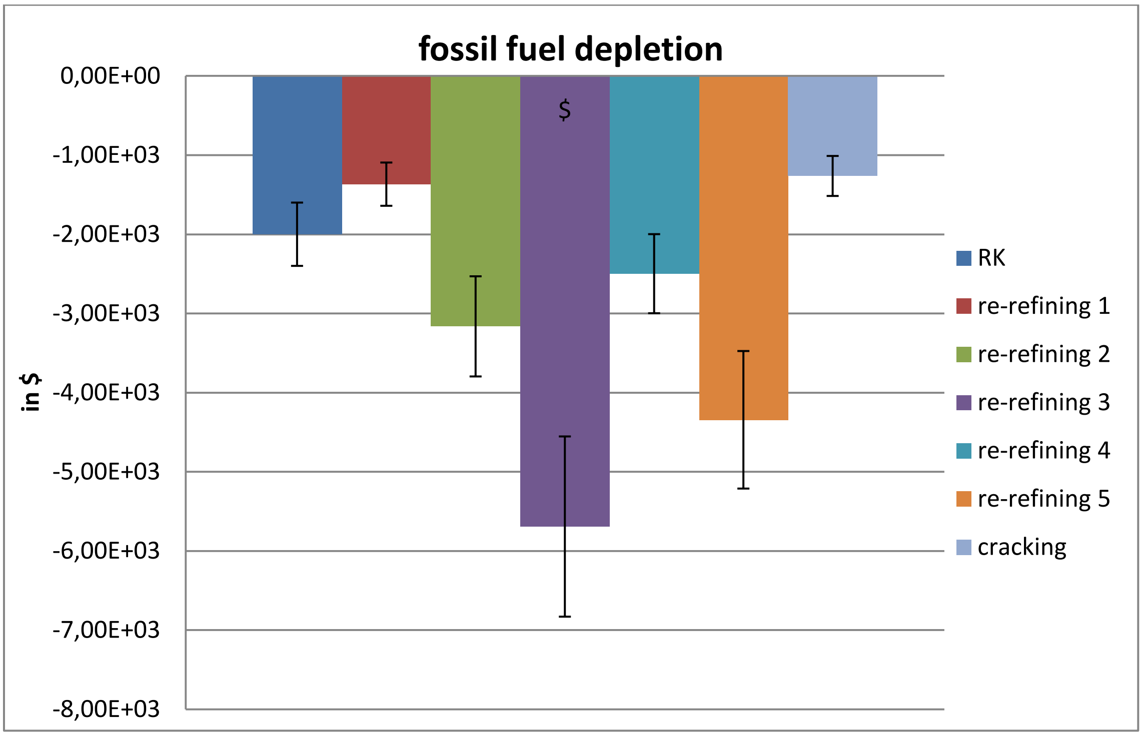

Figure 19 : damage to resources by the depletion of fossil fuel

5.1.4 Sensitivity analysis

5.1.4.1 Impact of transport

Of the evaluated installations only the RK is located in Flanders. Despite conclusions of previous LCA-studies regarding the insignificance of the impact related to transport an additional analysis was conducted to verify these conclusions.

For most impact categories this analysis confirmed the results of previous studies. The impact of 100 km transport of 1 ton of waste oils causes an impact <10% compared to the impacts that are caused or avoided by the treatment facilities evaluated in this study. Only for the impact category 'damage to human health, particulate matter formation' the impact related to transport can amount to 10 times the impact generated by the treatment options, as illustrated in Figure 20. This is however only the case for one of the treatment options. For the other options the impact lies between 5 and 15% (comparison based on the absolute value). A full overview of the results of this analysis is given in annex.

Based on this analysis we can assume that the impact of transport of the waste oil to the treatment facilities will not influence the overall outcome of this study.

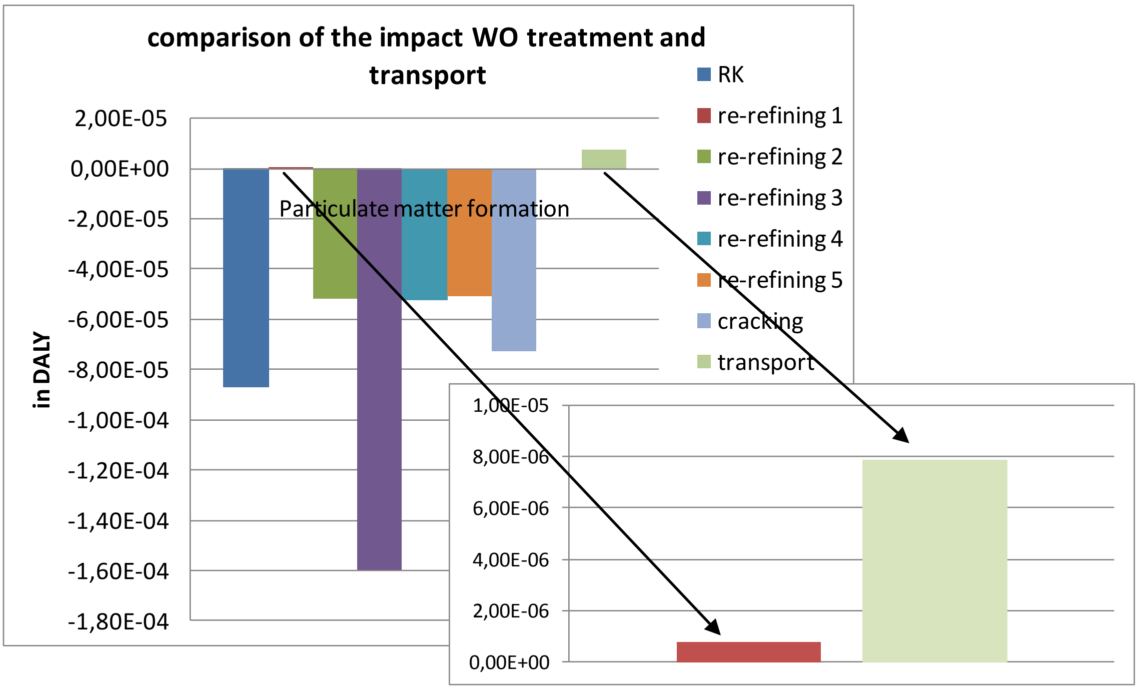

Figure 20 : illustration of the impact related to 100 tkm transport compared to the impact related to the treatment of 1 ton of waste oil

5.1.4.2 Impact of a 75% equivalency factor for base oil production

In the evaluation made above we assumed that the base oil that is produced by the re-refining installations has a quality that is equal to virgin base oil. Because this assumption has a significant influence on the results of the evaluation we made a sensitivity analyses to check the impact of this assumption on the results. We used an equivalency factor of 75%. This percentage is an assumption we made for comparison reasons. It is not intended to make any judgements about the techniques or the information that was supplied.

As can be seen in the results presented in Figure 21 this assumption has a significant influence for the impact categories damage to human health by climate change, damage to human health by toxic substances and damage to ecosystems by climate change.

Based on this analysis we can assume that if the base oil quality that is produced by the re-refining does not match virgin base oil on a 100% equivalency basis, this will have an influence on the results of this study.

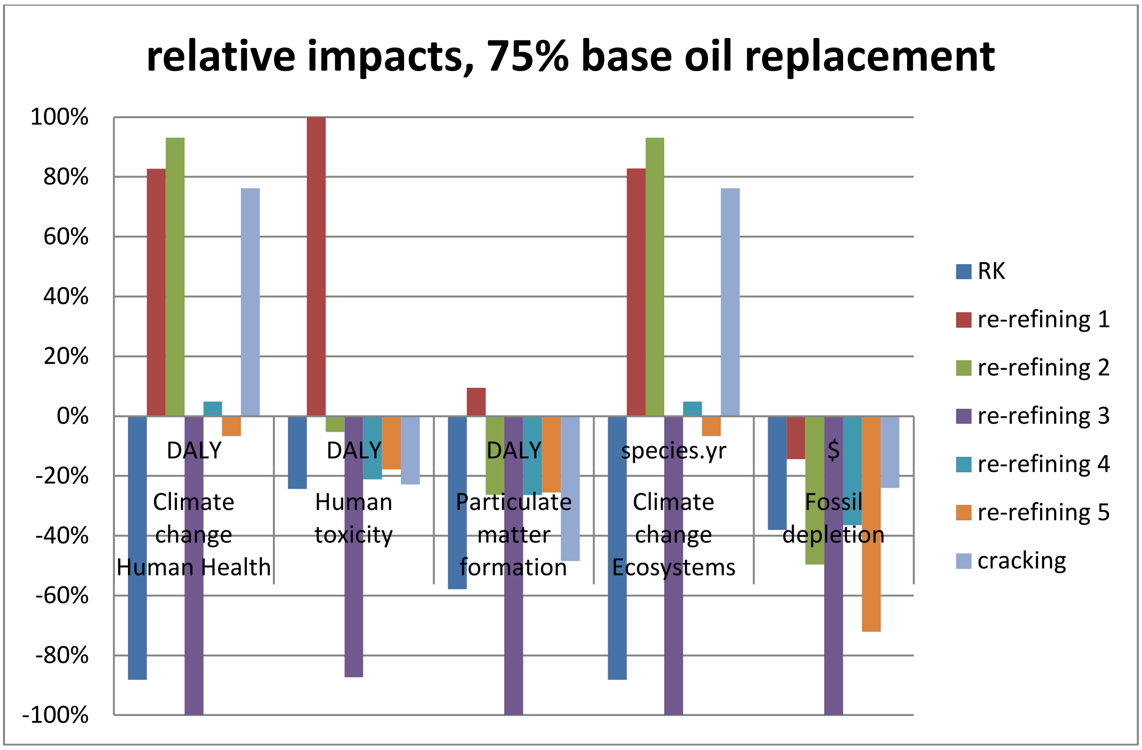

Figure 21 : overview of the relative impacts for the relevant impact categories assuming a base oil equivalent of 75%

5.1.4.3 Incineration of waste oil not replacing fuel oil

In the analysis made above we assumed that waste oil treated in the RK is used as an auxiliary fuel, and therefore replaces 100% virgin fuel oil. If however, waste oil is treated that does not replace auxiliary fuel, the full impacts and credits related to this treatment have to be taken into account. Following figure gives an overview of the impacts related to this treatment.

The incineration of waste oil in the RK generates a significantly higher impact compared to the treatment replacing auxiliary fuel, except for the impact category fossil fuel depletion. This is due to the fact that when waste oil is incinerated there is a net production of steam and electricity in the RK related to this incineration. The produced steam and electricity replaces the production of steam and electricity using virgin fuels. Especially the avoided production of steam has a great influence on this impact category.

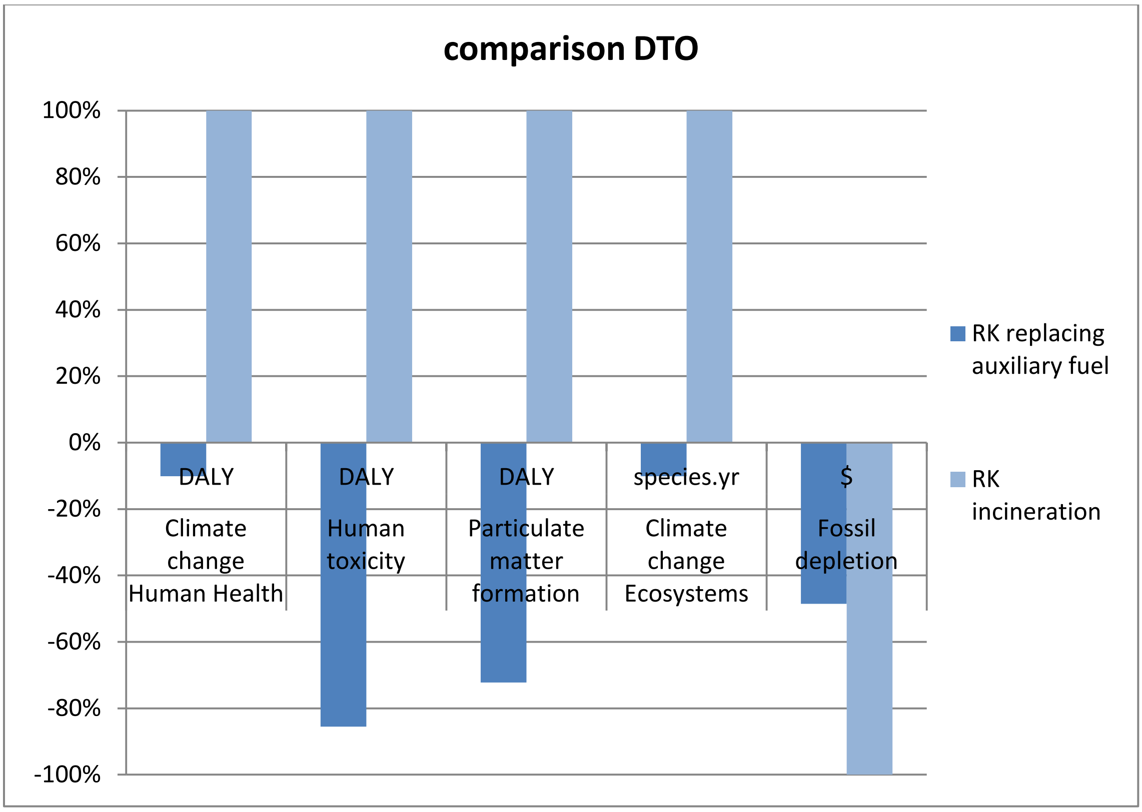

Figure 22 : comparison of the relevant impact categories for two RK options : WO replacing auxiliary fuel vs. incineration

5.1.5 Review of existing comparative studies on waste oil management options

5.1.5.1 Existing LCA studies

Since the very start of conducting standardized Life Cycle Assessments (LCA), researchers have analyzed different options for the treatment of waste oils. For the present report, conclusions of the following studies were taken into consideration:

1. Several LCA studies that were critically reviewed in 2001, commissioned by the European Commission, DG Environment, A2– Sustainable Resources Consumption and Waste.[a]
2. A Life Cycle Inventory Analysis for waste oil in Japan, from 2001[b]
3. An LCA on Californian used oil management methods, from 2003[c]
4. An LCA concerning the ecological and energetic assessment of re-refining used oils to base oils, from 2005 [d]
5. An LCA of a spent lube oil re-refining process, from 2006 [e]

These studies were selected after a web-based literature review because of their relevance.

5.1.5.2 Conclusions of the 2001 critical review

In this study relevant LCA studies were critically reviewed. The final conclusions were drawn on the basis of the results on **three specific regeneration technologies** (vacuum distillation + clay treatment, vacuum distillation + chemical treatment, hydrogen pre-treatment + vacuum distillation), **two burning options** (burning in a cement kiln and in an asphalt plant). The following **environmental impacts** were considered as the most reliable for comparing the waste oil (WO) management options in the reviewed LCAs:

- Consumption of fossil energy resources,
- Contribution to global climate change,
- Contribution to regional acidifying potential,
- Emission of Volatile Organic Compounds (VOC),
- Waterborne emissions,
- Solid waste.

However, waterborne emissions and the solid waste were thought not to constitute adequate indicators to differentiate the WO management options because both the magnitude of the absolute figures and the magnitude of the difference between options were not significant compared to the level of uncertainties linked to an LCA approach. Furthermore, regarding the solid waste, it was not very clear if and how the environmental impacts of the solid residues generated either by the regeneration plant or the burning plant had been assessed.

This critical review led to the following conclusions:

1. From a local impacts perspective, when considering only the recovery treatments, the impacts generated by the regeneration plant are generally lower than those generated by the incineration plant.
2. The environmental performance of an old regeneration process can be improved with a modern technology.

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[a] Taylor Nelson Sofres Consulting (2001).Critical review of Existing Studies and Life Cycle Analysis of the Regeneration and Incineration of WO. 20 AW 83-5, December 2001.
[b] C. Nakaniwa, Y. Yagita, A. Inaba (2001). Life Cycle Inventory Analysis for Waste Oil in Japan. Ecodesign, pp.962, 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign'01), 2001.
[c] Boughton, B. and A. Horvath, Environmental Assessment of Used Oil Management Methods, Environmental Science and Technology, Volume 38, No. 2, January 2004.
[d] Fehrenbach, H. (2005). *Ecological and energetic assessment of re-refining used oils to base oils: Substitution of primarily produced base oils including semi-synthetic and synthetic compounds. Institute for energy and Environmental Research (IFEU). Heidelberg, Germany*
[e] Kalnes, T., Shonnard D**.,** Schuppel, A. (2006). LCA of a Spent Lube Oil Re-refining Process. 16th European Symposium on Computer Aided Process Engineering and 9th International Symposium on Process Systems Engineering. Computer Aided Chemical Engineering,Volume 21, 2006, Pp 713-718.

3. The environmental impacts due to collection and transport of WO and primary materials are not significant within a life cycle perspective compared to the impacts of the industrial processes.
4. The environmental burden of the recovery treatment (regeneration or incineration) by itself is generally less important than the one of the avoided process (virgin base oil production or traditional fuel or energy production).
5. Within a life cycle perspective, the total contribution of the management system under consideration is indeed the result of the difference between two different quantities: the impact of the recovery treatment minus the impact of the main avoided system (this latter representing a bonus). The environmental impacts of WO recovery systems are mainly determined by this bonus and less by the direct impacts of the recovery processes themselves.[a]
6. All the WO recovery options under consideration are favourable in terms of environmental impacts (i.e. they contribute to avoid impacts) by comparison with a ‘do nothing’ system.
7. The amount of the bonus brought by the avoided process is determined by the choice of the substituted process. Especially in the case of the incineration of WO with energy recovery, the type of fuels that the WO replace is crucial: fossil fuel, hydroelectricity, thermal electricity, other wastes….
8. The following issues have not been addressed in the LCAs available and can be considered as gaps: noise, odour, nature conservation (biodiversity, etc.), land use, toxic emissions, the displacement of non fossil fuels by waste oils. As for toxic emissions (heavy metals, organic pollutants…), the LCA methodology is not currently relevant to quantify and compare reliable indicators with respect to human toxicity and ecotoxicity.
9. The following considerations, which may have a significant influence on the environmental impacts have not been covered by the available studies as well: the situations when WO replace other energy sources or wastes and not traditional fuels at the burning plants, and the influence of the base oil quality standard produced and/or regenerated on the environmental impacts of the different management options.
10. Although one of the studies integrates the analysis of a modern regeneration technology under development, the main results from the reviewed LCA studies are based on today's situation and mean technology.

Based on the conclusions drawn in 2001, and assuming the restrictions of the performed review to a few environmental impacts and the limited number of specific techniques, it seems reasonable in future assessments:

a. to redirect the attention from the direct impacts of waste oil recovery processes towards the environmental burdens of the avoided processes, mainly the avoided traditional fuel or energy production;
b. to include those issues - mentioned in conclusion number 9- that have not been addressed earlier, including the issues were local effects are more relevant;
c. to include or allocate effects of (changes in) technology and of oil quality;
d. not to include environmental impacts of collection and transport in a first approach.

5.1.5.3 Conclusions of the 2001 Japanese LCIA

Comparative life cycle inventories were examined and environmental impacts were assessed for the following two cases:

- re-refining waste oil and burning the re-refined oil; and
- extracting crude oil, refining it, and burning the resulting heavy oil.

In order to equalize the two cases, the process of incinerating the waste oil was included in the second, non-re-refining case. The process of power generation from fuel extraction in the re-refining case was also included. Energy consumption and CO_2, NO_x and SO_2 emissions, were compared with using virgin oil.

[a] For that reason, the representativeness of the final results depends more on the representativeness of the data related to the avoided processes than on the ones of the treatment processes.

The results depended on the fuel sources used to generate electricity. It was concluded that the use of virgin oil significantly increased consumption of natural energy resources.

Emissions by combustion largely accounted for the life cycle emissions of virgin oil, because of the very high amount of emission volume per unit when burned as fuel and when the waste oil is incinerated. The comparative system boundaries for [thermal] recycling that were used in this study were said to demonstrate the environmental benefits from reuse, recycling, and waste-to-energy strategies, for the analyzed effects.

The following specific conclusions were drawn:

The Recycling Case (RC) versus the Non-Recycling Case (NRC): Virgin heavy oil, which is used in the NRC, need not be consumed in the RC. The percentage of energy inputs from re-refining is extremely low. Consequently, the stage of burning oil is of greatest concern with respect to energy consumption. Because of the double oil incineration in the NRC, emissions were much higher in the NRC.

The Recycling Case with Power Generation (RCPG) versus the Non-Recycling Case with Power Generation (NRCPG): Results showed that the RCPG consumes less **energy** than the NRCPG. The amount of electricity generated used in the calculations in the RCPG was based on the average amount of power generated in Japan from all sources, including hydraulic and nuclear power and that generated by natural gas, coal, and oil. When this amount would be replaced with the amount of thermal power generated from petroleum, more energy is consumed by RCPG.

Emission of CO_2 from the RCPG was less than that from NRCPG. The RCPG emitted less CO2 than the NRCPG.

SO_2 emission was dependent on the composition of the fuel used and the efficiency of the installed de-sulphurizing equipment. Because most Japanese electricity was from hydroelectric, nuclear or other sources, sulphur content is lower than would be expected from generation from heavy oil only. When the fuel for power generation was replaced by petroleum, the SO_2 emission is higher in the RCPG.

Also in the case of **NOx** the volume of emission was likely to be influenced by the composition of the fuel used to generate electricity.

As was concluded from the 2001 critical review, this study again confirms the relevance of the choice of the substituted products or processes. In this case, an opposite outcome was obtained on consumption of energy, depending whether power generation from Japanese energy mix or from petroleum was being substituted. Similar effects could be observed regarding SO2 en NOx emissions.

5.1.5.4 Conclusions of the 2003 Californian LCA

Life-cycle assessment (LCA) methodology was used to compare California used-oil management methods. The goal of the study was to assess and compare the environmental impacts and benefits of each management method. The combustion of used oil as fuel with energy recovery was compared to two alternative management methods:

- Re-refining of used oil to produce lube oil base stock and other products, and
- distillation of used oil to produce MDO and an asphalt flux by-product

The study concluded that, on the basis of potential human health and environmental impacts, used oil re-refining and distillation were significantly better management practices than combustion of used oil as fuel. The results of the end-of-life impact assessment showed that heavy metal air emissions dominated the comparison of the three used oil management methods studied. The results were not sensitive to re-refining or distillation process yields, energy input rates, or chemical (e.g., NaOH and H_2) consumption rates. The conclusions were also not affected by the range of concentration of contaminants, including the key heavy metals in the used oil.

As it was assumed for this paper that the majority of used oil fuel was combusted in units with limited or no emission controls, results should not be extrapolated to combustion in installations with efficient flue gas cleaning systems and other emission controls.

The results were not sensitive to relevant process parameters of the waste treatment options used as an alternative for burning waste oils.

5.1.5.5 Conclusions of the 2005 German LCA

The study focused on the ecological and energetic aspects of the re-refining of used oil. The conclusions of previous LCA studies representing basically the situation of the 1990's were actualized by:

- Modelling and comparing five advanced techniques of re-refining considering their environmental impact and their environmental benefits because of substituting primary products.
- Comparing an average of the advanced re-refining techniques considered with combustion.

This study addressed several of the limitations that restricted the applicability of the conclusions of previous studies, especially by **updating the used techniques**, **considering human toxicity,** taking into account a **growing share of synthetic or semi-synthetic compounds** in lubricant formulations, and **substitution by secondary fuels**, whilst different **transport distances** were proofed according to different ways of recovery.

All **external processes** due to re-refining (e.g. fuel production or electrical power supply, crude oil drilling and production, digging and mining) were taken into account. Also, downstream processes like waste disposal were included. The analysis of a re-refining option ended where a specified product entered the economic cycle. The quality specification was recognized because **production of an equivalent product** had 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 – were assessed. The benefit of these side-effects was also considered within the system of substituted primary products. The **geographical boundary** corresponded to Europe in terms of provenience of used oil and technical standard. Imported materials – like crude oil or coal from overseas – were likewise considered as far as they are consumed within the systems. The production of input materials that didn't extend 1 % of mass of the reference flow (e.g. used oil in the re-refining plant) were not considered and the sum of neglected materials within one process did not extend 5 % of the reference flow.

The following **impact categories** were considered: resource depletion, global warming, acidification, terrestrial nutrification, and human toxicity with as indicators carcinogenic pollutants and fine particulates. Aquatic impact indicators could be neglected.

The following re-refining techniques were considered:

- A hydro treatment technology;
- Vacuum distillation (using Thin Film Evaporation) and hydrotreating (also known as hydrofinishing);
- HyLube^{TM} technology with special catalysts which are connected in line and the hydrogen which is circulated in the system and is used as an auxiliary material as well as an energy source;
- A solvent extraction technique
- Revivoil technique, with hydrogen at high pressure and hydrofinishing

The following conclusions were drawn from the comparison between the five regeneration techniques:

1. 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. **Differences** between the five techniques **are** relatively **low**.
3. The **most beneficial** re-refining techniques are those with a **high yield of regenerated base oil** and additional benefits from by-products.

An average regeneration technique was then compared with combustion. As the most decisive aspect concerning comparative eco-balancing of combustion is the character of fuel substituted, as former studies show, the comparison in this assessment was 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.

The study states that 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 would adapt the fuel band. So the determination of a certain fuel type for an eco-balancing assessment reflecting the current situation is naturally a snap-shot that might differ in the near future.

General conclusions of the study were:

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.
2. A direct comparison of regeneration and primary base oil refining shows, in terms of energy demand, a **high efficiency of the considered** recovery and innovative re-refining **techniques**.
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. This is due to the fact that the production of synthetic oil has a higher environmental impact compared to the production of mineral oil. By regenerating waste oil the production of primary synthetic oil is avoided.
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.
    a. 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.
    b. In the second case, the advantages are 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 assessment shows a trend strengthening the pros for re-refining and weakening the (unique) draw-back.

This study again confirms the relevance of the choice of the substituted fuels, uncovering furthermore the impacts of developments regarding oil quality and allocation by secondary fuels.

5.1.5.6 Conclusions of the 2006 HyLubeTM LCA

A life cycle analyses of a re-refining technology, the HyLube^{TM} process, was undertaken to quantify the intrinsic benefits of HyLube re-refining over the current practice of recovering used oils for fuel value. The study modelled the effects of the re-refining of used oil generated on the European market, by the HyLube process. These effects were then compared to the impacts of burning the same oil in cement kilns as a substitute for the primary energy sources of either coal, heavy fuel oil (HFO) or natural gas. For combustion in a cement kiln, only the avoided flows of coal, HFO, or natural gas were modelled.

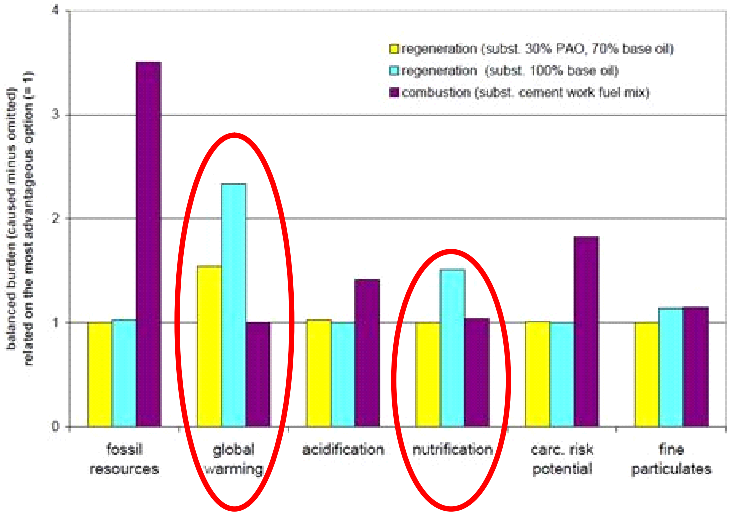
Four impact categories were considered: cumulative energy demand, climate change, acidification/eutrophication, and fossil fuel use. Data on emissions from cement kilns, especially for metals, has not been included, and therefore toxicological effects are limited to fuels production steps.

General conclusions of the study per impact category were:

1. The greatest **savings of energy** is achieved by re-refining of used oil (UO) in the HyLube process. This maximum benefit is realized by avoiding the production of virgin base oil, fuel oil and diesel in a refinery, and synthetic oil(s) in petrochemical plants. The next best alternative is combustion of UO with displacement of fuel oil, followed by displacement alternatives of natural gas and then coal. The maximum difference in energy savings among these alternatives is only 16%.
2. The greatest benefit for **climate change** is for the case of UO combustion with coal displacement. The next best case is re-refining, followed by UO combustion with fuel oil displacement. The least desirable alternative for climate change is UO combustion with natural gas displacement. When UO displaces natural gas in cement kiln combustion, a higher rate of CO2 release occurs, but this increase is almost exactly compensated for by avoiding emissions from natural gas production.
3. For the category of **acidification / eutrophication**, re-refining of UO is the best alternative. The least desirable alternative for this category is UO combustion with coal displacement.
4. For **fossil fuel consumption**, the best alternative is re-refining of UO followed closely by UO combustion with displacement by either fuel oil or natural gas. The least desirable alternative for fossil fuel consumption is the alternative using coal displacement and UO combustion.

5.1.5.7 Conclusions of comparative waste oil management studies

1. The environmental burden of the recovery treatment (regeneration or incineration) by itself is generally less important than the one of the avoided process (virgin base oil production or traditional fuel or energy production).
2. The environmental impacts of WO recovery systems are mainly determined by the bonus brought by the avoided process and less by the direct impacts of the recovery processes themselves.
3. The amount of the bonus is determined by the choice of the substituted process. Especially in the case of the incineration of WO with energy recovery, the type of fuels that the WO replace is crucial: fossil fuel, hydroelectricity, thermal electricity, other wastes…., which is reflected most clearly in the global warming impact category. The greater the environmental impact of the displaced fuel, the greater the avoided burden of waste oil incineration. For instance, displacing coal, with a higher emission of CO2 per unit of fuel energy compared to other fuels, lower greenhouse emissions will occur.
4. Only in the following cases (see Figure 23), the environmental impacts of modern re-refining techniques were higher than those of the incineration of the waste oil:
    a. In the climate change (formerly global warming) impact category when displacing coal or a hard coal and pet coke mix in cement kilns.
    b. In the nutrification impact category when displacing a hard coal and pet coke mix with used oil (only when the regenerated oil substituted 100% virgin mineral base oil).



Source: Adapted from Fehrenbach, H. (2005)

Figure 23 : balanced burden of regeneration vs. combustion options

5. In the fine particulates impact category differences between modern re-refining techniques and burning in a cement kiln were very small.

Results of existing LCA and LCIA studies suggest, in general, that environmental impacts of different waste oil treatments are in line with what could be expected based on the waste hierarchy. The environmental burden of the different treatment options of waste oil is less important than the impacts of the avoided processes, whilst the magnitude of the avoided burden is determined by the primary or secondary fuels or fuel mixes that are substituted.

5.1.6 Conclusion

The evaluation shows that the most important impact categories include damage caused by climate change (both to human health and the ecosystem) and fossil fuel depletion. This could be expected as on the one hand the treatment techniques are quite energy consuming and on the other hand the avoided useful outputs are in all cases petroleum derivatives. This is also very clear when the impacts are presented as a single score. The average weighing factors used to calculate this single score are:

- Damage to Human Health : 40%
- Damage to ecosystems : 40%
- Damage to resource availability : 20%

In the interpretation of the figure below it has to be kept in mind that the rules of thumb to define whether the results of techniques are different or not (as given in §5.1.2) also apply for this figure.

The results are presented in Figure 24. It shows that all evaluated techniques have a net avoided impact. Furthermore this figure confirms the results presented above. But additionally shows that also damage to human health by particulate formation has a relevant impact. The presence of heavy metals and sulphur in the treated waste oil generates an impact when incinerated in the RK, but this impact is compensated by the avoided production of fuel oil.

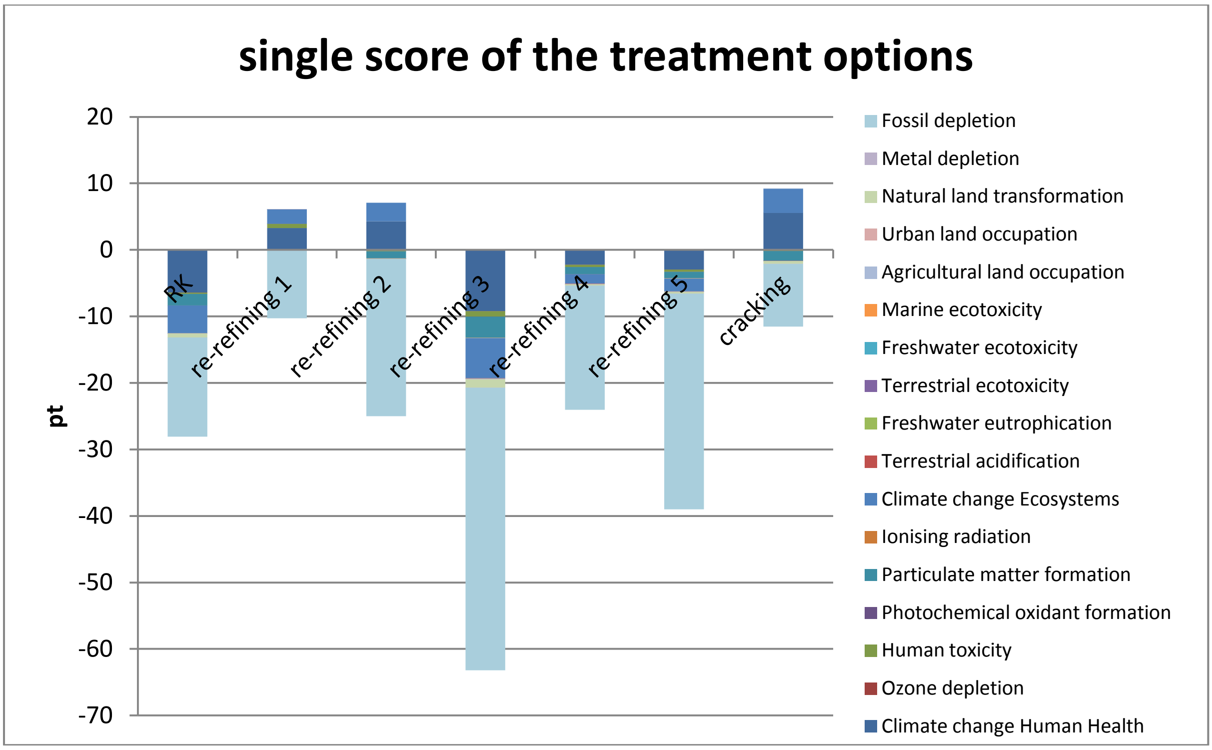


Figure 24: overview of the single scores of the different treatment options

The environmental profiles show that the differences in environmental impacts related to the different re-refining techniques themselves can be similar to the differences between these techniques and the RK and cracking. This makes it inappropriate to define one average re-refining technique.

Re-refining technique 3 is the re-refining technique with the best single score. This score is mainly a result of the maximisation of the (internal) re-use of energetic fractions rather than maximising the production of base oil. Even more, despite the fact that this technique has the best overall environmental performance, it does not meet the criterion stated in the BREF Waste Treatment that re-refining processes of waste oil should achieve a yield higher than 65%. This shows that an assessment of environmental impacts and Best Available Technique evaluation do not always go hand in hand and that an evaluation to check if the treatment techniques are compliant with the BREF would be complementary to the current assessment of the techniques.

It is noted that for all studied waste oil treatment options, the extraction of crude oil and the subsequent desalting process were left out of the inventory analysis, and were considered to take place outside the boundaries of the studied system. It was thus assumed that the impacts of crude oil extraction are equal for all avoided oil products. If these impacts would be taken into account, the benefits that result from avoiding crude oil extraction would be considerably higher for most impact categories.

Concerning impacts related to climate change (both to human health as on ecosystems) re-refining techniques 1 and 2 and cracking have a net impact. The differences between these techniques are not significant. The other techniques avoid impacts for this impact category. The difference between the re-refining 4 and 5 is not significant. The same goes for the difference between RK end re-refining 3.

For the impact categories damage to human health by toxic substances and particulate matter only re-refining 1 causes a (small) net impact. The differences in impact between RK, re-refining 2, 4, 5 and cracking are not significant.

For the impact category fossil fuel depletion all techniques avoid impact.

The sensitivity analysis shows that impacts related to transport are small. Therefore it can be assumed that the difference in transport distances between the different treatment facilities will not lead to significant differences in the results. Furthermore it shows that if the produced base oil replaces base oil on a 75% equivalency base (instead of the assumed 100%), this has a significant influence on the environmental profiles of the re-refining techniques.
Finally, an additional analysis shows that if waste oil is incinerated in the RK as hazardous waste (and not as an auxiliary fuel) this will cause a significant higher impact compared to the use as an auxiliary fuel, except for the impact category fossil fuel depletion.

5.2 Social, economical and socio-economical impacts

5.2.1 Method

A wide range of analytical and procedural methods is available to assess social and socio-economical impacts of products and processes, within the frame of Life Cycle Thinking. As the need for analytical tools for decision-making and policy support is growing, the use of the method of Social Life Cycle Assessment is increasingly accepted, mainly at product level. Recent examples are the socio-economic assessment of the refurbishing and e-waste recycling sector in Ghana[a], and assessment of social impacts of the production of notebook PCs in China[b].

An SLCA is a social impact (and potential impact) assessment technique that aims to assess the social and socio-economic aspects of products and their potential positive and negative impacts along their life cycles encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal.[c] It can be applied separately, or in combination with an environmental LCA.

Social Life Cycle Assessment (SLCA) is at a young stage of development. Kloepffer (2008)[d] states that the central problems seem to be how to relate the social indicators (social impact assessment) to the functional unit of the product-system and how to restrict the many social indicators proposed to a manageable number. Meanwhile, qualitative and semi-quantitative approaches are used as substitutes for a full, quantitative SLCA.

In a stakeholder approach, different socio-economic indicators are allocated to pre-defined stakeholder categories. Social impacts can also be classified by impact categories. Furthermore, subcategories can be distinguished and classified both by stakeholder categories and by impact categories. The subcategories are socially significant themes or attributes. They are assessed by the use of inventory indicators, measured by unit of measurement (or variable). Several inventory indicators and units of measurement/reporting types may be used to assess each of the subcategories. Inventory indicators and units of measurement may vary depending of the context of the study. An example of stakeholder categories and subcategories is given in Table 23.[e]

Stakeholder categories	**Subcategories**
Stakeholder "worker"	Freedom of Association and Collective Bargaining
	Child Labour
	Fair Salary
	Working Hours
	Forced Labour
	Equal opportunities/Discrimination
	Health and Safety
	Social Benefits/Social Security
Stakeholder "consumer"	Health & Safety
	Feedback Mechanism
	Consumer Privacy
	Transparency

[a] *Prakash, S, Manhart A, Amoyaw-Osei Y, Agyekum O (2010). Socio-economic assessment and feasibility study on sustainable e-waste management in Ghana. Commissioned by the Inspectorate of the Ministry of Housing, Spatial Planning and the Environment of the Netherlands (VROM-Inspectorate) and the Dutch Association for the Disposal of Metal and Electrical Products (NVMP). Öko-Institut e.V. & Green Advocacy Ghana. Freiburg, Germany / Accra, Ghana, August 2010.*

[b] *Manhart, A; Grießhammer, R. (2006). Social impacts of the production of notebook PCs - Contribution to the development of a Product Sustainability Assessment (PROSA). Freiburg, 2006.*

[c] *JRC (2010) Supporting environmentally sound decisions in waste management A technical guide to life cycle thinking and assessment in waste management for waste experts and LCA practitioners.*

[d] *Kloepffer, W. (2008). Life Cycle Sustainability Assessment of Products (with Comments by Helias A. Udo de Haes, p. 95). International Journal of Life Cycle Assessment 13 (2) 89–95*

[e] *Guidelines for Social Life Cycle Assessment of Products. (2009), available on www.unep.fr/shared/publications/pdf/DTIx1164xPA-guidelines_sLCA.pdf*

	End of life responsibility
Stakeholder "local community"	Access to material resources
	Access to immaterial resources
	Delocalization and Migration
	Cultural Heritage
	Safe & healthy living conditions
	Respect of indigenous rights
	Community engagement
	Local employment
	Secure living conditions
Stakeholder "society"	Public commitments to sustainability issues
	Contribution to economic development
	Prevention & mitigation of armed conflicts
	Technology development
	Corruption
Value chain actors* not including consumers	Fair competition
	Promoting social responsibility
	Supplier relationships
	Respect of intellectual property rights

Table 23: Examples of stakeholder categories and subcategories in S-LCA

To assess the economical impact of waste oil treatment, a short analysis of some key figures on the waste oil treatment sector was performed.

5.2.2 Results

All the facilities where Flemish MBO-subject waste oil is treated are located in Belgium, Germany, France and the Netherlands. These countries integrate global organisations and networks that actively promote social and economical development and sustainability, and are all member states of the European Union, where common European regulations and standards regarding to socio-economic issues apply. Furthermore, they all have similar UNDP Human Development Index (HDI) values, as is shown in Table 24.

Country	HDI (2010)	Ranking
Belgium	0,867	18
France	0,872	14
Germany	0,885	10
Netherlands	0,890	7

Source: http://hdr.undp.org/en/media/HDR_2010_EN_Table1_reprint.pdf

Table 24: Human Development Index (2010)

In this context it is relatively safe to assume that no important differences exist between potential social and socio-economical indicators for the different subcategories that are listed in Table 23. To corroborate this assumption, a detailed assessment with sector or installation specific data should be performed.

Actually, MBO-subject waste oils have a positive economic value that varies depending on the waste oil characteristics, the presence or concentrations of certain components, the crude oil prices and the suitability for re-use or recycling. Sector related sources revealed values between 70 and 220€ per ton. Considering the total Factors that determine the economic value of MBO-subject waste oils include Total Acid Number, flashpoint, viscosity, content of chlorines, sulphur, heavy metals, esters, water, sediments, etcetera. MBO-subject waste oils that are not suitable for recycling can still be used as auxiliary fuel in a hazardous waste incinerator. Nevertheless, the demand of these waste burners is limited to the need for auxiliary fuels, which actually represents only about 4% of the total volume of Flemish waste oils. When the need for auxiliary fuel is exceeded, there is no more replacement of primary fossil fuels, and waste oil is then burned as any hazardous waste, with energy recovery.

From the above it can be concluded that the value of the total volume of the Flemish MBO-subject waste oil at the gate of the treatment facilities lies somewhere in between 3 and 6,5 million euro.

The considered waste oil treatment facilities that carry out incineration, thermal cracking and re-refining activities operate within a formal and mature European economic sectoral frame and all form part of multinational companies based abroad. Economic and social benefits (and eventual burdens) generated by the treatment of Flemish waste oil will thus be realized for a large part outside of Flanders. This was also the case for the avoided environmental impacts, which are determined basically by the avoided production of the substituted primary fossil resources.

To be able to perform a basic economic assessment, in Table 25 the value of the primary fossil substitutes of the outputs generated by the different treatments is calculated. No additional figures on volumes and waste oil values at the entrance gate of treatment facilities were included for reasons of confidentiality.

The first column of Table 25 presents the treatment options for Flemish waste oils under study, being considering the use as auxiliary fuel in a rotary kiln, thermal cracking and re-refining.
In the second column, the different primary products are listed that could be substituted by the different outputs of the treatment processes. The approximate yield of each of these outputs per ton waste oil input is given in the next column. It is assumed for this exercise that every ton of waste oil that arrives at the re-refining or the cracking facility effectively is re-refined or cracked. For the outputs of thermal cracking, the values of Table 10 were used. For the re-refining outputs the process yields given in the Valorlub report were considered, with base oil representing between 65 and 75% of the output, gasoil between 10 and 15%, and a bituminous fraction from between 10 and 12%. The market value (February – May 2011) of each of the primary products that could be substituted by the treatment outputs are given in column four. For reasons of simplicity, it is assumed that one ton of output perfectly substitutes one ton of primary fossil product. In general, on the real market, the origin from waste as well as eventual differences in quality will cause the treatment outputs to have a lower market price than the substituted primary products.

With the above information, the total value of all substituted primary products can be calculated for the three studied treatments, in relative terms per ton (column five). So, the last column reflects the total equivalent product value per ton of treated waste oil. By subtracting the value of the input waste oil from the total substituted product value, a net added value per ton of waste oil could be obtained. The absolute value of substituted fossil products will be the highest for the re-refining facilities of Flemish MBO-covered waste oil, as re-refining is by far the most important destiny of this oil.

The table shows that the difference between the sum of equivalent output values of the re-refining option on one hand and the use of auxiliary fuel on the other, is only €33 per ton of waste oil. Therefore, from the moment that the waste oil price paid by the re-refining facility operator is at least €33 higher than the price paid for the waste oil to be used as an auxiliary fuel, the highest net added value will be achieved by burning the waste oil as auxiliary fuel, where each ton of waste oil replaces a ton of gasoil. From the moment that all required auxiliary fuel is replaced, the net added value of this treatment is replaced by the value of the electricity (or heat) generated by one ton of waste oil minus the gate price of the waste oil, which under actual market conditions would result in a negative figure.

It is noted that the above mentioned net added value per ton of waste oil will be distributed between company profits and production and capital costs associated with a particular waste oil treatment.

Treatment option	Equivalent output	Ton eq. output per ton waste oil	Equivalent primary product value (€/ton)	Equivalent output value per ton waste oil (€/ton)	Sum of equivalent output values per ton waste oil (€/ton)
Auxiliary fuel	Replaced gasoil	1,00	645(1)	645	645
Thermal cracking	Naphtha	0,12	690(2)	83	585
	Gasoil	0,67	645(1)	432	
	Heavy fraction	0,14	498(3)	70	
Re-refining	Base oil	0,70	802(4)	561	678
	Gasoil	0,12	645(1)	77	
	Bitumen	0,11	360(5)	40	

(1) www.tijd.be/grondstoffen/olieproducten, Prijs Excl. BTW Gasolie, lichte stookolie (+2000 l) 0,6451 €/l on 21/05/2011, and assuming 1 litre = 1000 gram

(2) www.tijd.be/grondstoffen/olieproducten, Prijs Nafta FOB (Rotterdam barges), on 29/05/2011, 984,83 US$/mT, with 1€ = 1,4272 US$

(3) www.tijd.be/grondstoffen/olieproducten, Prijs Excl. BTW Gasolie, extra zware 1,0%, 498,3719 €/ton 21/05/2011

(4) www.argusmedia.com, Prices effective 14 January 2011, Europe, Group I SN 150 fob domestic NEW, Low, 1.070 US$/t, with 1€ = 1,3349 US$

(5) www.argusmedia.com, European bitumen prices, Rack prices, fob, 21-25 feb. 2011, Belgium – Antwerp, Low, 360 €/ton, including 31€/t tax

Table 25: Economic considerations on the selected waste oil treatment options

The fact that waste oil can often be readily used as a substitute fuel oil will tend to give it a market value a little below premium quality new fuel oils. Such market value will apply similarly to oils that could be subjected to regeneration processes, thereby establishing what is in effect a minimum raw material feedstock price for regeneration processes. Regenerated products such as lubricants cannot usually command prices higher than premium quality new materials - in fact they would usually sell for somewhat less. Thus, regeneration processes are constrained both by feedstock and product prices dictated by oil product prices generally, and the margin between feedstock costs and product income must cover the total regeneration process costs if the activity is to be economically viable.

6 Conclusions

A thorough analysis of both the waste oil market covered by the Flemish Environmental Agreement and several treatment techniques for this waste oil, shows that the waste oil business is very complicated. This is because of the flexibility of treatment installations to accept waste oil and to produce a variety of useful outputs and the possibility of integration and interaction with other, large (and often complex) petrochemical installations. This integration and flexibility have as a side effect that it is not always clear whether the final destination of waste oil that is transported and delivered to recovery facilities will be treated using the anticipated technique(s).

The assessment shows that the environmental profiles of the considered treatment techniques (use as auxiliary fuel in a rotary kiln, 5 re-refining techniques, 1 cracking technique) are dominated by the impacts related to climate change and fossil depletion. This could be expected as on the one hand the treatment techniques are quite energy consuming and on the other hand the produced useful outputs are in all cases petroleum derivatives. The presence of heavy metals, sulphur and chlorine in the waste oil (which can be considered parameters with a potential environmental impact) does not or nearly influence the environmental profiles of the treatment techniques.

When the environmental impacts are combined to a single score, all treatment techniques have a net avoided impact, because the impacts of the treatment technique itself are more than compensated by the avoided impacts of the useful outputs. This means that the treatment of waste oil by all these techniques results in a net environmental benefit and to saving resources in general. It is further noted that for all studied waste oil treatment options, the extraction of crude oil and the subsequent desalting process were left out of the inventory analysis, and were considered to take place outside the boundaries of the studied system. It was thus assumed that the impacts of crude oil extraction are equal for all avoided oil products. If these impacts would be taken into account, the benefits that result from avoiding crude oil extraction would be considerably higher for all impact categories.

The environmental evaluation of the treatment techniques under study shows that the variation in environmental impacts related to the different re-refining techniques can be larger than the variation between these techniques and the rotary kiln and/or cracking. Because of this variation it is inappropriate to define one average re-refining technique that is representative for all re-refining techniques. Furthermore, it proves the diversity of re-refining techniques that exist today and makes it impossible to make a clear general prioritisation between rotary kiln, cracking and re-refining.

The use of waste oil in a rotary kiln will only avoid impacts as long as this waste oil replaces auxiliary fuel during normal operation of the rotary kiln to maintain optimal temperature conditions. Under these circumstances, waste oil incineration constitutes a R1 recovery operation. The use of waste oil as auxiliary primary fuel replacement during installation start-up and shut-down is not permitted, and the incineration of waste oil just as hazardous waste is not in the scope of the present study. However this practice is self regulating, as the operator of the rotary kiln will only be willing to pay for the waste oil as long as it actually replaces auxiliary fuel oil (and wants to be paid for incinerating waste oil as a waste).

When comparing the different re-refining techniques, it is remarkable that the electricity use of re-refining 1 is high compared to the other re-refining techniques (3 to 7 times higher). This electricity use has a negative impact on the environmental profile of this technique, despite the high base-oil yield of this process. Re-refining 2 has a high energy demand, that is only partly covered internally. This technique has a large external input of energy under the form of steam that is modelled as produced with natural gas. This natural gas use has a significant influence on the environmental results, especially for the impact categories related to climate change.

The evaluation shows that re-refining 3, the treatment technique with the best environmental performance (based on the single score), focuses on the maximisation of (internal) re-use of energetic fractions rather than optimising the production base oil.
The environmental profiles of re-refining 4 and 5 indicate that they use comparable techniques. The results of these techniques show no significant differences, except for the impact category fossil fuel depletion. This difference can be found in the net external energy demand by re-refining 5 whereas re-refining 4 has a more optimised coverage of its energy demand (internal use plus a net deliverance of process heat).

Analysis of the comparison between cracking technique and the re-refining techniques reveals that the energy use of the cracking is low compared to the re-refining processes. However, the avoided impacts related to the produced outputs of this process are predominantly lower than the avoided impacts related to base oil production. Therefore the net impact that is caused by this process is less compensated compared to the processes that produce base oil.

In Table 26 the conclusions from 5 comparative waste oil treatment studies, as described in 5.1.5, are set out against the conclusions that are drawn from the results of the present study.

Study[a]	Conclusion	Actual results
1	The environmental impacts due to collection and transport of WO and primary materials are not significant within a life cycle perspective compared to the impacts of the industrial processes.	Confirmed for transport of collected oil to treatment facility, for transports < 100 km
1	The environmental burden of the recovery treatment by itself is generally less important than the one of the avoided process	Confirmed
1	The environmental impacts of WO recovery systems are mainly determined by this bonus and less by the direct impacts of the recovery processes themselves	Confirmed
1	All the WO recovery options under consideration are favourable in terms of environmental impacts	Confirmed
1,2,5	The amount of the bonus brought by the avoided process is determined by the choice of the substituted process.	Not analysed
1	The following considerations, which may have a significant influence on the environmental impacts have not been covered by the available studies as well: the situations when WO replace other energy sources or wastes and not traditional fuels at the burning plants, and the influence of the base oil quality standard produced and/or regenerated on the environmental impacts of the different management options.	A sensitivity analysis was performed on the influence of base oil quality standard regenerated
1	The following issues have not been addressed in the LCAs available and can be considered as gaps: noise, odour, nature conservation (biodiversity, etc.), land use, toxic emissions, the displacement of non	Not covered

[a] Studies:

1. Taylor Nelson Sofres Consulting (2001).Critical review of Existing Studies and Life Cycle Analysis of the Regeneration and Incineration of WO. 20 AW 83-5, December 2001.
2. C. Nakaniwa, Y. Yagita, A. Inaba (2001). Life Cycle Inventory Analysis for Waste Oil in Japan. Ecodesign, pp.962, 2nd International Symposium on Environmentally Conscious Design and Inverse Manufacturing (EcoDesign'01), 2001.
3. Boughton, B. and A. Horvath, Environmental Assessment of Used Oil Management Methods, Environmental Science and Technology, Volume 38, No. 2, January 2004.
4. Fehrenbach, H. (2005). Ecological and energetic assessment of re-refining used oils to base oils: Substitution of primarily produced base oils including semi-synthetic and synthetic compounds. Institute for energy and Environmental Research (IFEU). Heidelberg, Germany
5. Kalnes, T., Shonnard D**.,** Schuppel, A. (2006). LCA of a Spent Lube Oil Re-refining Process. 16th European Symposium on Computer Aided Process Engineering and 9th International Symposium on Process Systems Engineering. Computer Aided Chemical Engineering,Volume 21, 2006, Pp 713-718.

	fossil fuels by waste oils. As for toxic emissions (heavy metals, organic pollutants…), the LCA methodology is not currently relevant to quantify and compare reliable indicators with respect to human toxicity and ecotoxicity.	
3	The results [of comparison between burning with energy recovery and distillation or re-refining] were not sensitive to re-refining or distillation process yields, energy input rates, or chemical (e.g., NaOH and H_2) consumption rates. The conclusions were also not affected by the range of concentration of contaminants, including the key heavy metals in the used oil.	Not analysed
4	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	Confirmed
4	A direct comparison of regeneration and primary base oil refining shows, in terms of energy demand, a **high efficiency of the considered** recovery and innovative re-refining **techniques**	Could not be analysed (data confidentiality)
4	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.	Not covered
4	In comparison with utilities, other than cement ovens, substituting fuel oil by used oil the advantages are 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	Not covered
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.	Not covered

Table 26: Results set out against conclusions of comparative waste oil treatment studies

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Annex Detailed results environmental impacts

Results at the mid-point level

Impact category	Unit	RK	re-refining 1	re-refining 2	re-refinig 3	re-refining 4	re-refining 5	cracking
Climate change	kg CO2 eq	-2,31E+02	1,18E+02	1,54E+02	-3,32E+02	-8,09E+01	-1,07E+02	2,00E+02
Ozone depletion	kg CFC-11 eq	-4,41E-05	-1,95E-05	-6,93E-04	-1,09E-04	-3,30E-05	-7,44E-05	-4,23E-05
Human toxicity	kg 1,4-DB eq	-1,40E+01	4,49E+01	-1,43E+01	-5,91E+01	-2,40E+01	-2,16E+01	-1,31E+01
Photochemical oxidant formation	kg NMVOC	-7,74E-01	-1,65E-01	-1,52E+00	-1,57E+00	-5,93E-01	-6,48E-01	-5,30E-01
Particulate matter formation	kg PM10 eq	-3,34E-01	2,84E-03	-1,99E-01	-6,13E-01	-2,01E-01	-1,94E-01	-2,80E-01
Ionising radiation	kg U235 eq	-1,75E+01	5,29E+01	-2,73E+01	-4,52E+01	-2,34E+01	-2,25E+01	4,96E+01
Terrestrial acidification	kg SO2 eq	-1,13E+00	1,35E-02	-6,27E-01	-2,14E+00	-6,45E-01	-6,14E-01	-1,08E+00
Freshwater eutrophication	kg P eq	-2,32E-02	6,71E-02	-2,02E-02	-5,99E-02	-3,03E-02	-2,94E-02	-8,80E-03
Marine eutrophication	kg N eq	-1,64E-01	-5,18E-03	-1,37E-01	-4,32E-01	-1,81E-01	-1,77E-01	-8,58E-02
Terrestrial ecotoxicity	kg 1,4-DB eq	1,04E-02	1,36E-03	-9,39E-03	-2,63E-01	-3,14E-02	-1,24E-02	-2,51E-02
Freshwater ecotoxicity	kg 1,4-DB eq	-5,04E-01	8,88E-01	-3,47E-01	-1,27E+00	-5,37E-01	-4,97E-01	-2,49E-01
Marine ecotoxicity	kg 1,4-DB eq	-3,13E-01	8,93E-01	-3,78E-01	-2,94E+00	-6,88E-01	-5,70E-01	-3,30E-01
Agricultural land occupation	m2a	-3,68E-01	5,80E-01	-6,20E-01	-1,30E+00	-9,23E-01	-8,86E-01	1,00E-01
Urban land occupation	m2a	-6,67E-01	-2,17E-01	-4,52E-01	-1,56E+00	-6,51E-01	-6,41E-01	-4,18E-01
Natural land transformation	m2	-1,76E-01	-3,38E-02	-3,08E-02	-3,92E-01	-7,72E-02	-1,21E-01	-1,32E-01
Water depletion	m3	-1,22E+00	-3,20E+01	-3,09E+01	-2,46E+01	-3,15E+01	-2,97E+01	-5,20E-01
Metal depletion	kg Fe eq	-1,80E+00	1,14E+00	-1,64E+00	-4,82E+00	-1,74E+00	-2,09E+00	-8,17E-01
Fossil depletion	kg oil eq	-1,24E+02	-8,49E+01	-1,97E+02	-3,54E+02	-1,55E+02	-2,70E+02	-7,87E+01

Results at the end point level

Impact category	Unit	RK	re-refining 1	re-refining 2	re-refining 3	re-refining 4	re-refining 5	cracking
Climate change Human Health	DALY	-3,23E-04	1,65E-04	2,16E-04	-4,65E-04	-1,13E-04	-1,50E-04	2,79E-04
Ozone depletion	DALY	-1,17E-07	-5,22E-08	-1,83E-06	-2,87E-07	-8,70E-08	-1,97E-07	-1,13E-07
Human toxicity	DALY	-9,80E-06	3,14E-05	-1,00E-05	-4,13E-05	-1,68E-05	-1,51E-05	-9,17E-06
Photochemical oxidant formation	DALY	-3,02E-08	-6,43E-09	-5,94E-08	-6,11E-08	-2,31E-08	-2,53E-08	-2,07E-08
Particulate matter formation	DALY	-8,68E-05	7,40E-07	-5,16E-05	-1,59E-04	-5,24E-05	-5,06E-05	-7,27E-05
Ionising radiation	DALY	-2,88E-07	8,68E-07	-4,48E-07	-7,42E-07	-3,83E-07	-3,68E-07	8,13E-07
Climate change Ecosystems	species.yr	-1,83E-06	9,33E-07	1,22E-06	-2,64E-06	-6,42E-07	-8,51E-07	1,58E-06
Terrestrial acidification	species.yr	-6,56E-09	7,80E-11	-3,64E-09	-1,24E-08	-3,74E-09	-3,56E-09	-6,25E-09
Freshwater eutrophication	species.yr	-1,02E-09	2,95E-09	-8,88E-10	-2,63E-09	-1,33E-09	-1,29E-09	-3,87E-10
Terrestrial ecotoxicity	species.yr	1,32E-09	1,72E-10	-1,19E-09	-3,34E-08	-3,99E-09	-1,58E-09	-3,19E-09
Freshwater ecotoxicity	species.yr	-1,31E-10	2,31E-10	-9,03E-11	-3,32E-10	-1,40E-10	-1,29E-10	-6,49E-11
Marine ecotoxicity	species.yr	-2,50E-13	7,15E-13	-3,03E-13	-2,35E-12	-5,50E-13	-4,57E-13	-2,64E-13
Agricultural land occupation	species.yr	-4,17E-09	6,49E-09	-6,96E-09	-1,47E-08	-1,04E-08	-9,95E-09	1,08E-09
Urban land occupation	species.yr	-1,29E-08	-4,20E-09	-8,73E-09	-3,02E-08	-1,26E-08	-1,24E-08	-8,07E-09
Natural land transformation	species.yr	-2,53E-07	-3,34E-08	-3,08E-08	-5,42E-07	-9,39E-08	-1,17E-07	-1,95E-07
Metal depletion	$	-1,29E-01	8,11E-02	-1,17E-01	-3,45E-01	-1,24E-01	-1,50E-01	-5,84E-02
Fossil depletion	$	-2,00E+03	-1,37E+03	-3,16E+03	-5,69E+03	-2,50E+03	-4,34E+03	-1,26E+03

Results at the endpoint level for tranport with a lorry with a capacity between 16 ad 32 ton, per 100 tkm.

100 tkm		**lorry 16 - 32t**		
		min	used	max
Climate change Human Health	DALY	1,01E-06	2,41E-05	1,71E-06
Human toxicity	DALY	1,43E-08	1,38E-06	2,42E-08
Particulate matter formation	DALY	2,03E-06	7,83E-06	2,56E-06
Climate change Ecosystems	species.yr	5,71E-09	1,37E-07	9,67E-09
Fossil depletion	$	3,92E+00	1,02E+02	6,62E+00