ISSN 1831-9424

JRC SCIENCE FOR POLICY REPORT

Environmental and socio-economic sustainability of waste lubricant oil management in the EU

A comparison of regeneration and energy recovery of waste oil

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2023

EUR 31575 EN

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JRC133752

EUR 31575 EN

PDF ISBN 978-92-68-05061-3 ISSN 1831-9424 doi:10.2760/7597 KJ-NA-31-575-EN-N

Luxembourg: Publications Office of the European Union, 2023

How to cite this report: Garcia-Gutierrez, P., Klenert, D., Marschinski, R., Tonini, D. and Saveyn, H., *Environmental and socio-economic sustainability of waste lubricant oil management in the EU*, Publications Office of the European Union, Luxembourg, 2023, doi:10.2760/7597, JRC133752.

Contents

Abstract

According to Article 21(4) of the Waste Framework Directive (2008/98/EC), the Commission is required to consider the feasibility of adopting measures for the treatment of waste oils, in particular further measures to promote waste oil regeneration. In 2017, of the approximately 4.3 Mt lubricating oils placed on the market in the EU-28, 2 Mt (47%) are potentially collectible. Of the 1.6 Mt collected waste oils, about 61% were estimated to be regenerated and 39% followed energy recovery pathways, such as conversion to fuel or incineration in industrial boilers and hazardous waste incineration plants.

The first part of this study applies life cycle assessment and life cycle costing methods to assess the impacts of eight alternative scenarios (pathways) for the management of 1 tonne of waste oil with certain physico-chemical properties, including three regeneration pathways (hydro-treatment, solvent extraction and distillation) and five energy recovery pathways (two types of distillation into fuel oil, direct incineration in cement kilns, direct incineration in hazardous waste incinerators and direct incineration in industrial boilers). Whereas regeneration outperforms all energy recovery pathways from a climate change perspective, the results are more nuanced when considering the societal life cycle costs, i.e. the sum of internal and external costs (monetised environmental emissions). In the latter case, regeneration - depending on the specific technology and context – is superior or comparable to treatment to fuel, and only clearly superior to direct incineration (in cement kilns, in hazardous waste incinerators and in industrial boilers).

In the second part of this study, we analyse different policies to achieve higher regeneration rates in terms of their environmental and socio-economic impacts. In particular, we quantify the impacts of a 70% and an 85% regeneration target at EU level. Both targets indicate rather minor benefits. The 70% target leads to 0.6 Mt total CO_2-equivalent savings and 124 million € net savings in terms of societal costs over the period 2024-2045. Net employment creation would be limited, namely to 124 jobs by 2045 in the EU as a whole, although some Member States could be affected by job losses due to the geographical heterogeneity of the employment dynamics. For the 85% target, CO_2-equivalent savings amount to 1.7 Mt, net savings in terms of societal costs to 330 million € (both over the period 2024-2045) and net employment creation to 329 jobs by 2045. These benefits are rather moderate and do not always exceed the estimated administrative costs, which would make it questionable whether this would justify a policy intervention to move waste oil from energy recovery to regeneration.

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Executive summary

Article 21 of the Waste Framework Directive (2008/98/EC) as amended in 2018 introduced provisions regarding the environmentally sound management of waste oils, i.e. any mineral or synthetic lubrication or industrial oils which have become unfit for their originally intended use. In particular, the Commission is required, by 31 December 2022, to examine information on waste oils provided by Member States with a view to considering the feasibility of adopting measures for the treatment of waste oils, including quantitative targets on the regeneration of waste oils and any further measures to promote waste oil regeneration.

In 2017, of the 4.3 Mt of lubricants placed on the market in the EU-28, 2 Mt are estimated to be potentially collectible. About 1.6 Mt of waste oil were collected and around 61% were regenerated, while 39% followed energy recovery pathways, such as conversion to fuel or incineration in industrial boilers, hazardous waste incineration plants and cement kilns.

The main objective of the present study is to perform a life cycle-based comparison between regeneration and energy recovery of collected waste oil for a number of relevant treatment scenarios, with a view to providing a basis for a subsequent socio-economic assessment of possible waste oil policies. The scope of the study includes all waste oil collection and transport activities as well as the treatment of by-products and residues arising from any of the management routes. Informal treatment of non-collected waste oils is not part of the scope of the study. The report equally excludes policies that address the non-regulated or illegal use of collected waste oils, in particular for certain marine fuel applications, due to a lack of reliable data on these practices.

The study starts by surveying existing literature with regard to life cycle assessment and socio-economic analysis of waste oil treatment options. For the life cycle assessment studies, regeneration generally emerges as the preferred option compared to energy recovery when considering climate change, but results are more ambiguous when considering other environmental impact categories. Shortcomings observed for the life cycle assessment studies include a lack of a properly reported life cycle impact assessment, omission of the base oil grade specification and a lack of quantifying uncertainty on the life cycle inventory results. Only one relevant study could be identified that evaluates the economic and social impacts of waste oil recycling options (CalRecycle, 2016). Yet the CalRecycle study does not monetise the external environmental costs and only compares policies in terms of their impact on employment, a partial assessment of their cost (for instance, spending on subsidies, increased local economic activity) and their emissions (in quantities). The calculations in the study of economic spillover effects on other sectors were criticised by external reviewers, mainly based on the high uncertainties involved.

In terms of methodology, the life cycle assessment (LCA) in the present study was carried out in accordance with the guidelines of the ISO 14040/14044 standards and following established practice for waste management life cycle assessment. The functional unit is the management of 1 tonne of waste lubricant oil in the EU, with certain physico-chemical properties. Co-products generated via the management operations are assumed to replace corresponding market products according to the respective quality and substitutability. The system boundary included all the operations involved in the life cycle of the waste, i.e. waste oil collection and transport to intermediate storage plants first and then to waste oil regeneration or energy recovery facilities up until regeneration, transformation into fuel or incineration. The generated waste is assumed to carry no environmental burden (common burden-free approach) since the impacts associated with the waste production are the same across all the end-of-life scenarios investigated. Eight alternative scenarios (pathways) for waste oil management were assessed, which include three regeneration pathways (hydro-treatment, solvent extraction and distillation) plus five energy recovery pathways (two types of distillation into fuel oil, direct incineration in cement kilns, direct incineration in hazardous waste incinerators and direct incineration in industrial boilers).

Life cycle inventory and economic data were collected and aggregated by a third party, in order to ensure data confidentiality of individual installations. Both conventional life cycle costing and societal life cycle costing evaluations were made. The latter sums internal and external costs, both expressed as shadow prices, to quantify the total cost incurred by society. Sensitivity analyses were performed on key framework conditions by varying the average energy mix used (to simulate a future decarbonisation), varying waste oil quality and varying crude oil price. Sensitivity scenarios were also analysed in which only emissions taking place in EU countries were considered or in which only greenhouse gas emissions were taken into account that are neither covered by the EU Emission Trading System nor by effort sharing regulations. As for the uncertainty of input parameters, uncertainty propagation was calculated analytically. Furthermore, a Monte Carlo-based pairwise discernibility analysis was performed to determine how often out of 1000 calculations one treatment option would outperform the others, by changing the various input parameters within their uncertainty range for each occurrence (i.e. calculation run).

The results of the environmental impact assessments show that all direct incineration scenarios produce net greenhouse gas emissions, while the rest of the scenarios achieve greenhouse gas savings. Among the scenarios achieving greenhouse gas net savings, the regeneration scenarios provide larger savings than the energy recovery to fuel scenarios. For particulate matter, net savings are achieved by all scenarios, with the regeneration scenarios showing the largest savings. For acidification, net savings are achieved by all scenarios except for energy recovery in hazardous waste incinerators. Finally, the management of waste oil through any of the assessed scenarios results in net savings of fossil resource use as a result of virgin material and energy substitution.

In terms of conventional life cycle costs, net savings are obtained for the three regeneration scenarios investigated, as well as for the two energy recovery scenarios producing fuel. Net costs are observed for the remaining three energy recovery scenarios based on direct incineration. In terms of societal life cycle costs (sum of conventional and external costs), all energy recovery routes that involve direct incineration of waste oil show net societal costs. All three regeneration scenarios achieve larger savings than any of the energy recovery scenarios in the societal life cycle cost category, although the difference is very small in some cases.

The results of the sensitivity analyses show that the savings on the climate change impact indicator are generally higher when high quality waste oil is treated, rather than low quality waste oil. A future decarbonisation of the energy mix increases the net savings for the climate change impact indicator for pathways that are net energy importers (regeneration and energy recovery to fuel), whereas it further exacerbates the net burdens for the climate change impact indicator for pathways that are net energy exporters (direct incineration). A higher crude oil price lowers the societal life cycle cost, via a decrease of the internal costs, for pathways that produce petroleum products, with the effect being more pronounced in the regeneration scenarios than in the energy recovery scenarios that produce distillate fuel. When only emissions are considered that take place within EU countries, the relative ranking of the different pathways in terms of life cycle costs does not change except between pathways that incinerate waste oil directly. When only greenhouse gas emissions are taken into account that are not covered by the EU Emission Trading System or by effort sharing regulations, the life cycle cost ranking changes with the solvent-based regeneration pathway displaying a higher life cycle cost than one of the fuel production pathways, while incineration in cement kilns replaces incineration in hazardous waste incinerators as the pathway with the highest life cycle cost.

The Monte Carlo-based discernibility analysis reveals that, with regard to climate change, solvent-based regeneration is the only scenario that is superior to all the remaining scenarios in a majority of the occurrences, followed by hydrotreatment-based regeneration. Regeneration scenarios are superior to scenarios of energy recovery via fuel in a majority of the occurrences. Both regeneration and energy recovery via fuel scenarios are superior to direct waste oil incineration scenarios in a large majority of the occurrences. With regard to societal life cycle costs, regeneration via hydrotreatment is the only scenario that is superior to all other scenarios in more than half of the occurrences, followed by solvent-based regeneration. Notably, energy recovery to fuel is superior to regeneration via distillation in over half of the occurrences. Both regeneration and energy recovery to fuel scenarios are superior to direct waste oil incineration scenarios in an overwhelming majority of the occurrences.

Policy options were reviewed that could be applied to increase the share of regenerated waste oils, following the observation that waste oil regeneration outperforms direct incineration in almost all the environmental impact categories investigated and conversion to fuel in most of them. These policy options can be classified into four categories: i) measures restricting the use of waste oils for energy recovery; ii) regeneration targets; iii) price-based instruments such as levies and subsidies; and iv) policies related to the collection of waste oil. Following a brief discussion of an extended set of possible policies, the study analyses selected policies related to regeneration targets and price-based instruments in more detail.

For the socio-economic analysis of the expected policy impact, policies are calibrated such that they are all consistent with the same target of achieving a certain EU-wide increase in the regeneration rate. In particular, we analyse two targets specifically: a less ambitious target which corresponds to an increase in the regeneration rate from 61% to 70% by 2030 and a more ambitious target corresponding to an increase to 85% over the same period. The policies build on different means to achieve the target: the first analysed policy (2a) simply sets the regeneration target and leaves it up to Member States how to achieve it; Policies 2b and 2c set targets for the share of regenerated base oil in total base oil put on EU markets, either in the form of an average market-wide quota (2b) or a recycled content target applied to each lubricant product unit

(2c). Policies 3a and 3b consist of subsidies for regeneration, either financed from the general budget (3a) or via a levy on base oils from virgin production (3b).

Whereas the environmental effects and benefits are - by design of the assessment approach - the same for all policies, some economic, social and distributional effects differ. Nonetheless, the EU-wide gains in the environmental and economic dimension as well as employment are rather minor and some Member States and sectors may actually incur negative impacts in terms of employment. For the 70% target, CO_2 savings amount to 0.6 Mt over the period 2024-2045, accumulated societal life cycle cost savings to 124 M€ over the same period and net employment gains to 124 jobs by 2045. For the 85% target, CO_2 savings amount to 1.7 Mt, accumulated societal life cycle cost savings to 330 M€ over the same period and net employment gains to 329 jobs by 2045.

Apart from policies 3a and 3b (subsidies financed through different means), which lead to excess costs that are a multiple of the expected benefits, all other policies are similar in terms of costs and benefits. The policies differ, however, in terms of who bears their main financial burden: While the incidence of the burden of policy 2a is undefined (implementation left to MS), the main burden of policies 2b and 2c would initially fall on lubricant producers and eventually on lubricant consumers. In policy 3a it would fall on the central government (and thus ultimately on taxpayers) and in policy 3b initially on virgin base oil producers and eventually on lubricant consumers. When considering the administrative cost of the policies (which we estimate to be in the range of 11 to 213 M€), as well as taking into account that mainly low-quality waste oils are allegedly used for direct incineration, there seems to be no clear case at this moment for a policy intervention that would induce a deterrent effect to energy recovery. Better data on waste oil treatment options could help to develop more fine-tuned policy options in the future.

1 Introduction

1.1 Policy context and background

Article 21 of the Waste Framework Directive (WFD)[1] as amended in 2018[2] introduced provisions regarding the environmentally sound management of waste oils (WO). In particular, the Commission is required, by 31 December 2022, to examine information on waste oils provided by Member States with a view to considering the feasibility of adopting measures for the treatment of waste oils, including quantitative targets on the regeneration of waste oils and any further measures to promote waste oil regeneration. The Commission will submit a report to the European Parliament and to the Council, accompanied, if appropriate, by a legislative proposal. According to Article 3(3) of the WFD, 'waste oils' are defined as any mineral or synthetic lubrication or industrial oils that have become unfit for the use for which they were originally intended, such as combustion engine oils and gearbox oils, lubricating oils, oils for turbines and hydraulic oils[3].

The regulation of waste oils management in the EU has a long-lasting history, with Directive 75/439/EC opening the way more than 40 years ago to a harmonised management of such waste across the EU. Today, the Waste Framework Directive (WFD) 2008/98/EC, amended by Directive (EU) 2018/851, regulates the management of waste oils, establishing guidelines to protect the environment and human health, as well as to promote resources efficiency by encouraging the recycling of waste oil (WO). Figure 1 depicts the current life cycle of lubricants in the EU.

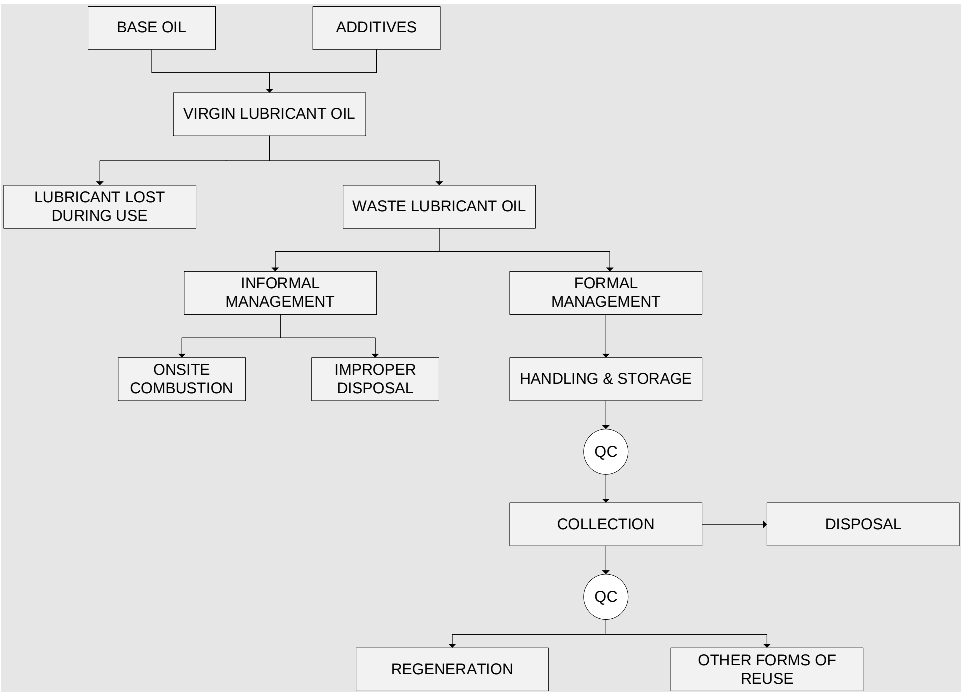

Figure 1 Life cycle of lubricants in the EU; QC: quality control; "OTHER FORMS OF REUSE" includes mainly energy recovery to fuels (Adapted from (Pinheiro et al., 2020)).

[1] Directive 2008/98/EC on Waste – OJ L312, 22/11/2008, p 3 -30.
[2] Directive (EU) 2018/851 – OJ L150, 14/06/2018 p 109-140.
[3] Used oils classified under Code 01.3 of the "Guidance on classification of waste according to EWC-Stat categories – Supplement to the Manual for the Implementation of the Regulation (EC) No 2150/2002 on Waste Statistics"

Article 21 of the WFD states that the Member States shall take measures to guarantee that:

- waste oils are collected separately unless this is not technically feasible;
- waste oils are treated, giving priority to regeneration or alternatively to other equivalent recycling operations;
- waste oils of different characteristics are not mixed, and waste oils are not mixed with other kinds of waste or substances, if such mixing hampers regeneration or another recycling operation;

In 2017, approximately 4.3 Mt of lubricating oils were placed on the market in the EU-28, of which 2 Mt (47%) are estimated to be collectible as waste oil (Stahl and Merz, 2020). This refers to the waste oil generated in the Member States and excludes the export and import of waste oils. Of the 1.6 Mt of collected waste oil, about 61% is estimated to be regenerated and 39% follows energy valorisation pathways (Stahl and Merz, 2020). Through its New Circular Economy Action Plan[4], the European Commission (EC) aims to foster and encourage a sustainable, resource efficient and competitive economy, in which the value of materials and products is kept in circulation for as long as possible, instead of being discarded or destroyed. Given that it can be recycled with a technically well-established process, waste oil has a potential to contribute to these objectives of the circular economy.

As shown in Figure 2, treatment and disposal of waste oil in the EU can be done in a variety of ways, including regeneration, processing to fuel, direct application as fuel and combustion as hazardous waste. All of these options are assessed in this study.

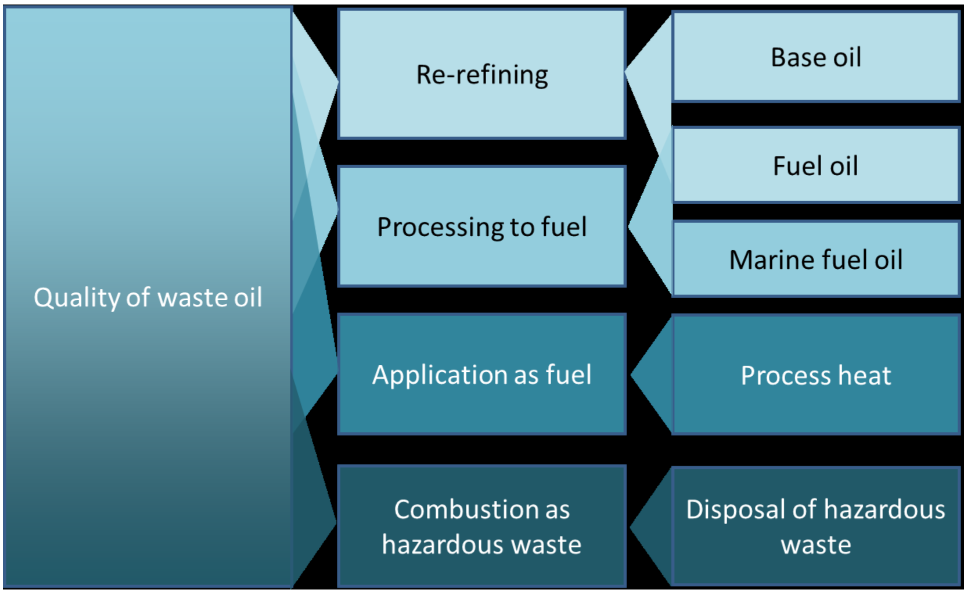

Figure 2 Treatment and disposal routes for waste oil available in Europe (source: IFEU, 2021).

There is a wide variation between Member States in the way waste oil is managed (see Figure 3). While seven Member States (MS) show regeneration rates of 90% or more, for another ten MS rates are below 10%. Use in cement kilns and power plants is overall not very significant, but in three MS it accounts for more than 50%. We understand from consultations with different stakeholders that only the lowest quality waste oils are used in cement kilns, industrial boilers and hazardous waste incinerators.[5] It is suggested that these waste oil qualities cannot be regenerated, at least not within a financial cost that would be economically viable. Based on 2018 data, the average share of low quality waste oil used in cement kilns, industrial boilers and

[4] COM/2020/98 final, 11/03/2020

[5] Crucial determinants of waste oil quality are water content and contamination with polychlorinated biphenyls (PCBs), which is often found in transformer oils. Emulsions from metal working activities or harbour activities are also unsuitable for regeneration due to their water content.

hazardous waste incinerators in the EU-28 might be as high as 15% (Stahl, Hartmut; Merz, 2020)This implies - as a conservative assumption - an upper limit of 85% for waste oil that could be regenerated. This percentage aligns with estimates communicated from several stakeholders active in waste oil regeneration and hazardous waste treatment that 5 to 15% of collected waste oil is not suitable for regeneration (with current collection practices).

Figure 3 suggests that there are some countries in which regeneration rates reach 100%. However, evidence suggests that such high regeneration rates are in many cases artefacts of accounting, as some countries report the initial sediment and water separately from dry waste oils and others report only on the regeneration of waste oil of sufficient quality (Le Bihan et al., 2021; RDC Environment, 2023).

Several policy options could help to further prioritise regeneration, ranging from restrictions on certain uses of waste oil to quantity targets for regeneration or financial incentives such as subsidies, levies and policies that target collection, e.g. Enhanced Producer Responsibility (EPR) schemes. Selected policies are already implemented in some Member States (Stahl and Merz, 2020). A large set of possible policies is discussed in detail in Section 5, including an assessment of the policies' socio-economic impacts.

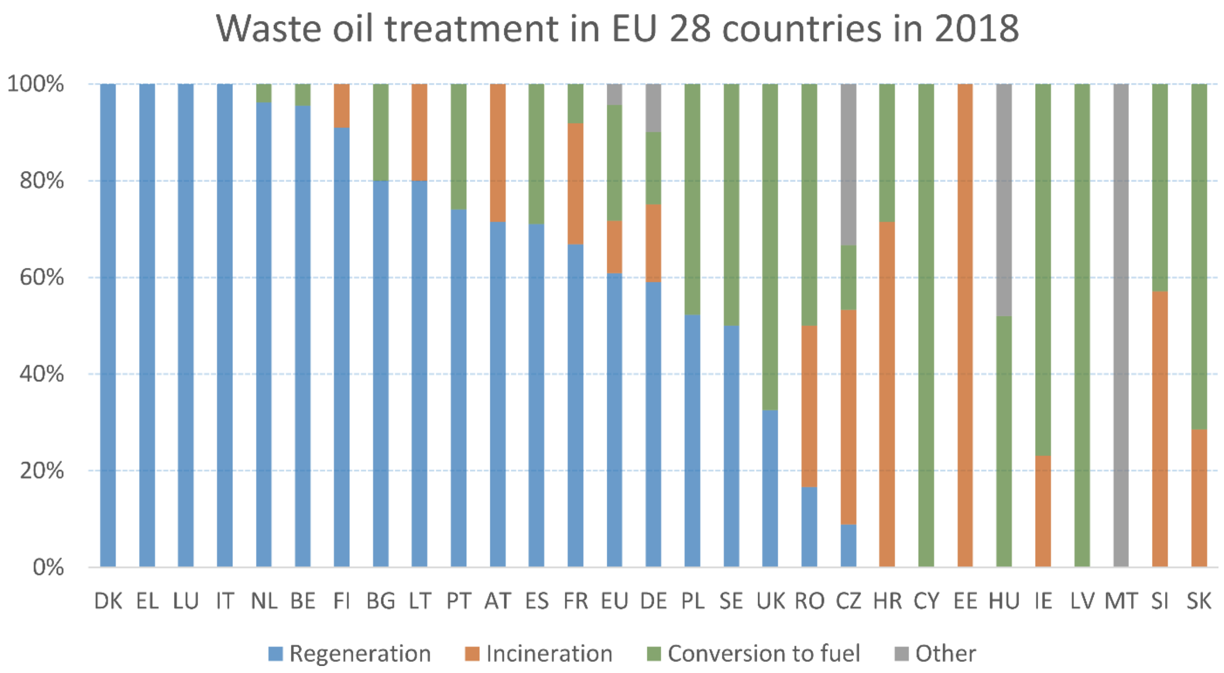

Figure 3 Waste oil treatment in EU 28 countries in 2018 (based on (Stahl, Hartmut; Merz, 2020). Note that the accounting of waste oil quantities and regeneration rates can differ between countries. In many cases, particularly in countries with high regeneration rates, the initial sediment and water are reported separately from dry waste oils or only the regeneration of waste oil of sufficient quality is reported, which both leads to higher reported regeneration rates.

1.2 Objectives of the study

The main objective of this study is to perform a life cycle-based comparison between regeneration and energy recovery of waste oil for a number of relevant scenarios, with a view to providing a basis for an assessment of possible waste oil policies. Such comparison aims to:

i. Quantify the potential environmental impacts and life cycle costs resulting from managing waste oil in the EU via regeneration or energy recovery.

ii. Identify the conditions under which a certain waste oil management option may be the most effective one, from a life cycle perspective.

iii. Calculate the total uncertainty of the outcome of the study, based on the uncertainty of all the parameters and model choices of the modelled waste management system.

iv. Select policies that promote waste oil management pathways that were found to have the most benefits in the life cycle assessment, to discuss these policies in terms of their effectiveness, efficiency and technical, legal and political feasibility and to analyse them regarding their environmental, economic and social impact.

1.3 Scope of the study

The study addresses waste oil regeneration and energy recovery as a means to treat used lubricant oil. Energy recovery may be carried out either through direct combustion of the waste oil as fuel, e.g. in cement kilns, or through processing of the waste oil into a fuel with certain specifications. More details on the waste oil management technologies assessed in this study can be found in Section 3.1.6. In the analysis of different treatment pathways, the following elements are considered:

- Greenhouse gas (GHG) emissions resulting from the different management options for waste oils (resulting from combustion as fuel, from displaced production of virgin base oil, from regeneration, etc.)
- Emissions (to air, soil, and water) of pollutants resulting from the different management options and link to environmental impacts (emissions of heavy metals, polycyclic-aromatic hydrocarbons (PAHs), etc.)
- Use of natural resources (e.g. energy resources, water and raw materials)
- Employment implications of each of the management options (labour intensity, skilled versus unskilled workforce, etc.)
- Economic indicators associated with each management option

Potential environmental impacts of these technologies are evaluated based on Life Cycle Assessment (LCA), while costs are assessed using Life Cycle Costing (LCC), which includes the estimation of both internal (financial) costs as well as environmental externalities (see Sections 3.1 and 3.2 for more details on the LCA and LCC methodologies).

These evaluations are complemented by a socio-economic assessment. The assessment focuses on the potential social, distributional and economic impacts of different policies that could be employed to promote the waste oil management pathway that has been shown to be the most beneficial in the LCA/LCC. It is largely based on the data obtained in the data collection carried out for this study (Section 3.1.4) and the LCA/LCC results (Section 4). It is further complemented with relevant scientific and technical literature.

The scope of the study includes all waste oil collection and transport activities as well as the treatment of by-products/residues arising from any of the management routes. All management options are assumed to treat the same waste oil, i.e., a waste oil with the same physicochemical characteristics, in order to ensure a level playing field for the comparison of environmental and economic performances.

1.4 Issues of policy concern

1.4.1 Impacts on emissions, health and resource depletion

According to the principles of the waste hierarchy, as outlined in Article 4 of the Waste Framework Directive, regeneration should generally be given priority over energy recovery. However, departing from the waste hierarchy can be justified in concrete cases by life cycle assessments of the overall impacts of the generation and management of certain waste streams. Hence, specific policies that aim at promoting the regeneration of waste oils over energy recovery should only be pursued after careful consideration of the environmental, economic and social impacts of different waste oil treatment pathways. In the following, we discuss different specific arguments - and their limitations - that could motivate a policy intervention in the waste oil sector.

First, there is evidence from other studies as well as from our own analysis (see Section 4) suggesting that in a majority of cases it is environmentally preferable to regenerate waste oil rather than using it for fuel production and energy recovery for the following reasons:

- *Non-GHG pollution*: Existing studies and our own analysis support the claim that regeneration is less polluting than energy recovery. The exact net benefit, however, depends on which specific regeneration technology is considered, against which energy recovery/fuel production pathway it is compared, and on context parameters, e.g. the energy mix in place. It is conceivable in certain cases that reducing the amount of waste oil used for energy recovery does not reduce emissions, for instance when the waste oil is substituted by an even more polluting fuel such as tyres. Whether there is a reduction in net emissions is hence determined by the substituted fuel mix[6] and the comparative environmental performance of the pathway the waste oil is redirected to.

- *Greenhouse gas emissions:* Existing studies and our own analysis indicate that regeneration is in most cases less GHG intensive than energy recovery/fuel production. However, as in the case of non-GHG emissions, this outcome depends on technologies and contexts. An additional complication is that industrial GHG emissions in the EU are already regulated and capped by the EU Emissions Trading System (ETS).[7] On the one hand, as this cap is binding (i.e. all available permits are used), a net reduction of GHG emissions in the EU is not possible, at least as long as all relevant activities are covered by the EU ETS. This is true for cement kilns and power plants but not for most regenerators and fuel producers, as they fall below the threshold of 20 MW of thermal input. In other words, if a cement kiln stops to burn waste oils and instead switches to CO_2 neutral biomass, it will reduce its CO_2 emissions and has to buy less ETS certificates, but some other ETS entity will be offsetting this by buying and emitting more. The effect will only play out on the EU ETS price, which – *ceteris paribus* - would marginally decrease. Of course, informal combustion of waste oil is not captured by the EU ETS.[8] On the other hand, the cap is subject to a political process of re-evaluation and readjustment. Additional emission reductions could be used as an argument in favour of lowering the cap and hence would result in a net savings effect, if not immediately, then at least in the medium term.

- *Preventing the use of untreated or lightly treated waste oils in marine bunker fuels:* Such a use would be a particularly polluting form of energy recovery and would be contrary to the EU Waste Framework Directive. The complexity of this topic merits further discussion and we hence review it in detail in the following Section 1.4.2.

Second, and leaving aside the environmental dimension, it is sometimes argued that more regeneration of waste oils would save fossil fuel resources and reduce EU dependence on oil imports:

- It might seem intuitive that recycling of used oils would reduce the need for new crude oil. However, the fact that currently the largest share of the non-regenerated used lubricating oil is used for energy generation makes it more complicated. The outcome then depends on how the non-combusted waste oil will be substituted, i.e. by which fuel energy will be generated instead and whether this fuel is made from crude oil For example, if it is replaced by fuel oil, the total consumption of crude oil for lubricating oils and energy generation will be about the same, independent of the regeneration rate. If instead sustainable biomass would replace waste oils for energy generation, then the total consumption of fossil fuels would indeed be reduced (caveats regarding interactions with the EU ETS still apply, though).

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[6] In an LCA context, a substituted mix can be the marginal or the average mix. While the average is the weighted average of the (capacity of the) available technologies in place in a selected year, the marginal is the mix of the unconstrained technologies able to respond to a change in demand (i.e. capable to supply an additional unit of demand in a selected period, present or future).

[7] The EU ETS sets a cap on the quantity of CO_2 (as well as N_2O and perfluorocarbons (PFCs)) than can be emitted in the EU (including Iceland, Liechtenstein and Norway; see here). It covers electricity and heat generation, energy-intensive industry sectors including oil refineries, steel works, and production of iron, aluminium, metals, cement, lime, glass, ceramics, pulp, paper, cardboard, acids and bulk organic chemicals and commercial aviation within the European Economic Area. An extension of the EU ETS to other activities and sectors, including marine transport, is currently under discussion as part of the "fit for 55" package. It becomes relevant for the topic of waste oil, whenever it applies to the sectors in question. A tonne of waste oil burned in the cement industry is covered by the EU ETS, while it is not covered by the EU ETS when burned in a Hazardous Waste Incineration (HWI) facility (IFEU final report, 2021). Otherwise, it is covered by the EU ETS when incinerated for electricity generation, but it is only covered for heat generation in plants with more than 20 MW capacity (DEFRA, 2011). In a similar vein, while the EU ETS covers power generation sectors and industry, the Effort Sharing Regulation (see here) sets binding national GHG emission targets for areas such as transport, infrastructure, agriculture, and waste management. Hence, whenever a sector is covered by the EU ETS or by the Effort Sharing Regulation, this needs to be accounted for to avoid double counting of GHG emissions.

[8] In general, GHG emissions that already fall under the scope of the EU ETS or the Effort Sharing Regulation should not be addressed by additional policies. Further GHG regulation on top of existing policies can generally be justified only in two cases: First, for GHG emissions that are captured neither by the EU ETS nor the Effort Sharing Regulation. Second, GHG-oriented technology policies could be employed where market failures/frictions impede an optimal development of low-carbon technologies (support policies for wind and solar energy are an example).

1.4.2 Use of waste oils as bunker fuel

In 2018, the International Maritime Organization (IMO) released a new amendment to the International Convention for the Prevention of Pollution from Ships ("MARPOL") that entered into force on 1 January 2020.[9] This amendment limits the sulphur content in marine fuels to 0.5%, which is a significant reduction from the previous limit of 3.5%. The regulation prohibits ships from using or carrying fuel oil for use with sulphur levels above 0.5%, unless they have an exhaust gas cleaning system ("scrubber").

The impact of this regulation on the waste oil market is not yet fully clear. In general, two scenarios are conceivable: In the first scenario, the new IMO regulation could make waste oil a more valuable resource in the maritime sector, due to its low sulphur content (GEIR, 2019). Depending on the class of base oil, the sulphur content is below 0.03% (classes 2 and 3) or above 0.03% (class 1), see Table 4.2 in Stahl and Merz (2020). Waste oil (or mildly treated fuel obtained from it) therefore can potentially be used to dilute other fuel oils with higher sulphur contents to achieve the desired sulphur content of just below 0.5%. While mixing a hazardous waste such as waste oil with a product is illegal under the Waste Framework Directive, a legal way to do this is to convert waste oil to fuel in countries with established EoW protocols for waste oil. This option becomes the more profitable the lower the stringency of the requirements on the EoW conversion process are.

This practice, however, has several drawbacks. First, through the surge in demand from the maritime transport sector, there is upward pressure on waste oil prices. Above a certain price level of waste oils, regeneration and eventually also treatment to fuel via distillation pathways become uneconomic, which reduces the amount of waste oil that is recycled. Second, diluting high sulphur fuel with waste oil or waste oil derived fuels instead of removing sulphur from the fuel (through costly processes) only partially addresses the goal of reducing total sulphur emissions, as some of the higher sulphur fuels would still be used, albeit in a diluted way (see Mestl et al., 2013). Third, waste oil that is converted to fuel in countries with less stringent requirements on the process (see, e.g., the quality protocol for the production and use of processed fuel oil from waste lubricating oils in the UK, UK Environment Agency, 2011) could then be exported as such (or blended with other fuels) to countries or regions that either have stricter requirements such as Flanders in Belgium or that have no EoW regulation for waste oils at all. While Flanders requires waste oil to be distilled to become a fuel[10], this is not the case in the UK.[11] Even though the practice of exporting lightly treated waste oil derived fuels to countries where the competent authority considers it to still be a waste is illegal under the Waste Shipment Regulation (EC/1013/2006), it is much harder to trace once the lightly treated waste oil derived fuels are blended with other fuels to be exported as marine fuel.

As a result, such a recycled fuel may still contain other contaminants, which are released when the fuel is combusted, even when the fuel is purchased in countries that prohibit using lightly treated waste oil as fuel. Moreover, marine fuels blended with waste oil have been linked to engine failures (de Buck et al., 2011) and, according to (ORA, n.d.), waste oil treated according to the UK PFO protocol has the potential to increase engine wear significantly.

In the second scenario, the new International Maritime Organization regulation could lead to more ships switching to different fuel types, which would thus reduce the overall demand for waste oil (as hypothesized in United States Department of Energy 2020, p. 93-94). This might push waste oil streams into regeneration, but it might also reduce incentives for waste oil collection because of falling prices, which in turn might

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[9] The full text of the amendment can be downloaded here; See also here.

[10] The conditions under which waste oil can be reprocessed to fuel oil in Flanders are outlined in OVAM (2019).

[11] The UK processed fuel oil (PFO) quality protocol specifies conditions under which waste oil may be processed into a replacement fuel for either distillate oil or residual fuel oil. The resulting PFO is classified as a "fuel manufactured from waste" and its combustion is regulated under Section 1.1 of Part 2 of Schedule 1 of the Environmental Permitting (England and Wales) Regulations 2007 (EPR). The specifications laid out in the PFO quality protocol can be met by a combination of mild treatment pathways such as gravity separation, filtration, dewatering and precipitation of metals with diammonium phosphate. The treatment does not necessarily include a distillation step. PFO contains other contaminants (copper, lead and zinc) than virgin fuels, which result from petrochemical additives that were dissolved in the lubricant oil. It has much lower levels of sulphur than virgin residual oil, which – at least in theory – makes it a desirable blending agent to lower sulphur levels in marine fuel. For more on the history of the UK PFO protocol see Footnote 40. It might be that the UK is a special case and that this does not occur in other countries due to stricter regulations. See also Table 16-2 in Stahl and Merz (2020) on EoW criteria in the EU.

increase the risk of improper disposal. Currently, this scenario appears less likely, as it contradicts the (mostly anecdotal) evidence of bunker fuel market diversion identified for Europe.[12]

One major obstacle for the formal analysis of the use of waste oils in the maritime sector is the lack of data. For the case of illegal practices of waste oil use, no data (other than anecdotal) exists. There is only some anecdotal evidence in relation to engine failures attributed to marine fuels blended with waste oil, however this might concern only a small fraction of ships that actually use these fuels (de Buck et al., 2011).

There are several considerations regarding the legal status of using waste oil in marine fuel production: A *legal way* for doing so is based on an EoW protocol that envisages use as marine fuel (e.g. Flemish and Spanish EoW, see OVAM (2019) and Ministerio de Agricultura, Pesca, Alimentación y Medio Ambiente, 2018). It would be *illegal* when using an EoW fuel material for which marine fuel use is not envisaged. Equally *illegal* would be a blending of waste oil with bunker fuels or any other non-waste product without the material previously achieving EoW status.

To summarise, the following cases can be distinguished:

a) Legal conversion of (distilled) waste oil to bunker/industry fuels: Only in compliance with EoW protocol that envisages this use.

    Evidence: personal communication from GEIR that 75% of all waste oil going into fuels ends up as marine fuel. It is assumed that the remaining 25% goes to the industrial sector. Not clear whether this also includes illegal or channels where the legal status in unclear, see b) and c) below.

    LCA modelling: these are our WODFa/b scenarios (see Section 3.1.3), with good data and reasonable certainty.

b) Illegal conversion of waste oils to bunker fuels (with or without EoW):

    i. Applying EoW protocol, but one that does not envisage marine bunker use.[13]
    Evidence: claims and documents from GEIR as well as some waste oil regenerators describing the export of UK PFO (EoW, but not suited for use as marine fuel) to the EU. Quantities unknown.

    ii. Applying no EoW protocol at all, simply blending (perhaps with basic cleaning).
    Evidence: none. Some reporting on the use of EU waste oil in Africa, but in car engines in the form of blended diesel fuel (Guénat et al., 2016). However, this should already be illegal under the WFD and the Waste Shipment Regulation (WSR).

    LCA modelling: not modelled.

c) Legal status unclear: perhaps export of EoW treated waste oil blended with other fuels to meet ISO 8217 specifications as marine fuel to other country that does not have same EoW.[14]

    Evidence: no specific evidence, except for the personal communication from GEIR that 75% of all waste oil going into fuels ends up as marine fuel. Given that only five EU Members have EoW protocols for this would imply that those five undertake exports. Valuable (but currently unavailable) information would be on the amounts of waste oil that undergo EoW treatment in these five countries.

    LCA modelling: not modelled.

Whether or not this issue should be addressed by EU policy, and by which one in particular, depends on which of the cases a), b) or c) are seen as relevant (they are not mutually exclusive) and in need to be addressed. Note that for case b), the natural response would be 'increased enforcement' of existing policy. At the current moment, although there are several anecdotal reports, there does not seem to be enough hard evidence that would justify a targeted policy intervention. For that reason, this report does not consider policies that address the marine fuel issue in the detailed analysis in Section 5.

[12] This might change in the long-run, however, once ships that use different fuel types become the norm.
[13] Marine fuels have to meet specifications laid out in ISO 8217.
[14] Assessing the legal status of such practices goes beyond the scope of this document.

2 Literature review of environmental, economic and socio-economic assessments

This section reviews existing studies developed at the European and international level related to life cycle and socio-economic analysis in the field of waste oil recycling. The purpose of the literature review is to:

- identify key methodological aspects and challenges;
- review the methodological choices and approaches commonly applied to address such aspects, focusing on the most challenging and controversial ones;
- map existing case studies to understand the availability of life cycle inventory data on the covered products, co-products and key intermediates;
- highlight possible knowledge gaps and research needs.

2.1 Terminology

Three main tools exist for assessing the environmental, economic and social impacts of different projects, processes and policies (Hoogmartens et al., 2014), and an additional meta-tool, socio-economic analysis, which we will describe at the end of this section. The three main tools are:

- Conventional life cycle assessment (LCA) is environmentally focused. It determines inputs and outputs of production processes in terms of flows of physical quantities such as mass, energy and volume (including use and end-of-life quantities). Based on such a list of input-output inventory exchanges (expressed as air, water, soil emissions and consumption of resources) environmental impacts are quantified. While future developments and scenarios can be considered depending upon the goal and scope of the assessment, most LCAs are static in the sense that no projections on future technological developments are included. LCA is defined by the ISO standards 14040[15] and 14044[16].
- Conventional life cycle-costing (LCC): focuses on lifecycle costs instead of exchanges with the environment (air, water, soil emissions and consumption of resources). LCC was originally designed to compare durable products with a purchase price that represents only a smaller part of the total life cycle cost. Other costs over the lifetime of the product are discounted to current values. As in LCA, the analysis is either static, or quasi dynamic, when including discounted future values. LCC generally focuses on project or production process assessment (see also UNEP, 2012).
- Cost-benefit analysis (CBA) is widely used to assess the attractiveness of projects or policies. A discount rate is applied to future costs and benefits in order to obtain a net present value (NPV) of the project or policy. A CBA is forward looking and therefore often dynamic in the sense that, for instance, changes over time in population or technology are accounted for and explicitly modelled. The focus is generally less on the assessment of individual processes and projects and rather on policy and welfare assessment.

Out of the three main methodologies, a number of modifications and hybrids have emerged, to account for a wider range of mainly environmental and social factors. Out of the three main methodologies, a number of modifications and hybrids have emerged, to account for a wider range of mainly environmental and social factors. The variant most relevant to this report is the societal life cycle costing (sLCC), which takes all costs borne by anyone in society, whether today or in the future, associated with the life cycle of a product into account. As the LCC expands from the traditional LCC, the system boundary expands equally and costs become increasingly difficult to estimate precisely. According to Martinez-Sanchez et al., 2015), the key difference between a purely financial LCC and sLCC is that environmental costs in the financial LCC are only

[15] ISO 14040 - Environmental management – Life cycle assessment – Principles and framework; (ISO, 2006a)
[16] ISO 14044 - Environmental management – Life cycle assessment – Requirements and guidelines; (ISO, 2006b)

accounted for as taxes (and possibly anticipated taxes and subsidies) while in the sLCC they are accounted for at their shadow prices (i.e. society's willingness to pay to avoid environmental damages).

Finally, the meta-tool of socio-economic analysis (SEA) aims at taking all impacts on economic, human, natural and social capital into account (see e.g., the CleaR framework, described in de Blaeij et al. (2019). This implies that SEA relies on insights from the previously mentioned methodologies and often comprises a sLCC. An sLCC relies on inputs from the corresponding environmental life cycle assessment and financial life cycle costing. Additionally, SEA can also take factors into account that are not traditionally analysed in the previous methodologies such as the distribution of the impacts across actors (equity concerns), job creation or destruction, the enforceability (of a policy), human rights concerns and workers safety and health concerns. Ideally, SEA weighs all societal impacts against each other, and this trade-off then leads to a conclusion.

2.2 Life cycle assessment of waste oil management options

According to the Waste Framework Directive, waste oil should be treated following the waste hierarchy, and options that deliver the best overall environmental outcome should be preferred. In the last 20 years, life cycle assessment (LCA) studies have been used to identify the best overall environmental outcome of different waste oil management options. Annex 3 summarizes the LCA studies that address waste oil management, highlighting some key methodological considerations such as system boundaries, functional unit, life cycle inventory (LCI) data, impact assessment method and impact categories.

The literature review carried out in this study indicates that the regeneration of waste oil to base oil reduces the environmental impacts compared with the production of base oil from virgin crude oil. Grice et al. (2014) assessed only the carbon footprint of re-refined base oil (RRBO) derived from a process consisting of dehydration, vacuum stripping, vacuum distillation, and hydro-treating. The results show that the global warming potential (GWP) of regenerated oil is significantly lower than that of virgin oil per unit of base oil produced. This difference is primarily due to differences in emissions associated with base oil production and used oil end of life (EoL) between the two systems studied. For instance, the study assumed that, for the virgin base oil case, the EoL consists of 80% burning as fuel and 20% improperly disposed of.

Abdalla & Fehrenbach (2017) compared the environmental performance of regenerated waste oil in Germany with virgin (refinery) base oil. The results show that regenerated waste oil has an environmental advantage in all impact categories compared to virgin base oil when both Group I oil and a mix of Group I-IV oils are considered as reference. These base oil groups are categorised by the American Petroleum Institute (API) and are based on the refining method and the base oil's properties in terms of, among other parameters, viscosity and the proportion of saturates and sulphur content. The study assumed that the EoL for the virgin base oil consists of 100% being treated to fuel oil (RFO). Compared to this, the treatment of waste oil to base oil (RRBO) results in lower impacts across all impact categories, assuming that the RFO substitutes fossil fuel oil. It is not possible to rank the different regeneration technologies by their environmental performance since the authors do not disclose which of the four evaluated technologies (Avista, LPC, Hylube and Viscolube) result in higher or lower impacts. However, from the results, it can be concluded that the savings of regenerated waste oil in global warming potential (GWP) range in-between 31-76% compared to refinery virgin oil. The GWP associated with the regeneration of 1 tonne of waste oil via the aforementioned technologies is in the range of 190-577 kg CO_2-eq/tonne base oil. These results are in line with a subsequent study by Abdalla et al. (2022), which showed that the substitution of higher grade (API Group II+) virgin base oil with re-refined base oil leads to even lower environmental impacts in all the investigated categories, except Acidification.

Botas et al. (2017) assessed five different environmental impacts of a regeneration process for waste oil upgrading. The authors proposed a regeneration process based on the extraction of organic contaminants with liquid propane followed by a cascade of three consecutive distillation stages. The results show that the regenerated waste oil from this process is a more environmentally friendly option than the conventional refinery counterpart. A cradle-to-grave approach was followed for both regenerated and virgin base oils. For instance, focusing only on global warming, the overall regeneration process generates 363 kg CO_2-eq/tonne base oil while the refinery process is estimated to generate approximately 1050 kg-eq CO_2-eq/tonne base oil, resulting in a 65% lower impacts for the regenerated product.

Du đak et al. (2021) examined different waste oil management options to be implemented in Serbia, namely: regeneration of waste oil into base oil (RRBO), the co-combustion of waste oil with conventional fossil fuel in cement kilns, and the combustion of waste oil in waste incinerators with energy recovery. The results reveal that the combustion of waste oil in waste incinerators has the lowest impact in the human toxicity category.

Conversely, the co-combustion of waste oils in cement kilns was the most favourable approach with regard to ecosystem toxicity potential and climate change, while regeneration of waste oil into base oil was the most favourable option in the fossil fuel resource use category. The results also revealed the dependency of the results and management ranking on the local context, e.g. substituted energy mix.

A similar outcome was found by Kanokkantapong et al. (2009), who argue that regeneration to base oil in Thailand is only preferred over energy recovery options when the focus is solely on global warming. When other impact categories than GWP are considered, e.g. acidification potential or heavy metals emissions, the study concludes that some energy recovery options such as combustion of waste oil in cement kilns are preferred over regeneration to base oil. Additionally, some regeneration techniques such as the acid-clay process pose environmental and safety concerns over the handling and disposal of the acid sludge residue.

Contrarily, a study by Kalnes et al. (2006) concludes that regeneration of waste oil in Germany via the HyLube process is more environmentally acceptable in all impact categories (global warming, acidification, eutrophication and depletion of fossil fuels) than combustion in cement kilns.

Pires & Martinho (2013) carried out a comparative LCA of 16 waste oil management systems in Portugal (one system that is currently in use (as of 2013) and 15 management alternatives). None of the systems had the highest or lowest environmental performance in all environmental impact categories. The authors concluded that the management alternative that best performed in most environmental impact categories was when waste oil is sent for regeneration.

A 2013 study commissioned by the California Department of Resources Recycling and Recovery (known as CalRecycle) (Geyer et al., 2013) compared the life cycle impacts of three different waste oil management options which, respectively, produced re-refined base oil (RRBO), recovered fuel oil (RFO) and regenerated marine diesel oil (MDO). The authors concluded that there was no single "best" option among the three disposition routes, although some environmental benefits could be achieved if more used oil was processed into MDO or RRBO rather than used as RFO. The authors warn that the models responsible for determining the impacts of RFO combustion rely on a number of assumptions that are uncertain due to outdated or unavailable data.

In 2017, the American Petroleum Institute commissioned a study (Collins et al., 2017) to extend the work done by CalRecycle and it was found that from all waste oil management options, "no single disposition shows consistently lower impacts under all framework conditions (mainly changes in the surrounding energy system), with greater benefits generally flowing from increasing collection, rather than from changing disposition". It is also argued that for a given collection rate, the environmental impacts of alternative dispositions of waste oil are highly sensitive to the mix of virgin products displaced by those from the used oil management system and the level of pollution control that is used, especially for combustion of RFO.

According to the ISO Standards 14040-44 (ISO, 2006a, 2006b) uncertainty may be introduced in the results of a life cycle inventory analysis (LCI) due to the cumulative effects of model imprecision, input uncertainty and data variability. The specific techniques to quantify this uncertainty and assess its significance may include:

i) Gravity analysis (e.g. Pareto analysis): a statistical procedure that identifies the part of data having the greatest impact on the indicator result. This part may be investigated with increased priority to ensure that sound decisions are made.
ii) Uncertainty analysis: a procedure to determine how uncertainties in data and assumptions propagate in the calculations and how they affect the reliability of the results of the LCI analysis.
iii) Sensitivity analysis: a procedure to determine how changes in data and methodological choices affect the results of the LCI analysis (sometimes also called "scenario analysis" and typically

conducted by changing one-at-a-time relevant framework conditions, e.g. energy system source mix).

None of the LCA studies reviewed in this document included a gravity analysis or an uncertainty analysis. The study by Fehrenbach (2005), updated in 2017 (Abdalla and Fehrenbach, 2017), includes a sensitivity analysis, which investigated the effect of the allocation method, fuel substitution and distribution distances on the LCI analysis results. A similar approach was followed in the study by CalRecycle (Geyer et al., 2013), which performed sensitivity and scenario analysis concerning system parameters such as collection rates, reverse logistics, and disposition routes, and modelling assumptions such as allocation procedures and market effects. The study commissioned by the American Petroleum Institute, (Collins et al., 2017), also performed sensitivity analyses, in this case over a range of model parameters such as used oil collection rates, pollution control systems in combustion plants and energy (or fuel) substitution mixes.

The literature review of environmental, economic and socio-economic assessments of waste oil reveals that studies have traditionally focused on environmental aspects, while the economic and social impacts have been less analysed. There is only one study that assesses the economic and social impacts of waste oil management (CalRecycle, 2016). Due to a lack of data on the external costs of emissions, CalRecycle (2016) does not perform a full cost assessment of recycling pathways. Instead, they compare different policy scenarios in terms of their impact on employment, cost (for instance, spending on subsidies) and emissions (in quantities). They find that the socio-economic effects of waste oil policies that aim at protecting the environment are in most cases small. They highlight, though, that in a few scenarios, the economic effects of environmental policies are more significant, and always positive.

According to environmental LCA studies, the production of regenerated base oil (RGBO) from waste oil reduces most environmental impacts compared with the production of virgin (refinery) base oil. When waste oil management options are compared, regeneration of waste oil is often most beneficial than energy recovery in terms of climate change effects. However, not all LCA studies confirm that regeneration is the best option regarding other impact categories, especially when compared with recovered fuel oil (RFO).

Table 1 provides an overview of the reviewed waste oil management LCAs and their main outcomes. Most studies demonstrate that regeneration is preferable over other waste oil treatment options when the focus is on the Climate Change impact indicator. However, different trends are observed when other environmental impacts are considered, with local conditions and methodological aspects playing an important role in the final outcome of the studies.

Table 1 Overview of reviewed LCA studies focussing on waste oil management and their main outcomes.

Study	Year	Regeneration preferred (Climate Change)	Regeneration preferred (other environmental impacts)	Comment
Grice et al	2014	Yes	Not assessed	-
Abdalla & Fehrenbach	2017	Yes	Yes	-
Abdalla	2022	Yes	Yes (except acidification)	-
Du dak et al.	2021	No	No	Results strongly depend on substituted

				local energy mix
Kanokkantapong et al.	2009	Yes	No	Results strongly depend on substituted local energy mix
Kalnes et al.	2006	Yes	Yes	Only HyLube process
Pires & Martinho	2013	Yes	No	-
Geyer et al.	2013	Yes	No	-
Collins et al.	2017	Yes	No	-

2.3 Socio-economic analyses

At the time of writing, we are only aware of one study that performs a full socio-economic analysis of waste oil recycling pathways (CalRecycle, 2016).[17] This is not too surprising, as the field of socio-economic analysis, including sLCC, is relatively new. In this section, we proceed as follows: We first discuss the methodology and results from CalRecycle (2016) in detail. To get a better idea what a socio-economic analysis could deliver, we then briefly summarise socio-economic analyses of other waste streams.

CalRecycle (2016) uses two different models: one for assessing the micro-impacts within the sector on individual economic entities such as collection centres or haulers, and one for analysing impacts on the macro level, affecting other sectors, as well as distributional impacts. The Direct Impacts Model (DIM) accounts for micro-impacts, while a “Cost-Benefit Analysis” (CBA) model is used for assessing impacts on the sector levels and for the distributional analysis. The DIM feeds into the Life cycle Assessment and into the CBA (see Figure 4). CalRecycle (2016) argue that, due to a lack of data on the external costs of emissions, a full cost assessment cannot be performed and recycling pathways are thus not compared exclusively in terms of cost. Instead, they compare different policy scenarios in terms of their impact on employment, a partial assessment of their cost (for instance, spending on subsidies, increased local economic activity) and emissions (in quantities).

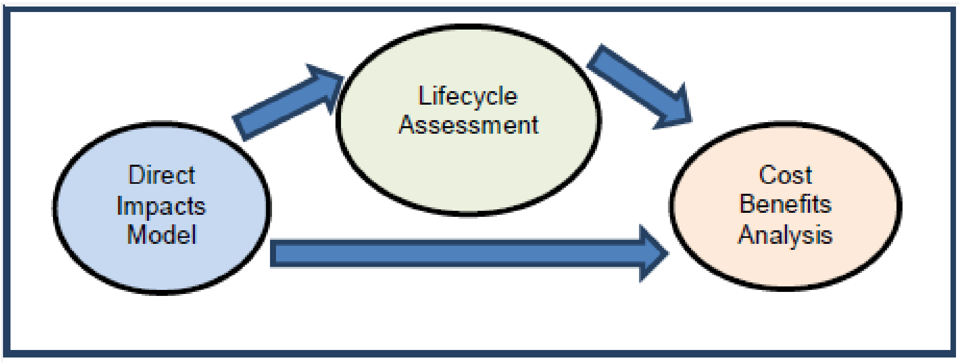


Figure 4 Interaction between CBA, DIM and LCA in the economic analysis by CalRecycle (2016).

The DIM analyses how the used oil market in California changes in response to economic forces and behavioural forces. Economic forces include the price of crude oil, the number of miles people drive in their

[17] The lack of studies in this field is confirmed by CalRecycle (2016), who write that “a comprehensive economic analysis with a traditional lifecycle analysis has not been attempted on this scale before [...]”.

cars, the number of miles between oil changes, fees, incentives and regulatory requirements. The behavioural forces include the price elasticity of consumers.

The CBA uses the outputs of the DIM and the LCA. It models the effects of all the changes made in the DIM on larger groupings of sectors, such as hospitality or construction. The distributional impacts analysis shows the effects of changes in the used oil management system on the rest of the economy, which may include, for example, jobs created in the construction industry if new waste oil processing facilities were to be constructed. It also attempts to estimate the number of restaurant and housing jobs created in response to the additional construction jobs. The external review of the economic analysis (CalRecycle (2016), p.42), however, was sceptical of this approach, stressing that in view of the high uncertainty regarding the quantification of the effects on other sectors, the impact analysis should have rather been done qualitatively.

The study analyses ten scenarios, which mainly differ in the type of actors who receive collection incentives and the type of recycling pathway for which incentives are paid. In scenarios 1-3, existing incentive payments for waste oil collection are increased by 0.4$ per gallon for private households (scenario 1), non-private vehicle waste oil generators such as auto repair stations, quick lube shops, and rental vehicle companies (scenario 2) and industrial oil generators (scenario 3). Scenario 4 analyses the effects of an increase of 0.4$ per gallon in the market price of used oil. In scenario 5, the fee paid for re-refined lubricating oil is reduced by $0.10 per gallon from the previous value of $0.12 per gallon to $0.02 per gallon, while the fee of 0.12$ per gallon still applies to virgin lubricating oil. Scenario 6 is similar to scenario 5, but the 0.1$ per gallon are used to increase the existing 0.02$ incentive payment to re-refiners. Scenario 7 analyses a 0.1$ incentive payment for the production of distilled fuel from used oil (MDO). Scenario 8 considers an incentive payment of 0.1$ per gallon for the production of recycled fuel oil from used oil. Scenarios 9 and 10 analyse different reductions in existing incentive payments and are hence not further discussed here.

The results from the DIM suggest that financial incentives, when applied at moderate levels, have only a small effect on collection rates or processing pathways. These impacts would be larger, however, for incentives above $5 to $10 per gallon. Further, increased market prices for used oil were found to have a much larger, increasing effect on collection rates.

The CBA compares different policy scenarios in terms of their impacts on economic activity and employment outside of the oil sector. CalRecycle (2016) find that the socio-economic effects of waste oil policies that aim at protecting the environment are in most cases small. They highlight, though, that in a few scenarios (2 and 4), the economic effects of environmental policies are more significant, and always beneficial.

To illustrate the scope of such type of analysis, we also identified nine socio-economic analyses of other waste streams (see Table 2). The waste streams analysed are biomass, solid waste and textiles. We also include a study on waste collection (Teerioja et al., 2012). Most studies are based on environmentally or socially extended LCC or LCA. Some studies include external social costs only in the form of the social cost of environmental damages (sometimes called shadow prices, or society's willingness to pay to avoid environmental damage). These studies include Martinez-Sanchez et al. (2015), Razon et al. (2020) and Teerioja et al.(2012).

Diaz et al. (2015) go one step further and additionally assess the impact on (local) employment. Even more social indicators are used in Leal et al. (2019), Morone et al. (2020), Stamford (2020), Tian et al. (2020), Yoewono et al. (2009). These additional indicators are highly context-dependent and can in some cases only be determined through citizen surveys (for example indicators of community approval). Some of these indicators include energy security and import independence (e.g., in the case of waste-to-energy), human rights, local or rural economic activity, food security, inequality (in terms of gender, inter-generational, income or race), large accident risk and other local impacts such as noise, traffic or pollution. As highlighted in Leal et al. (2019) and Yoewono et al. (2009), once several indicators are used, a multi-criteria decision-making model is required to be able to compare different options.

Table 2 Examples of socio-economic analyses (SEA) of other waste streams.

ID	Author(s)	Year	Material	Method	Socio-economic indicators
1	Leal et al.	2019	Textile	Systematic literature review	No concrete indicators, as it is a review. Main focus on social impact of environmental damages, but also local employment and local supply chains.
2	Morone et al.	2020	Biofuel (partially waste)	Literature review	Energy security and independence, local employment, investment and economic activity, rural economic activity, increased food crop prices, food security, gender/income inequality
3	Razon et al.	2020	Biofuel (partially waste)	A review of Life Cycling Costing (LCC) (financial, environmental, social) and an application of LCC to biodiesel production in Vietnam	Damages to society only through monetised environmental damages
4	Martinez-Sanchez et al.	2015	Solid waste	Strict methodological development of LCC, environmental LCC and sLCC and application to solid waste	Only environmental externalities priced at their shadow price level (i.e. society's willingness to pay for avoiding emissions).
5	Martinez-sanchez et al.	2016	Food waste	Environmental LCC and sLCC of food waste management	Only environmental externalities priced at their shadow price level (i.e. society's willingness to pay for avoiding emissions).
6	Yoewono et al.	2009	Solid waste	Multi-criteria decision analysis (MCDA) based on LCC applied to solid waste treatment technologies in Bandung, Indonesia	Job creation, community approval (through surveys)
7	Teerioja et al.	2012	Solid waste collection	sLCC of different waste collection methods in Helsinki, Finland	Environmental costs valued at their societal level (willingness to pay)
8	Stamford	2020	Biomass	Review of life cycle sustainability analyses and application to biomass combustion	Employment (low/medium/high-skill, gender), large accident risk, local impacts (noise, traffic, pollution), human rights, energy security, intergenerational equity

9	(Tian et al., 2020)	2020	Waste to energy	Review of life cycle sustainability analyses (building on LCC) methods	No concrete indicators
10	Diaz et al.	2015	Solid waste collection	Social LCA applied to local waste management in Canada	Employment

In summary, these studies show that including a wider range of socio-economic indicators into economic analyses of recycling options is generally possible, but strongly dependent on the context and the geographical scope of the analysis. Many of the above indicators are not practicable for the socio-economic analysis of waste oil policy, as they are either not relevant in this context (e.g. human rights, food security), or particularly hard to determine at the required level of geographical aggregation (e.g. community approval), which explains CalRecycle (2016)'s focus on economic activity and employment.

2.4 Discussion: Shortcomings and gaps in the existing literature

The literature review of LCA studies carried out in this document reveals several knowledge gaps and limitations.

Similarly to what was observed for the LCI analysis, most LCA studies lack a properly reported life cycle impact assessment. Even though it is required by ISO 14040-44, only a few studies provide an evaluation of the magnitude and significance of the potential environmental impacts of waste oil management. In most cases, not even the impact assessment method is reported.

An additional point of criticism is the fact that most LCA studies that assess the life cycle environmental impacts of regenerated base oil do not specify the grade of such base oil, e.g. API Group I, Group II, etc. The importance of reporting the specific product is twofold. Firstly, it has direct consequences on the substitution of a specific virgin base oil. Secondly, the price of the regenerated base oil is greatly influenced by its quality, grade, etc., which in turn affects the outcome of socio-economic analyses, e.g. life cycle costing (LCC), cost-benefit analysis, etc., that can be performed based on the LCA results.

A final point of criticism is the lack of systematic measures taken to identify and quantify the uncertainty introduced in the results of the life cycle inventory analysis. Although a few studies perform sensitivity analysis on different model parameters, a comprehensive propagation of uncertainty by performing analyses such as a Monte Carlo simulation is missing from all studies.

Regarding the socio-economic studies, the main limitation is that, to our knowledge, only one study on the topic of waste oils is available CalRecycle (2016). While CalRecycle (2016) is certainly breaking new grounds in how it analyses the socio-economic impacts of waste oil recycling options, it has several shortcomings which should be addressed in future studies: First, CalRecycle (2016) does not monetise the external environmental costs. Instead, the study compares emissions in terms of quantities over different scenarios. This can be improved by adopting a similar approach as Martinez-Sanchez et al. (2016) and Martinez-Sanchez et al. (2015), who use the shadow prices of emissions to determine their external cost. Second, the distributional impacts between workers are not fully accounted for, as CalRecycle (2016) only accounts for changes in aggregate employment. This can be overcome by analysing employment numbers by profession or skill level. Third, CalRecycle (2016) has been criticised in its external review (which is included in their main report) for the way in which they determine the economic spillover effects to other sectors. The main point of critique is that the high parameter uncertainty and the strong assumptions in their model calibration severely limit the robustness of their quantitative assessment. This can be addressed by either improving the model calibration or by doing only a qualitative analysis.

3 Methodology

This section details the methods used in the study to quantify the potential life cycle environmental and socio-economic effects (savings or burdens) of waste oil treatment. The aspects relevant to the environmental life cycle assessment (LCA) are described in 3.1, while Section 3.2 provides details on the life cycle costing (LCC) methodology. The methodological considerations of the sensitivity analyses carried in this study are detailed in Section 3.3 and Section 3.4 offers a description of how uncertainty is dealt with in this study. The approaches used for the socio-economic assessment are described jointly with the results in Section 5.

3.1 Life cycle assessment (LCA)

The LCA has been carried out in accordance with the guidelines of the ISO 14040/14044 standards (ISO, 2006a, 2006b) and following established practice for waste management LCA (Clift et al., 2000; Finnveden, 1999; Joint Research Centre, 2012). Specific methodological and modelling rules of the Environmental Footprint (EF) Method relevant to the goal and scope of the study were also applied (European Commission, 2021). These concern, for instance, the selection of impact categories and Life Cycle Impact Assessment (LCIA) methods, the modelling of relevant (ancillary) activities and processes beyond the investigated waste management systems, e.g. electricity, heat, transport, handling of any multi-functionality of such ancillary activities and processes. The selection of secondary datasets and data for modelling was done prioritising the use of EF-compliant datasets. Further details are provided in Section 3.1.6 (life cycle inventory) and Section 3.1.7 (life cycle impact assessment).

3.1.1 Functional unit and key methodological aspects

The functional unit (FU) of both the LCA and LCC defines qualitatively and quantitatively the service under assessment, to be used as a reference to quantify potential impacts and as a basis for comparison. In this study the FU is defined as *"the management of a unit-quantity of waste lubricant oil in the EU, with physico-chemical properties as detailed in Table 4 Waste oil physico-chemical composition, based on the evaluation of the data records by the waste oil regenerators. Values are provided on a dry basis, except when alternatively specified (wt%=weight percent)."* The application of this functional unit enables comparison of different technologies (or different systems of technologies) that are capable to handle the same input-waste while producing similar or different outputs. In this study, the functional unit corresponds to the reference flow of 1 tonne (wet) of waste oil to be managed, including any impurity contained in it. Different properties have been assessed via sensitivity analysis. Note that different products and co-products arise from the valorisation of waste oil, e.g. base oil, fuels, electricity, heat. As the focus is on the management/valorisation of the waste oil, a product-perspective LCA was not applied (i.e. defining a functional unit based on one of the abovementioned products, e.g. 1 kg fuel or 1 kg base oil). Note that a product-perspective would not allow to compare regeneration against energy or fuel recovery. Conversely, a waste management-LCA (at time also called 'process-LCA') perspective was applied, whereby the focus is on the management of a specific waste or feedstock, and the co-products generated via the management operations, whatever they are, are assumed to replace corresponding market products according to the respective quality and substitutability. Note that the use phase and end-of-life impacts of the different products and co-products arising from the valorisation of waste oil are not modelled since they are assumed to be identical between waste oil-derived and virgin product.

3.1.2 System boundary, geographical scope and supporting software

The system boundary includes all the operations involved in the life cycle of the waste, i.e. waste oil collection and transport to intermediate storage plants first and then to waste oil regeneration or energy recovery facilities up until regeneration, transformation into fuel or combustion. The generated waste was assumed to carry no environmental burden, following the common burden-free assumption (Ekvall et al., 2007; Finnveden, 1999), as the impacts associated with the waste production would be the same across all the scenarios investigated. To solve multi-functionality (along with the main service of treating the waste oil, different co-products are generated in each scenario), system expansion was applied following common practice in waste LCA (ISO, 2006a, 2006b). Accordingly, the products and co-products generated along with the management of the waste oil (base oil, fuels, electricity and heat) were credited to the waste management system by assuming the displacement of the corresponding market products obtained from virgin material (i.e. virgin base oil, virgin fuels, etc.) or from conventional energy sources. Notice that this system expansion approach is also in line with the end-of-life approach of the EF-Method, although adapted to the functional unit used in this study (management of waste). To represent the displaced products, the current market average for those products was used. In the default assessment, the current electricity mix considered to be replaced was the EU electricity mix, which is built as combination (weighted average) of the electricity grid mixes of single countries contributing to the total mix (i.e., 31 countries overall). As of 2021 the average EU grid mix consisted of 0.66% solar, 2.38% wind, 3.00% hydro & marine, 0.05% geothermal, 1.59% biomass, 31.56% nuclear, 19.97% lignite, 14.59% hard coal, 25.5% natural gas and 0.70% oil; (Sphera, 2021)). For industrial heat production, an average EU heat mix was calculated representing the supply and combustion of the different fuels (42.4% natural gas, 30.8% hard coal, 21.8% biomass, 5.0% heavy fuel oil; (Sphera, 2021)). A sensitivity analysis was carried out to investigate the effect of the energy mix (electricity and heat) on the life cycle impacts (see Section 3.3). As for the fuel mix used in the cement kilns, a mix consisting of 20% biomass, 30% alternative fuels (65% solid recovered fuel/refuse-derived fuel (SRF/RDF), 17% used tyres, 11% animal meal, 8% used solvents) and 50% fossil fuels (25% hard coal, 25% petroleum coke) was assumed, conforming to the current market shares (CEMBUREAU, 2021). As for electricity and heat, also here a dedicated sensitivity analysis was carried out to investigate the effect of the energy mix (fuel mix) on the life cycle impacts (see Section 3.3). For the base oils Groups I, II & III, as well as for the other products and co-products (gasoil, fuel oil, naphtha, etc.), the corresponding virgin product counterparts were assumed to be displaced (current market average mix).

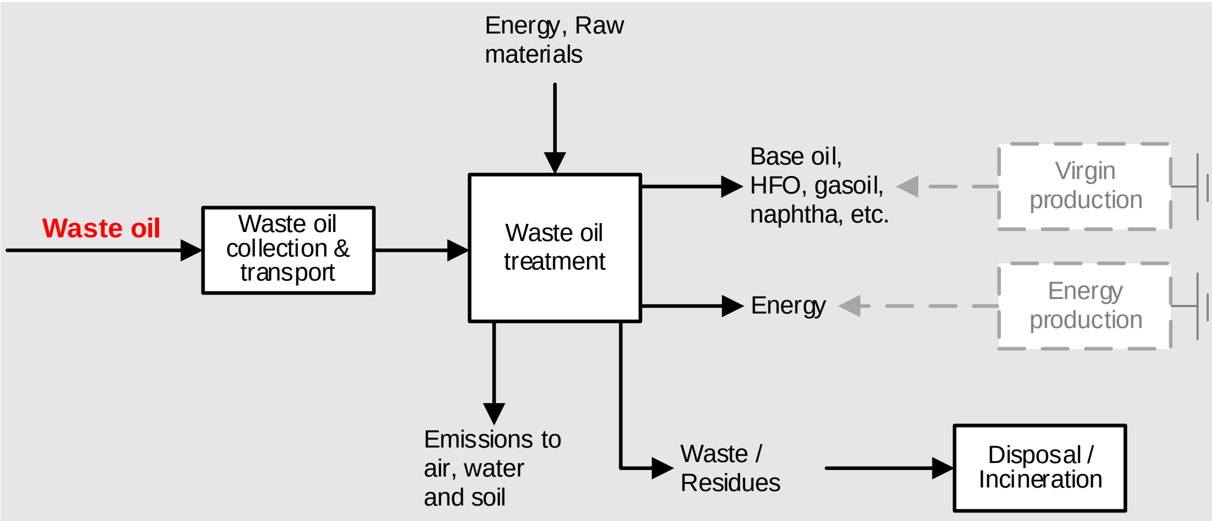


Figure 5 Simplified diagram of the system boundary. Waste enters burden-free (i.e. upstream impacts related to production, supply and use are not included) and products/co-products from treatment substitute primary production of energy and materials in the EU or global market. Accordingly, black-continuous lines and boxes indicate induced processes that are required to handle the waste, while grey-dotted lines indicate avoided processes thanks to the substitution of primary material and energy with waste-derived material and energy.

The geographical scope of the study is the European Union, represented by the entirety of its Member States, i.e. EU-27. The investigated waste oil regeneration and energy recovery pathways are therefore modelled with reference to this geography, or other enlarged European geographies[18] when no data for EU-27 were available.

The assessment of the investigated waste management scenarios and technologies is conducted with the support of the LCA software EASETECH v3.4.0 (Astrup et al., 2012; Clavreul et al., 2014), specifically developed to assess waste management technologies and systems. This tool was applied to model the different waste management activities and processes included in each scenario, and to calculate the respective potential environmental impacts and life cycle costs.

[18] For instance, “EU+EFTA+UK” or “Europe without Switzerland”.

3.1.3 Definition of scenarios

Eight alternative scenarios (pathways) for waste oil management were assessed in this study, which include three regeneration pathways plus five energy recovery pathways. A summary of the scenarios, their main treatment technologies and their main products and co-products can be found in Table 3.

Table 3 Summary of scenarios assessed in the study and main characteristics. DIST: distillation; CKLN: cement kiln; ER: energy recovery; HYDT: hydrothermal; HWIN: hazardous waste incinerator; INBO: industrial boiler; RG: regeneration; SOLV: solvent extraction; WODF: waste oil-derived fuel.

Scenario name	Type of treatment	Key technology	Main products
RG-HYDT	Regeneration	Hydro-treatment	Base Oil (Group I, II & III)
RG-SOLV	Regeneration	Solvent extraction	Base Oil (Group I)
RG-DIST	Regeneration	Distillation	Base Oil (Group I)
ER-WODFa*	Energy recovery	Distillation	Distillate fuel
ER-WODFb**	Energy recovery	Distillation	Distillate fuel
ER-CKLN	Energy recovery	Combustion – cement kiln	Heat
ER-HWIN	Energy recovery	Combustion – hazardous waste incinerator	Electricity and heat
ER-INBO	Energy recovery	Combustion – industrial boiler	Heat

*This scenario considers the gasoil/fuel oil fraction to be used as fuel replacing virgin marine fuel.
**This scenario considers the gasoil/fuel oil fraction to be used as fuel replacing virgin light fuel oil.

3.1.4 Data collection

In order to collect life cycle inventory and economic data on the various waste oil management technologies/processes, the JRC contracted a consortium formed by Ifeu and RDC Environment. More details on the number of stakeholders that were contacted, the proportion of stakeholders, etc. can be found in 3.1.6. In order to mitigate concerns about business confidentiality, the data was collected under the condition that only aggregate values were to be used, which would not allow to infer data for individual installations.

In addition, on 16 December 2021 the JRC organised a stakeholder workshop for operators that had participated in the data collection, for waste oil industry umbrella organisations and for other relevant stakeholders. The aim of this Workshop was to: i) illustrate the work performed so far by the JRC, including data collection by IFEU/RDC Environment and preliminary LCA results; ii) get feedback from the stakeholders, both during the workshop and as part of a follow-up written stakeholder consultation where stakeholders had about a month to provide further data and feedback to the study. The latter information has been used to improve the LCA modelling and is incorporated in the last version of the report.

3.1.5 Characterisation of waste oil

The average composition of the waste oil that is treated in regeneration and energy recovery plants was obtained from questionnaires sent to participating companies. Although there are indications that in practice the quality of waste oils treated at regeneration/WODF plants and at plants for energetic use (cement works, hazardous waste incinerators, industrial boilers, etc.) may differ, for a life cycle comparison of technical options the same input quality should be used as a basis for the comparison, i.e. the same functional unit. For this reason, the same waste oil quality was considered across all scenarios. In the *default* assessment, this is a waste oil with a water content of ca. 7%, as detailed in Table 4. In addition, a sensitivity analysis was carried out to investigate the effect of the water content on the life cycle impacts of each scenario (see Section 3.3). After consultation with experts, the waste oil's water content assumed in this *sensitivity analysis* was fixed to 20%.

Table 4 Waste oil physico-chemical composition, based on the evaluation of the data records by the waste oil regenerators. Values are provided on a dry basis, except when alternatively specified (wt%=weight percent).

Property	Value	Unit	Property	Value	Unit
Content of base oil	67.7	wt%	Copper - Cu	36.6	mg/kg
Water content	6.7[1]	wt%	Iron – Fe	674	mg/kg
Diesel content	7.3	wt%	Lead – Pb	51.1	mg/kg
Gasoline content	14.4	wt%	Magnesium - Mg	113	mg/kg
Asphalt content	3.0	wt%	Manganese - Mn	8.8	mg/kg
Sediment content	0.6	wt%	Mercury - Hg	0.8	mg/kg
Ash content	0.7	wt%	Nickel - Ni	4.8	mg/kg
PCB's	5.9	mg/kg	Silicon - Si	536	mg/kg
PAH's	86.8	mg/kg	Tin – Sn	4.6	mg/kg
Elemental composition			Thallium - Tl	0.7	mg/kg
Carbon - C	80.0	wt%	Vanadium - V	1.3	mg/kg
Hydrogen - H	12.0	mg/kg	Zinc - Zn	601	mg/kg
Oxygen - O	0.5	mg/kg	*Others*		
Nitrogen - N	0.1	mg/kg	Boron - B	61.9	mg/kg
Sulfur - S	5213	mg/kg	Fluor - F	31.6	mg/kg
Phosphorous - P	401	mg/kg	Iodine - I	2.7	mg/kg
Chlorine - Cl	1928	mg/kg	Silver - Ag	5.0	mg/kg
Metals			Molybdenum - Mo	25.7	mg/kg
Aluminum - Al	42.3	mg/kg	Selenium - Se	1.4	mg/kg
Antimony - Sb	2.4	mg/kg	Scandium - Sc	5.0	mg/kg
Arsenic - As	1.2	mg/kg	Strontium - St	2.7	mg/kg
Barium - Ba	9.3	mg/kg	*Other properties*		
Cadmium - Cd	0.8	mg/kg	Lower heating value	36.8	MJ/kg
Calcium - Ca	1373	mg/kg	Viscosity[2]	70.4	mm/s^2
Chromium - Cr	7.0	mg/kg	Density[2]	867	kg/m^3
Cobalt - Co	1.1	mg/kg			

[1]Set to 20% in the *sensitivity analysis*.
[2]Wet basis.

3.1.6 Life cycle inventory modelling

The collection of life cycle inventory data for all relevant technologies applied for waste oil management was based on primary data and information provided by stakeholders participating in the data collection exercise (Section 3.1.4). Whenever needed, these data were complemented with additional data from existing databases, the literature, or specific assumptions, as described in the following sections. For more information on the ranges of the input-output data provided by the stakeholders see Annex 1.

The LCI was developed at European level, using questionnaires sent directly to plant operators. The questionnaires addressed foreground technical data (i.e. process-related input-output flows under the control of operators such as energy, chemicals and materials consumption, plants emissions and output-products), economic data, data regarding logistics and regarding the physico-chemical composition of the treated waste oil. Where primary data from plant operators were not available, data gaps were closed in accordance with the following hierarchy:

- Data obtained by analogy with other measurements or plausible model data.
- Data from freely available sources, i.e. literature data or open source databases.
- Expert judgements.

The background (also called 'secondary') life cycle inventory data for ancillary materials and energy (i.e. data representing their supply and consumption in the global or EU market) was sourced from the Environmental Footprint (EF) database (Sphera, 2021) when data were available, using the ecoinvent database v3.7 as a back-up when EF-compliant data was not available (ecoinvent centre, 2021). These secondary datasets represent current (or recent past) average EU values, in line with the geographical scope of the study. If no datasets were available for EU, alternative datasets for single Member States were used as best available proxies. Similarly, proxy datasets were used when no representative datasets were available for the specific process to be modelled. Moreover, the selected datasets were complemented, where needed, with specific literature data or assumptions.

The same overall approach was applied to model non-elementary inputs and outputs of regeneration and energy recovery processes (e.g. base oils, naphtha, fuel oil, heat, electricity, wastewater, solid waste, etc.).

3.1.6.1 Collection and transport of waste oil

Waste oil was assumed to be transported by truck along an average distance of 60 km from waste producers to an intermediate storage facility. A lorry with a full load mass between 28-32 tonnes was assumed to be used, as modelled by the EF-compliant dataset: "*[EU+EFTA+UK] Articulated lorry transport, Total weight 28-32 t, mix Euro 0-5; diesel driven, Euro 0 - 5 mix, cargo | consumption mix, to consumer | 28 - 32t gross weight / 22t payload capacity*". For the transport of waste oil from the intermediate storage facility to the regeneration/energy recovery facility, an average distance of 242 km was assumed. The same EF-compliant dataset as in the previous case was used. In accordance with the reference geography of these aggregated datasets, the diesel mix for countries in EU-27, EFTA and UK is considered as a fuel input to both of them.

3.1.6.2 Regeneration of waste oil

Within this study, 21 companies were identified as currently operating in the business of regeneration in Europe. They were contacted and a questionnaire was sent to each company. Nine companies provided completed records. Two others confirmed their willingness to provide data, but did not have sufficient data available due to the recent start of operations. In the regeneration business, three different process archetypes exist to re-process waste oil back into base oil:

- Hydro-treatment
- Solvent extraction
- Distillation

Hydro-treatment or solvent extraction facilities are mostly combined with one or more additional treatment steps, such as atmospheric or vacuum distillation, thin film evaporation or thermal de-asphalting chemical treatment.

In typical waste oil hydro-treatment process, waste oil and hydrogen are mixed and heated to 250-350 °C prior to being fed into the reactor. The hydrogenation reaction takes place at high pressure (20-60 bar) in the presence of a catalyst. Depending on the desired selectivity of the reaction, different catalysts, such as Co-Mo or Ni-Mo with alumina and alumina-silica as the most applied catalysts (Kupareva et al., 2013). In a subsequent step, the liquid phase is separated from the gaseous phase and stripped from remaining dissolved gases and water, with the excess hydrogen being recirculated back to the first step. A depiction of a typical waste oil hydro-treatment process is shown in Figure 7.

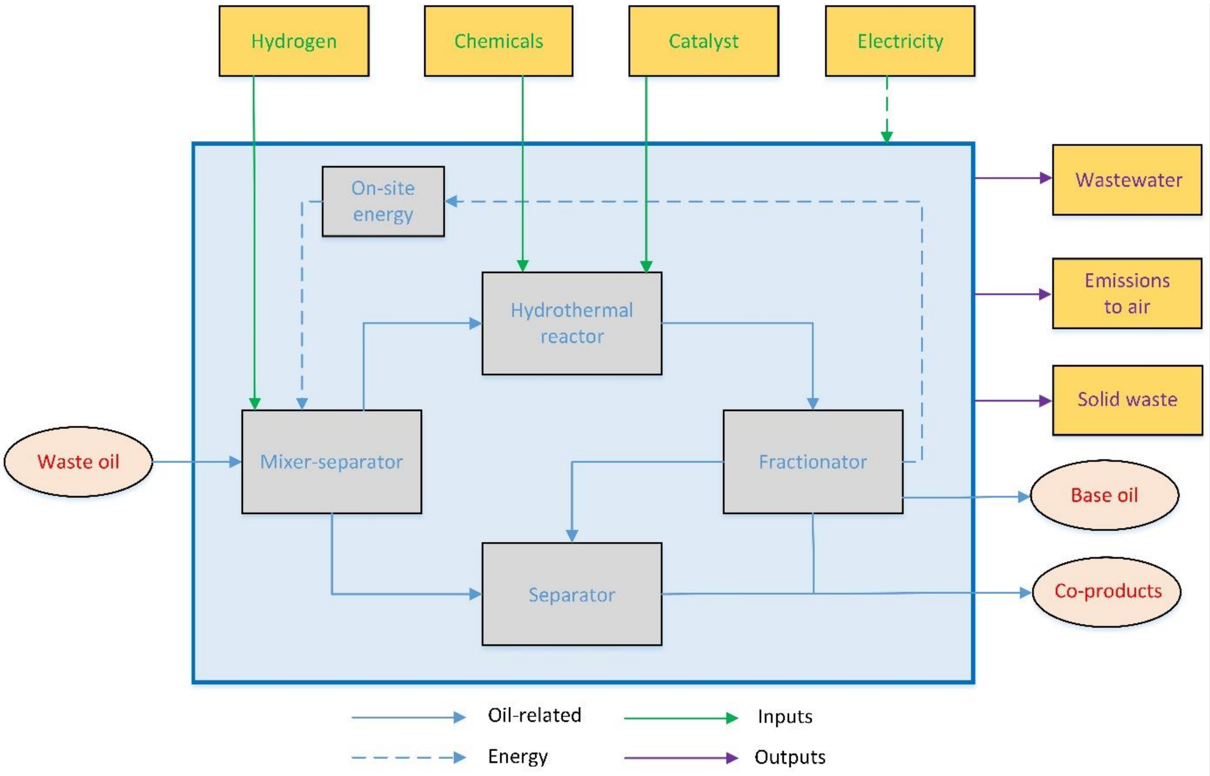


Figure 6 Process flow diagram of the hydro-treatment regeneration process.

The hydro-treatment process is seen as superior to other technologies in terms of yield and product (base oil) quality. Furthermore, it is not greatly affected by the feedstock chemical composition and can effectively remove contaminants present in the waste oil such as chlorides. However, when compared to solvent-extraction, a number of disadvantages can be observed, namely: high operating temperatures and pressures, resulting in a higher energy consumption; the need for a hydrogen supply, catalyst regeneration steps and hence high operational costs. The hydro-treatment process is implemented in the EU by the HyLube Process (Puraglobe, Germany), Revivoil (Itylium, Italy), the Cyclone process (LPC, Greece) and TECOIL (Finland).

The solvent-extraction process relies on a solvent, e.g. liquid propane, to selectively enrich and subsequently remove aromatic components from the waste oil. The liquid-liquid separation is based on the different solubility of the individual substances in the solvent. As it is common in liquid–liquid extraction processes, two different outputs are obtained: the extract, which is enriched in the dissolved substances, and the raffinate, which is the fraction that is depleted in the waste oil's dissolved compounds. The latter fraction consists of a mixture of the desired saturated compounds and parts of the solvent. Both fractions, the raffinate and the extract, are subsequently separated and treated to recover the solvent to be reused in the process. The recovered fraction, i.e. the raffinate, undergoes a de-asphalting process to be further processed into base oil and asphalt as a by-product. Typically, the extraction is set up in an extraction tower, similar to e.g. a distillation column, with rising temperatures from bottom to top and a counter-current solvent feed (top to bottom), with rising temperatures increasing selectivity (Kupareva et al., 2013).

The main advantages of the solvent-extraction route are:

- Preservation of all synthetic base oil compounds
- Low pressure and temperatures
- Solvent recovery
- Complete removal of toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs)
- Low waste quantities

On the other hand, the main disadvantage of this technology is the dependence on the waste oil feedstock quality. As no chemical processing of the waste oil's hydrocarbons takes place, the re-refined base oil is limited to the feedstock quality and cannot exceed its properties, no upgrading is possible (Kupareva et al., 2013). This results in lower grade base oils when compared with the more complex hydro-treatment process route described above. A graphical representation of a typical waste oil solvent extraction process is shown in Figure 7.

The solvent extraction process is implemented in the EU by AVISTA (Germany) and AVISTAGreen (Denmark) with the “Enhanced Selective Refining” and by Sertego (Spain).

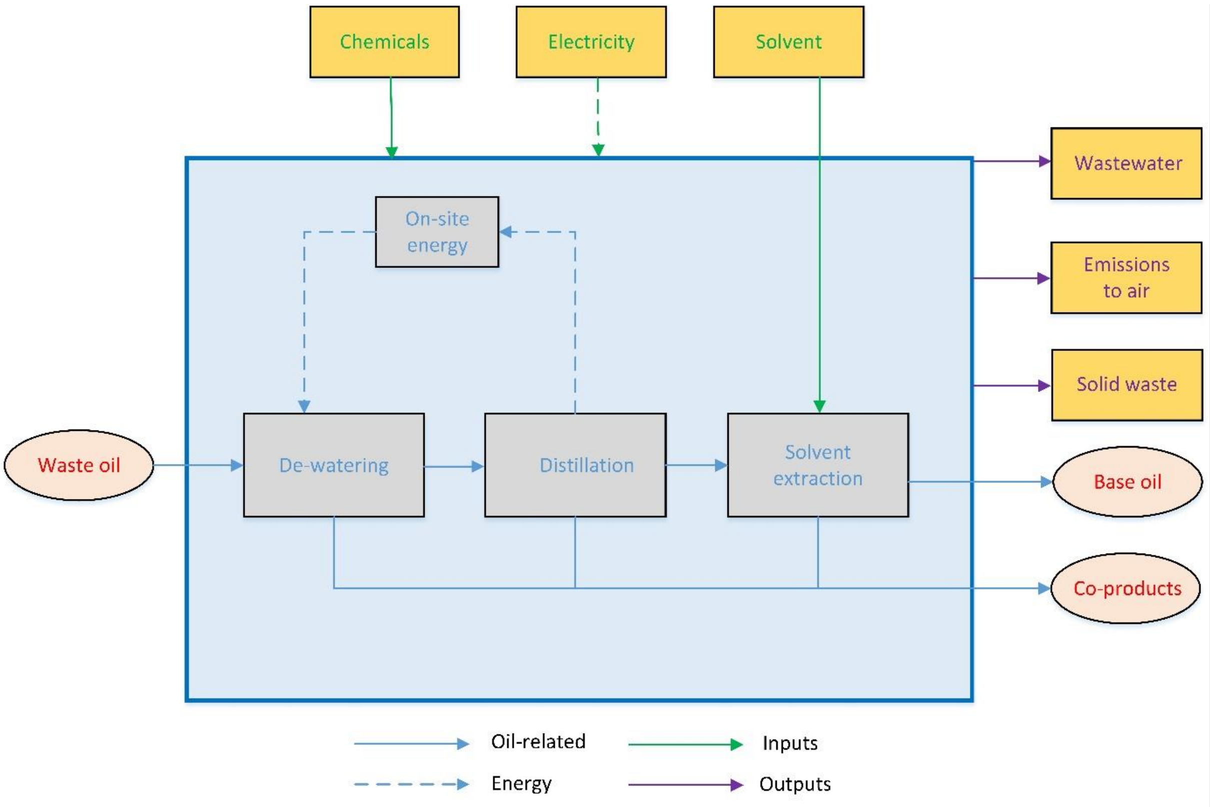


Figure 7 Process flow diagram of the solvent extraction regeneration process.

As described earlier in this section, the majority of regeneration plants in the EU do not exclusively employ hydro-treatment or solvent extraction as a major process step. In some cases, extraction or hydrogen is used for finishing the core distillate. On the market, there exists a number of different distillation techniques, such as:

- Vacuum distillation
- Thin film evaporation
- De-asphalting

The distillation process is implemented in the EU by Cator, Eco Huile (Aurea group), Electrical Oil Services, Enviroil, Enviroil / R.A.M. Oil, Flucar Refinery /Jasol, Green Oil and Lubes, Jedlice Oil Refinery / Orlen Group, Lubrica, OSILUB, Südöl Eislingen and Whelan refining. A graphical representation of a typical waste oil distillation process is shown in Figure 9.

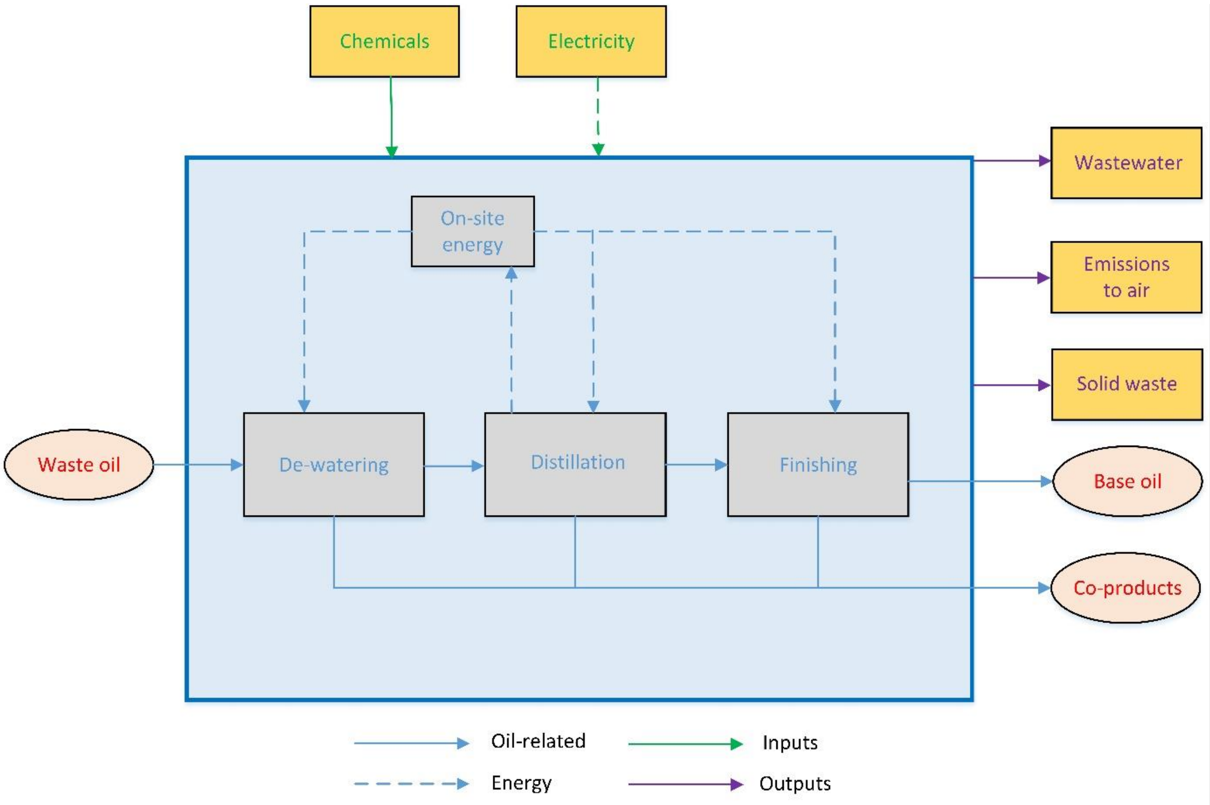


Figure 8 Process flow diagram of the distillation regeneration process.

Across all the modelled waste oil regeneration processes, electricity use was assumed to be entirely sourced from the grid, regardless of any specific energy source reported in the originally collected data (which refer to particular installations), since the assessment aims at reflecting average EU conditions and recycling plants, rather than very local situations that would restrict the validity and applicability of the results. For the same reasons, thermal energy requirements of the processes were assumed to be fulfilled by the estimated EU average mix of thermal energy, regardless of any specific source referred to in the collected data. Further details on the modelling of electricity and thermal energy inputs are provided in Section 3.1.6.

Suitable EF-compliant datasets representative of average EU conditions were applied, where available, to model production of ancillary inputs (e.g. chemicals, additives, detergents, washing agents), supply of fuels for internal movement and of process water not directly withdrawn from nature, as well as external treatment of wastewater, sludge and process waste due to material and product use. Alternatively, relevant datasets from the ecoinvent database were used when EF-compliant datasets were not available.

3.1.6.3 Energy recovery of waste oil: processing to fuel

Eleven companies were identified in Europe as currently operating in the business of processing waste oil into fuel, which involves separating the light components (and thus those with a lower flash point) from the heavy ones via evaporation/distillation. This process generates a distillate fuel, which is the one assessed in this study under scenarios ER-WODFa and ER-WODFb. The former scenario considers the recovered distillate fuel to substitute marine fuel in ships while the latter considers the recovered distillate fuel to substitute light fuel oil in industrial boilers. In order to avoid confusion due to nomenclature (different names are used in the existing literature to refer to this type of processes, e.g. processed fuel oil, recycled fuel oil, recovered fuel oil, etc.) the distillate fuel is referred to in this study as *waste-oil derived fuel* (WODF). It should not be confused with lower grade recovered fuel oil (RFO), also known as processed fuel oil (PFO) in the UK, a sub-category that can be achieved by basic purification processes, such as dewatering or the removal of suspended matter through chemical precipitation, filtration, sedimentation and centrifugation. The latter waste oil treatment route (mild processing to RFO) was not assessed in this study due to lack of input-output life cycle inventory data.

One of the main uses of waste oil-derived fuel (WODF) is in the marine sector. Since 1 January 2020, the sulphur content in marine fuels must be reduced from 3.5 % to 0.5 %, according to an IMO[19] resolution, which is implemented by Directive 2012/33/EU[20]. Owing to the low sulphur content of WODF, it appears to be increasingly attractive for use in the marine sector, rather than in stationary boilers. Note that WODF may be used as marine fuel (either "as is" or blended with virgin fuel oil) as it would comply with the ISO 8217:2017[21] standard, whereas lower-grade RFO would not comply with such standard due to the very high level of calcium, phosphorus, zinc (among the others) present in lower-grade RFO. See Section 1.4.2 for more details on legal and illegal use of waste oil in the marine fuel sector.

3.1.6.4 Energy recovery of waste oil: direct incineration

In the EU, direct incineration of waste oil for energy recovery is established in:

- Cement works
- Lime works
- Steel industry
- Power plants
- Hazardous waste incinerators

Co-combustion in cement kilns was considered to be the currently most relevant technical option for direct energy recovery of waste oil in Europe. In this study we attempted, supported by the cement producer's umbrella organisation CEMBUREAU, to retrieve specific data on the emissions attributable to waste oil combustion in cement kilns, the so-called transfer coefficients. Yet, this was not possible as transfer coefficients are not collected on a regular basis and, when they are collected by plant operators, the emissions measured at the stack are strongly dominated by release from the burning of the raw meal. For this reason, combustion transfer factors were retrieved from the literature. The combustion transfer factors of the scenarios considering the direct incineration of waste oil in a hazardous waste incinerator (HWI) and in an industrial boiler were calculated using an in-house Excel-tool developed by RDC environment (IFEU, 2021). This tool, which is mainly based on the Best Available Techniques (BAT) Reference Document for Waste Incineration[22], allows the user to obtain combustion transfer coefficients to air, water and soil for a specific waste oil composition and incinerator configuration. The default parameters of this tool needed to be adapted to represent the European average waste oil composition as well as the average process conditions of waste incinerators and boilers. Note that burning waste oil in these facilities does not lead to changes in the configuration of the process.

3.1.6.5 Recovered products and substitution of corresponding market products

Recovered products and co-products were identified as those process outputs that can be directly sold on the market and used as such to replace their virgin material counterparts. The same strategy was followed to identify fuels or energy (electricity and heat mix) that were produced as part of the waste oil treatment. Waste-derived fuels such as heavy fuel oil, light fuel oil, light ends may be used, partly or entirely, as a source of energy to be used on-site in the plant. In such case, they are assumed to substitute the EU average heat mix, as described in Section 3.1.2.

As described earlier in Section 3.1.2 with the applied methodological approach and system boundary, all recovered products and co-products were assumed to replace equivalent primary products on the market, obtained from virgin or conventional production routes. No substitution factors (quality ratios) were applied since it was assumed that the waste oil-derived products and co-products have the same quality as the virgin materials that they replace, i.e. they can be used in the same application without further processing. Cradle-to-gate burdens associated with avoided market-average production of replaced primary/conventional products were modelled based on suitable EF-compliant or ecoinvent datasets for each substituted product.

[19] International Maritime Organisation, an agency of the United Nations
[20] Directive 2012/33/EU of the European Parliament and of the Council of 21 November 2012 amending Council Directive 1999/32/EC as regards the sulphur content of marine fuels
[21] ISO 8217:2017 Petroleum products — Fuels (class F) — Specifications of marine fuels
[22] EUR 29971 EN

Table 5 *Summary of the modelling of the (virgin) market products substitution by products and co-products generated from the investigated waste oil management scenarios.* presents a summary of the modelling choices regarding the (virgin) market products substitution by products and co-products produced from the waste oil management scenarios investigated.

The distillate fuel that is produced in the energy recovery scenario ER-WODFa is assumed to be blended with virgin heavy fuel oil in a proportion of 5:1 (5 parts WODDF:1 part virgin heavy fuel oil; HFO), which is then used in the marine sector. Both the emissions from the combustion of the WODF-virgin HFO blend and the avoided emissions from the combustion of virgin marine fuel (assumed as 75% light fuel oil, 25% heavy fuel oil) were taken into account in the scenario.

In the case of waste oil replacing conventional and other alternative fuels used in cement kilns, the avoided burdens considered not only those from extraction and supply of the specific fuel, but also avoided airborne and waterborne emissions from its combustion in the kiln (estimated based on RDC's dedicated, input-specific model for hazardous waste incineration; (IFEU, 2021)). Additional emissions from combustion of waste oil in the kiln, estimated based using the same model, were also taken into account in the scenario, as these emissions differ from those associated with combustion of the replaced fuel mix. The fuel mix used in the cement kilns consisted of 20% biomass, 30% alternative fuels (65% solid recovered fuel/refuse-derived fuel (SRF/RDF), 17% used tyres, 11% animal meal, 8% used solvents) and 50% fossil fuels (50% hard coal, 50% petroleum coke), conforming to the current market shares (CEMBUREAU, 2021).

Table 5 Summary of the modelling of the (virgin) market products substitution by products and co-products generated from the investigated waste oil management scenarios. CKLN: cement kiln; DIST: distillation; ER: energy recovery; HYDT: hydrothermal treatment; HWI: hazardous waste incineration; INBO: industrial boiler; SOLV: solvent extraction; WODF: waste oil-derived fuel.

Scenario name	Type of treatment	Main products/co-products	Substituted (virgin) products
RG-HYDT	Regeneration	RGBO (Group I, II & III) Naphtha Light fuel oil Heavy fuel Oil Bitumen Light ends	Base oil (Group I, II & III) Naphtha Light fuel oil Heavy fuel oil Bitumen Average EU heat mix (industrial)
RG-SOLV	Regeneration	RGBO Group I Light fuel oil Heavy fuel Oil Bitumen Flux	Base oil Group I Light fuel oil Heavy fuel Oil Bitumen Heavy fuel oil
RG-DIST	Regeneration	RGBO Group I Light fuel oil Heavy fuel Oil Bitumen Light ends	Base oil Group I Light fuel oil Heavy fuel oil Bitumen Average EU heat mix (industrial)
ER-WODFa*	Energy recovery	Distillate fuel Naphtha Heavy fuel oil Sludge Light ends	Marine fuel Naphtha Heavy fuel oil Light fuel oil Average EU heat mix (industrial)
ER-WODFb**	Energy recovery	Distillate fuel Naphtha Heavy fuel oil Sludge Light ends	Light fuel oil Naphtha Heavy fuel oil Light fuel oil Average EU heat mix

			(industrial)
ER-CKLN	Energy recovery	Heat	Average EU heat mix (cement kilns)
ER-HWIN	Energy recovery	Electricity and heat	Average EU electricity and heat mix
ER-INBO	Energy recovery	Heat	Average EU heat mix

*This scenario considers the recovered distillate fuel to be blended with virgin heavy fuel oil in a proportion of 5:1 and replacing virgin marine fuel (assumed as 75% light fuel oil, 25% heavy fuel oil)

**This scenario considers the recovered distillate fuelto be replacing virgin light fuel oil

3.1.7 Life cycle impact assessment (LCIA)

The LCA software EASETECH v3.4.0, specifically developed to assess waste and technology systems (Astrup et al., 2012; Clavreul et al., 2014), has been used to model the waste management scenarios and quantify the environmental impacts, following the EF Life Cycle Impact Assessment method (v3.0) (EC-JRC, 2012). The following 14 impact categories included in the EF 3.0 method were considered: Climate change (CC), Ozone depletion (OD), Human toxicity, cancer (HT-cancer), Human toxicity, non-carcinogenic (HT-non-cancer), Particulate matter (PM), Ionising radiation (IR), Photochemical ozone formation (PCOF), Acidification (AC), Eutrophication, Terrestrial (EUT-terrestrial), Eutrophication, Freshwater (EUT-freshwater), Eutrophication, Marine (EUT-marine), Ecotoxicity freshwater (ET-freshwater), Resource use, minerals and metals (RU-minerals and metals), Resource use, fossil (RU-fossil). The impact categories "Water Use" and "Land Use" originally included in the EF method were not considered in the assessment, due to current absence of regionalised water and land use flows in the EASETECH software, leading to potential discrepancies between regionalised life cycle inventory flows originally used in the applied background (EF-compliant) datasets and non-regionalised flows currently used for life cycle impact assessment in EASETECH. However, water and land use are not expected to be relevant categories for the waste management scenarios assessed, as waste management activities do not generally involve substantial water use or land use and/or land transformation burden (no agricultural or forestry activities are normally involved) relative to virgin production activities. Completeness of results is thus only marginally affected by these exclusions.

3.2 Life cycle costing

The LCC adheres to state-of-the-art LCC methodology as presented in Hunkeler et al. (2008) and Martinez-Sanchez et al. (2015). The LCC and LCA share the same object, scope, functional unit, and system boundaries. For the former, differently than the LCA where a zero-burden assumption was taken, the waste oil was assigned a price to reflect different qualities (represented in the default and sensitivity analysis).

The cost assessment includes two types of costs: internal costs and externalities (external costs). Internal costs include budget costs and transfers; strictly speaking, budget costs are costs incurred by the different actors involved in the management chain of the waste oil (collectors, operators, transporters, etc.), while transfers refer to money redistributed among stakeholders (taxes, subsidies, value added tax - VAT, and fees). In our analysis, for the purpose of simplicity and the resolution of the data obtained, we will refer only to the aggregated internal costs.

Externalities are non-monetary transactions representing the costs caused by each emission to society, reflected by the so-called shadow prices of emissions as proposed in Bijleveld et al. (2018). Notice that these include prices for air/soil/water emissions but not for disamenities such as nuisance, noise, odour, congestions, or other similar social effects. Notice that any externality that is currently already priced, e.g. in form of a tax by an authority and paid by a stakeholder within the management system becomes a transfer, i.e. an internal cost[23].

[23] This is the case for the scenario ER-CKLN modelled in this study (waste oil incineration in cement kilns), which falls under the EU Emissions Trading System.

As for the overall assessment, we distinguish two types of LCC: the conventional LCC (CLCC) describes the financial cost as the sum of budgets costs and transfers, i.e. internal costs, of managing the waste oil, and thus represents a classic financial assessment. The societal LCC (SLCC) sums internal and external costs, both expressed as shadow prices[24], to quantify the total cost incurred by society, thus reflecting a socio-economic assessment.

No discounting or deflation was applied to costs or externalities occurring in the future. All costs that were found in the literature or collected as primary data were adjusted for inflation to EUR2019. Capital investments (CAPEX) were first amortised, assuming a 5% market interest rate, and then annualised using a 20-year lifetime for buildings and 5-8-year for equipment, as detailed in Martinez-Sanchez et al. (2015). Maintenance and insurance were accounted for and assigned to the CAPEX.

The CLCC also allows deriving the total employment associated with the waste management system, expressed as full-time equivalent jobs per tonne of waste oil managed (FTE/tonne). For the specific shadow price of CO_2 we used the updated figure suggested by CE Delft and DG MOVE for 2030, i.e. 100 €/tonne CO_2 that is recommended as a default value (van Essen et al., 2019; Bijleveld et al., 2018).[25] The LCC was implemented using the software EASETECH v3.4.0 (Astrup et al., 2012; Clavreul et al., 2014).

3.3 Sensitivity analysis

Five sensitivity analyses were performed to test important framework assumptions: with the first (SA1 – Energy), we tested the sensitivity of the results to the average energy mixes applied in the model (e.g. average electricity, heat, and fuel mix at the kiln). The second sensitivity analysis (SA2 - Waste quality), tested the sensitivity of the results to the specific waste oil quality (physico-chemical composition). The third sensitivity analysis (SA3 – Crude oil price) tested the effect of crude oil prices on the LCC results. In the fourth sensitivity scenario (SA4 – Intra EU emissions), we only consider emissions that take place within EU countries. Finally, in the fifth sensitivity analysis (SA5 – EU ETS), we assume that GHG emissions are already covered by the EU ETS or by effort sharing regulations.

First, in view of the Green Deal, the EU energy mix is expected to change substantially over the coming years. To take this into account, for the electricity provision analysis (SA1), a future mix was calculated based on the 2030 EU27-wide projections of the GECO report (42% wind, 23% solar, 7% nuclear, 12% natural gas, 7% hydro, 3% hard coal, 3% oil, 3% biomass; (Keramidas et al., 2018)), instead of using current average values. The same was done for industrial heat (43% biomass, 27% natural gas, 24% heavy fuel oil). The mixes were calculated as the difference between 2030 and 2015 (last year reported), in the attempt to represent the changes in the energy market in the next decade (marginal suppliers; (Consequential-LCA, 2020). For the future (2030; SA1) fuel mix at the kiln, a mix consisting of 30% biomass, 30% alternative fuels (65% SRF/RDF, 17% used tyres, 11% animal meal, 8% used solvents) and 40% fossil fuels (of which, 50% hard coal, 50% petroleum coke) was assumed on the basis of (CEMBUREAU, 2021).

Second, stakeholders agree that the quality of waste oil in the EU is heterogeneous; in particular with respect to the water content, which represents an economically relevant cost factor for its processing. To reflect this, we performed a sensitivity analysis (SA2) by assuming an increase in the water content from 7% (base case) to 20% of the wet weight. Because of this, a pre-treatment for water removal was applied in the regeneration and WODF scenarios, assuming to use a technology based on thermal evaporation of the water (to lower it from 20% to 7%, as in the default) consuming 3.4 MJ heat/kg water evaporated (including both sensible heat and latent heat of vaporisation). The removed water (130 kg/tonne waste oil) was assumed to be treated at an industrial wastewater treatment plant assuming a treatment cost of 29 €/tonne wastewater (storage costs not included) and using a background dataset representing wastewater treatment from ecoinvent v3.7 (ecoinvent centre, 2021).

[24] In the CLCC, budget costs are accounted for in “factor prices” (market prices excluding transfers). Internal costs are then the sum of budget costs expressed as factor prices (market prices) plus transfers. Instead, budget costs in the LCC should be accounted for in “shadow prices” (also called accounting prices or opportunity costs, and representing the willingness to pay for a good or service). Thus, when reporting the internal costs in the LCC one should in principle remove the transfers and recalculate the remaining budget costs as shadow costs (e.g. the literature suggests the following calculation: market price x 1.325; (Martinez-Sanchez et al., 2015). In this analysis, we assume that the shadow price (of the LCC) is equal to the internal price (of the CLCC), which implies assuming perfect market conditions. This approach was also taken in recent LCCs on other waste streams (Albizzati et al., 2021).

[25] This value also roughly corresponds with EU ETS prices at the time of writing (Nov. 2022).

Third, given the historically high volatility of the crude oil price, and its significant impact on, e.g., regeneration economics, a sensitivity analysis (SA3) was performed by assuming an increase from 65€/barrel (base case) to 120€/barrel. Note that the sensitivity analysis considered only direct effects of crude oil prices, i.e. changes in the price of crude oil itself or petroleum products (base oil, naphtha, fuel oil, etc.). Therefore, the indirect effect of crude oil variations on other process inputs such as natural gas, electricity or chemicals was not considered.

Fourth, given that environmental impacts occurring outside the EU might be of lesser concern to EU policymakers than those occurring inside, and that outside impacts might be in the regulatory scope of third countries, we defined a fourth scenario (SA4), where only emissions within the EU are taken into consideration, based on the following specific assumptions: emissions from petroleum extraction and transport to the EU are not accounted for (assumed to occur outside as the majority of oil is imported); Natural gas/coal extraction: accounted for according to current shares in the EU consumption mix; Production of all other products (base oil, naphtha, fuel oil, bitumen) is assumed to take place in the EU; All other activities (collection, transport, treatment of waste oil, treatment of process residues, etc.) are assumed to take place in the EU.

Fifth, given that a share of the GHG emissions from all of the processes analysed are regulated (internalised) either by the EU ETS or by the effort sharing regulation, the question arises whether EU GHG emissions related to waste oil treatment should be considered as fully internalised or not.[26] To explore this setting, we assume in SA5 that GHG emissions from the different pathways are either covered by the EU ETS and thus pay the EU ETS price as an internal cost of CO_2 emissions, or through effort sharing mechanisms, which can be viewed as an internalisation by increased capital and/or operational costs. As a result, savings in GHG emissions do not count when societal life cycle costs are calculated. Similar to the previous sensitivity analysis (SA4), we also do not consider GHG emissions occurring outside the EU (which might be regulated by a third country).

3.4 Quantifying uncertainty in LCA

3.4.1 Analytical uncertainty propagation

Uncertainty propagation consists in propagating input-data and other model/modelling uncertainties to calculate the result's overall uncertainty, normally expressed as a range around a default or most likely value. Typically in LCA studies, uncertainty propagation can be performed via analytical (e.g. application of the Taylor's series) or stochastic methods (e.g. Monte Carlo simulations). In this study we apply the analytical method developed by Bisinella et al. (2016) and available in the EASETECH LCA model to propagate input-data uncertainties and calculate the overall result's uncertainty. It should be noticed that only uncertainties related to the technology input-output data (e.g. energy and chemical consumption, emissions, output products) are addressed in this study. The analytical uncertainty is chosen because it allows to quantify the individual uncertainties associated with the single parameters (or input-data) used to model the individual technologies and pathways. This allows identifying the most important contributions to the total uncertainty, i.e. which input-data (i.e. parameters in the model) have the highest uncertainty contribution. To represent the uncertainty range around the 'default' value of the input-output data, a specific distribution (uniform, triangular, normal, or logarithmic) is required. We apply normal distribution with a mean and a standard deviation obtained from aggregating different plants into one technology cluster, i.e. hydro-treatment, solvent extraction, distillation, etc. This choice of representation is common practice in LCA and is based on the central limit theorem, which establishes that for identically distributed independent parameter samples, the standardized sample mean tends towards the standard normal distribution (Bisinella et al. (2016)). The remaining model and modelling uncertainties, notably those related to the implemented equations (model-specific) and to the impact characterisation factors (i.e. factors describing the impact of an environmental

[26] Cement kilns, for instance, are covered by the EU ETS, as are regenerators with a thermal capacity above 20 MW (some regenerators, however, are below this threshold and are thus not covered). Companies that convert waste oil to fuel are mostly large enough to exceed this threshold, but we lack data on this regarding both regenerators and fuel converters. Hazardous waste incinerators are covered by the Effort Sharing Regulation. In sum, all treatment pathways are covered to some extent, but for regeneration and conversion to fuel we lack data on the share of companies (and thus of emissions) that is covered. For more details see Section 1.4.1 and Footnote 7 in particular.

exchange on a specific impact category, e.g. the impact of CH_4 or CO_2 emitted to air on the category climate change) are not addressed in this study as they fall outside the scope.

3.4.2 Discernibility analysis

The analytical (or stochastic) uncertainty produces a range around the 'default' result value. While this information is valuable when looking at a single scenario and the variability of its performance, often it is the case that two scenarios show overlapping uncertainty bars (ranges around the 'default' result), which makes it impossible to say when, or if, one is better than the other. For this purpose, we perform discernibility analysis using the tools available in the EASETECH LCA model. Applying Monte Carlo simulations on two scenarios simultaneously, e.g. hydro-treatment versus solvent extraction, (i.e. a pair-wise comparison), the discernibility analysis quantifies the number of occurrences for which one scenario is better than the other under the parameter uncertainties considered in the study. We set a number of 1000 Monte Carlo iterations (runs) for this, i.e. scenarios are compared in a pair-wise mode 1000 times by varying randomly their parameters under the given uncertainty ranges. The choice of the number of runs (1000) is a compromise between the need for a population of results propagated via Monte Carlo sampling and the related computational effort (beyond this number, significant computational time/efforts were observed).

By comparing scenarios in a pair-wise mode, common parameter uncertainties (common to the two scenarios that are compared) are cancelled out and do not impact the final result of the pair-wise comparison. This is important because some uncertainties may have the same influence on the two scenarios but no influence on the actual ranking between them. For instance, if two scenarios have the same consumption of electricity and the electricity mix is highly uncertain, both scenarios may result in high uncertainty (translating into a large range around the 'default' value) but this does not affect the ranking between them.

3.5 Socio-economic analysis

In the socio-economic analysis we quantify the impacts of different policies aimed at increasing the regeneration of waste oil in the EU in terms of their societal life cycle costs, their greenhouse gas emissions and their employment effects. For this purpose, we compare the different policy scenarios over the period 2024-2045 against a business-as-usual scenario in which no additional policies are implemented.

The life cycle analysis provides us with the amount of pollution and employment associated with treating one tonne of waste oil in each pathway. Moreover, the life cycle costing analysis calculates the societal cost of treating on tonne of waste oil for the individual pathways, relying on estimates of the external costs of different pollutants from Bijleveld et al. (2018) and van Essen et al. (2019). Based on this, in the socio-economic analysis, the additional tonnes of waste oil going to regeneration in the different policy scenarios are translated into monetary savings, emission savings and employment changes.

Since the single objective of all policies is to channel waste oils towards regeneration, we render the policies comparable with regard to their economic impacts by calibrating them such that they all lead to the same outcome with respect to regeneration. We specifically analyse two targets. The less ambitious target corresponds to an increase in collected waste oil that goes to regeneration from 61 to 70% until 2030. In the more ambitious scenario, regeneration increases from 61 to 85% until 2030. Note that 85% also corresponds to our conservative estimate of the upper limit of regeneration that could be achieved with current waste oil qualities and collection practices (see Section 1.1). The policies hence only differ in their economic and social impacts. Table 13 summarizes the corresponding targets for each policy and the methods used to derive them.

In addition, to determine which economic actors bear the main burden of each policy, we use uncalibrated partial equilibrium models. In economics, these models are used to illustrate how total output and price levels are determined in (partial) equilibrium in well-functioning markets. The equilibrium is partial in the sense that it only considers one product (in our case base oil), assuming that all other prices and quantities remain constant.

4 Results

This section reports the results of the life cycle assessment (LCA; Section 4.1) and life cycle costing (LCC; Section 4.2) for the investigated waste oil management scenarios. In both analyses, the default (base) case is presented, as well as the sensitivity analyses SA1- SA5 (see Section 3.3). The results are expressed per tonne (t) of waste oil managed (i.e. sent to each of the regeneration and energy recovery routes). Positive values reflect burdens to the environment in the LCA case, or costs in the LCC, while negative values reflect environmental savings in the LCA case, or revenues in the LCC[27].

The results regarding the impacts on Climate change, Particulate matter, Acidification, and Fossil resource use, with a breakdown of each life cycle stage are presented herein, while the net savings and burdens across the remaining environmental impact categories are presented in Annex 2. This annex also includes detailed numerical results for the four categories addressed in this section as well as a ranking of the assessed scenarios according to their result in each impact category indicator. The "Net impact" at the scenario level is calculated as the difference between the impact of the management route (burdens) and the savings from the substituted products and co-products arising from that route. Note that the waste oil is considered to enter the system as "burden-free" (the impact of producing the waste would be the same across all scenarios).

4.1 Life cycle impact assessment results

The impact contributions are aggregated into four categories, representing the main processes and activities of the modelled waste oil treatment pathways and investigated scenarios:

- Collection: it includes the impacts from collection of the waste oil from producers and transport to an intermediate (centralised) facility where waste oil is temporarily stored.
- Transport: it includes the impacts from transport of waste oil from centralised storage facilities to the regeneration or energy recovery facilities.
- Treatment: it includes the impacts from energy consumption (electricity and heat) by the treatment facility, as well all other non-energy inputs such as fuels for internal transport/movement, water, chemicals, additives, detergents, antifoaming agents, etc.), and with the external treatment or disposal of outputs generated from plant process operation, i.e. wastewater, sludge, and other waste streams.
- Substitution of products: it includes the savings due to the substitution of market energy, products and co-products substitution, i.e. substitution of waste oil derived products (base oil, bitumen, etc.), fuels (naphtha, fuel oil), as well as heat and electricity generated from incineration of waste oil in energy recovery scenarios.

Figure 9 shows the effects on the climate change, particulate matter, acidification and fossil resource use impact indicators following the management of 1 tonne of waste lubricant oil, i.e. our functional unit. The parametric uncertainty around the mean result value is also shown in Figure 9. The uncertainty is obtained with the analytical procedure illustrated in Bisinella et al. (2016). Across all scenarios, the most important contribution to the burdens is represented by the 'treatment' stage (processing and combustion, depending upon the pathway), while the savings are attributed to the substitution of conventional market products via re-refinery, recovery to fuel, or direct energy conversion via combustion. More insights on the contributions are detailed hereinafter for the single impact categories.

Climate change: net savings are obtained for the three regeneration scenarios investigated, as well as for the two energy recovery scenarios producing fuel (ER-WODFa and ER-WODFb), although the former are

[27] A burden of *X kg pollutant-eq./t waste oil*, means that the processing of waste oil by this option releases *X kg* of this *pollutant-eq.* into the environment for each tonne of waste oil processed. Savings of *X kg pollutant-eq./t waste oil* means that the products and co-products derived from the waste oil processing allow to avoid the release of *X kg* of this *pollutant-eq.* into the environment, which would have occurred if the products and co-products had been produced not from waste oil but from virgin raw materials. Similarly for life cycle costs, a cost of *X €/t waste oil* refers to economic expenditures (CAPEX and OPEX) to manage 1 tonne of waste oil, while a saving of *X €/t waste oil* refers to revenues from selling products and co-products obtained when treating one tonne of waste oil. If the 'net' is negative, it means that the waste management pathway is profitable (for LCC: revenues > costs) or leads to a net environmental saving (for LCA: savings > burdens).

higher. Net burdens are observed for the remaining energy recovery scenarios based on combustion (ER-CKLN, ER-HWIN and ER-INBO), i.e. the GHG released from combustion are not compensated by the GHG savings from energy substitution. Regeneration of waste oil via solvent extraction (RG-SOLV) results in the largest savings, amounting to 536.5 kg CO_2-eq./t waste oil. This is followed by regeneration via hydro-treatment (RG-HYDT; -393.9 kg CO_2-eq./t waste oil) and regeneration via distillation (RG-DYST; -343.6 kg CO_2-eq./t waste oil). Energy recovery to fuel achieves lower savings, with scenarios ER-WODFa and ER-WODFb resulting in -249.4 and -163.8 kg CO_2-eq./t waste oil, respectively. The highest net burdens are generated by energy recovery in a hazardous waste incinerator (ER-HWIN) resulting in 2500.5 kg CO_2-eq./t waste oil. This is followed closely by ER-INBO (1969.3 kg CO_2-eq./t waste oil), while ER-CKLN produces 250.6 kg CO_2-eq./t waste oil. The overall uncertainty around the mean for Climate change is quantified in the range of 7-78% of the baseline result. The lowest end of uncertainty corresponds to the scenario ER-INBO, while the highest end corresponds to RG-DIST. The relative high uncertainty in the on-site thermal energy consumption parameter for RG-DIST is partially responsible for the significant total uncertainty of the climate change category.

Impact contribution: in the three regeneration scenarios the savings due to recovery of regenerated waste oil and substitution of virgin base oil and other co-products are comparable. The difference between the three regeneration scenarios is determined by the burdens from processing, which is more intensive for hydrothermal and distillation-based regeneration (RG-HYDT and RG-DIST) due to their electricity and thermal energy demand. The two energy recovery to fuel scenarios (WODFa and WODFb) achieve comparable savings and burdens on Climate change: the savings come from recovery of distillate fuel and substitution of either marine fuel (ER-WODFa) or fuel oil (ER-WODFa). The burdens are associated with the processing, notably heat and electricity consumption, as well as with process waste management. Overall, one may observe that both burdens and savings are significantly lower than in the case of regeneration (i.e. both processing and products are less energy and CO_2-intensive). Last, for the three energy recovery scenarios (combustion-based), the burdens are the same as they are mainly related to CO_2 emissions from direct combustion of the WO. The savings, instead, differ because they depend mainly on the substituted fuel mix and partly on the energy recovery efficiency of the plant itself. The fuel mix substituted at cement kiln has a higher C-footprint (ca. 75 kg CO_2-eq./GJ_{th}) than the EU heat mix (ca. 35 kg CO_2-eq./GJ_{th}) substituted at industrial boilers and incinerators. Hazardous waste incinerators, additionally, have typically low energy recovery efficiency (24% heat, 5% electricity).

Particulate matter: net savings are achieved by all scenarios investigated. The regeneration scenarios provided the largest savings, while ER-HWIN resulted in the lowest savings. Energy recovery shows the worst performance, but it is still achieving environmental savings overall. The overall uncertainty around the mean for Particulate matter is negligible (<0.01%) for all investigated scenarios. This is partly explained by the poor information available on the uncertainty of the emissions impacting on this category. For the combustion-based energy recovery scenarios, the burdens are the same as they are mainly related to PM emissions from direct combustion of the WO. The savings, on the other hand, differ because they depend mainly on the substituted fuel mix and partly on the energy recovery efficiency of the plant itself.

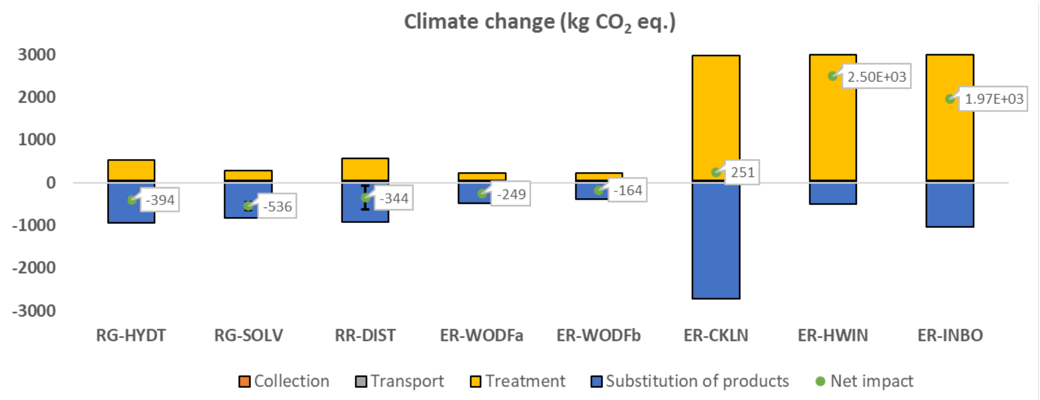
Impact contribution: the burdens of the three regeneration scenarios are comparable and arise mainly from electricity and heat consumptions. The difference between the three regeneration scenarios is determined by the savings from recovery of regenerated waste oil and substitution of virgin base oil and other co-products that is more intensive in the solvent extraction and distillation-based regeneration (RG-SOLV and RG-DIST). The two energy recovery to fuel scenarios (WODFa and WODFb) achieve comparable savings and burdens in Particulate matter: the savings come from recovery of distillate fuel and substitution of either marine fuel (ER-WODFa) or fuel oil (ER-WODFa), while the burdens are associated with the processing stage, notably electricity consumption.

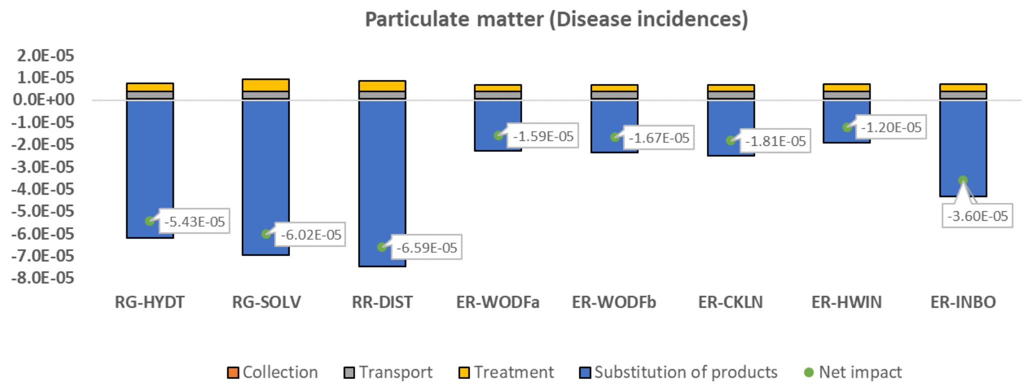
Acidification: net savings for all scenarios investigated except for ER-HWIN. Regeneration via solvent extraction (RG-SOLV) achieves the largest net saving, followed closely by hydro-treatment (RG-HYDT), while ER-INBO results in the lowest savings. Energy recovery shows the worst performance compared with regeneration, but it is still achieving environmental savings overall. Like in the Particulate matter category, the overall uncertainty around the mean for Acidification is negligible (<0.01%) for all investigated scenarios. This is partly explained by the poor information available on the uncertainty of the emissions impacting on this category.

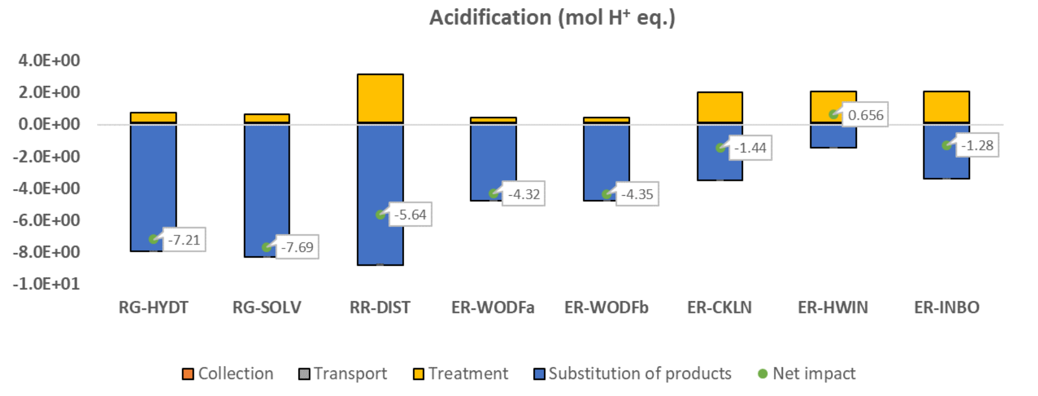
Impact contribution: in the three regeneration scenarios the savings due to recovery of regenerated waste oil and substitution of virgin base oil and other co-products are comparable. The difference between the three regeneration scenarios is determined by the burdens from processing that is more intensive in the distillation-based regeneration (RG-DIST) due to its electricity and thermal energy demand. The two energy recovery to fuel scenarios (WODFa and WODFb) achieve comparable savings and burdens in Acidification: the savings come from recovery of distillate fuel and substitution of either marine fuel (ER-WODFa) or fuel oil (ER-WODFa), while the burdens are associated with the processing stage, notably electricity and heat consumption. For the energy recovery scenarios (combustion-based), the burdens are related to NOx emissions from waste oil direct combustions, while the savings are related to the avoided SO_2 and NOx emissions from the fuel mix otherwise used, in a similar fashion as for CO_2 in Climate change. Energy recovery in industrial boilers (ER-INBO) achieve comparable performance as cement kilns (ER-CKLN) because the fuel mixes substituted have similar emissions of SO_2 and NOx. Incinerators (ER-HWI) achieve less savings because of the reduced recovery efficiency.

Fossil resource use: net savings are observed for all scenarios investigated, i.e. the management of waste oil through any of the assessed scenarios results in net savings of Fossil resource use as a result of virgin material and energy substitution. Regeneration via distillation (RG-DIST) results in the largest savings, followed closely by RG-SOLV and RG-HYDT. On the other hand, ER-HWIN shows the lowest savings. Like in the Acidification case, energy recovery shows the worst performance, but it still achieves environmental savings overall. The overall uncertainty around the mean for Fossil resource use is quantified in the range of 1-12% of the baseline result. The lowest end of uncertainty corresponds to the scenario ER-CKLN, while the highest end corresponds to RG-SOLV.

Impact contribution: in the three regeneration scenarios the savings due to recovery of regenerated waste oil and substitution of virgin base oil and other co-products are comparable. The difference between the three regeneration scenarios is determined by the burdens from processing that is more intensive in the hydrothermal-based regeneration (RG-HYDT) due to its hydrogen consumption. The two energy recovery to fuel scenarios (WODFa and WODFb) achieve comparable savings and burdens on Climate change: the savings come from recovery of distillate fuel and substitution of either marine fuel (ER-WODFa) or fuel oil (ER-WODFa). The burdens are associated with the processing, notably heat and electricity consumption, as well as with process waste management. Last, for the three energy recovery scenarios (combustion-based), the net results are driven by the savings, which depend mainly on the substituted fuel mix and partly on the energy recovery efficiency of the plant itself.







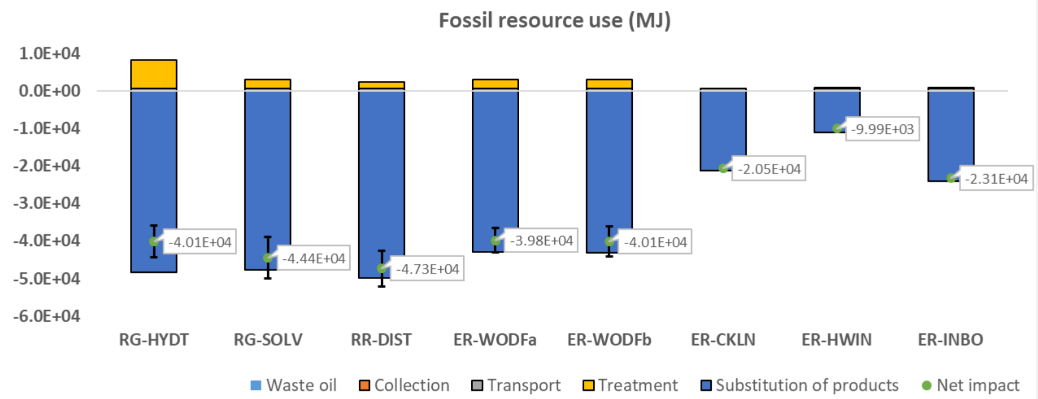


Figure 9 Effects on the Climate change, Particulate matter, Acidification and Fossil resource use impact indicators from the management of 1 tonne of waste lubricant oil in the EU. Negative values represent savings, while positive ones represent burdens. The 'Net impact' at scenario level is obtained as the sum of burdens and savings. The error bars represent the full extent of the parameters uncertainty (±σ) around the 'Net impact' value (the default one). Refer to Section 3.1.3 for a definition of the deferent treatment scenarios.

4.2 Life cycle costing results

The cost contributions are aggregated into five categories, representing the main processes and activities of the modelled waste oil treatment pathways and investigated scenarios:

- Waste oil: this is the cost of the waste oil that is paid by waste oil treatment facilities. Refer to Table 4 for more details on the waste oil's physico-chemical characteristics.
- Collection: it includes the costs associated with collection of the waste oil from producers and transport to an intermediate (centralised) facility where waste oil is temporarily stored.
- Transport: it includes the costs from transport of waste oil from centralised storage facilities to the regeneration or energy recovery facilities.
- Treatment: it includes the treatment (processing) costs associated with OPEX, CAPEX, and labour, as well as costs associated with external treatment or disposal of outputs generated from plant process operation, i.e. wastewater, sludge, and other waste streams.
- Substitution of products: it includes the savings (revenues) associated with the sale of energy, products and co-products.

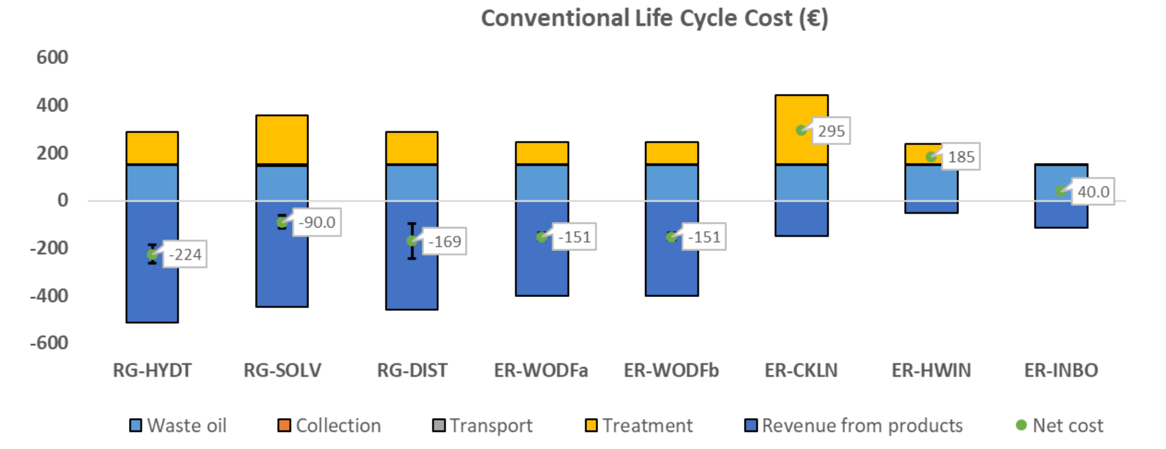
Figure 10 shows the effects on the Conventional, External and Societal Life Cycle Cost indicators following the management of 1 tonne of waste lubricant oil. The parametric uncertainty around the mean result value is also shown in Figure 10. The uncertainty is obtained with the analytical procedure illustrated in Bisinella et al. (2016).

The most important contributions to the Conventional Life Cycle Costs are: waste oil (feedstock) price, treatment (processing), and revenues from products/co-products sales. Note that the waste oil price affects all management options equally, hence not having impact on the ranking. In the External Life Cycle Costs the waste oil price is not a contribution. The Societal Life Cycle Costs are the sum of internal and external costs, with varying contribution of the former or latter depending upon the scenario considered.

Conventional Life Cycle Costs: net savings are obtained for the three regeneration scenarios investigated, as well as for the two energy recovery scenarios producing fuel (ER-WODFa and ER-WODFb). Net costs are observed for the remaining three energy recovery scenarios based on combustion (ER-CKLN, ER-HWIN and ER-INBO), i.e. costs from combustion are larger than savings from energy sales. Regeneration of waste oil via hydro-treatment (RG-HYDT) results in the largest savings, amounting to -224.1€/t waste oil. This is followed by regeneration via distillation (RG-DIST; -169.4 €/t waste oil). Energy recovery to fuel achieves lower savings, with scenarios ER-WODFa and ER-WODFb resulting in -150.8 and -150.9 €/t waste oil, respectively. The highest costs are incurred by management in cement kiln (ER-CKLN) resulting in 295.2 €/t waste oil. Since cement kilns are required to pay EU-ETS tariffs, the cost of CO_2 emissions are internalised in this case, unlike all other scenarios where CO_2 emissions are counted as external costs. Note that the treatment of waste oil in industrial boilers do not incur any internal costs (sum of CAPEX and OPEX) since these facilities are not purposely built nor run to treat waste. In other words, even if waste oil did not exist, cement kilns and industrial boilers would still operate. The overall uncertainty around the mean for Conventional Life Cycle Costs is quantified in the range of 1-43% of the baseline result. The lowest end of uncertainty corresponds to the scenario ER-INBO, while the highest end corresponds to RG-DIST.

External Life Cycle Costs: net savings are achieved by all scenarios investigated but ER-HWIN. The regeneration scenarios provided the largest savings, ranging between 133.2-107.1 €/t waste oil. ER-HWIN resulted in the highest costs (210.5 €/t waste oil). The major contribution to the external costs is CO_2 emission (price ca. 100 €/t CO_2), except in ER-CKLN where the CO_2 emissions costs are internalised due to the EU-ETS levy paid by such facilities. The overall uncertainty around the mean for External Life Cycle Costs is quantified in the range of 1-43% of the baseline result. The lowest end of uncertainty corresponds to the scenario ER-INBO, while the highest end corresponds to RG-DIST.

Societal Life Cycle Costs: this is the sum of the last two. Here, all the energy recovery routes that involve direct combustion of waste oil namely, ER-CKLN, ER-HWIN and ER-INBO, show net societal costs. All three regeneration scenarios achieve larger savings than any of the energy recovery scenarios in the Societal Life Cycle Cost category, although the difference is very small between RG-SOLV and ER-WODFa (~2.5%). The overall uncertainty around the mean for the Societal Life Cycle Costs is quantified in the range of 1-43% of the baseline result. The lowest end of uncertainty corresponds to the scenario ER-INBO, while the highest end corresponds to RG-DIST.



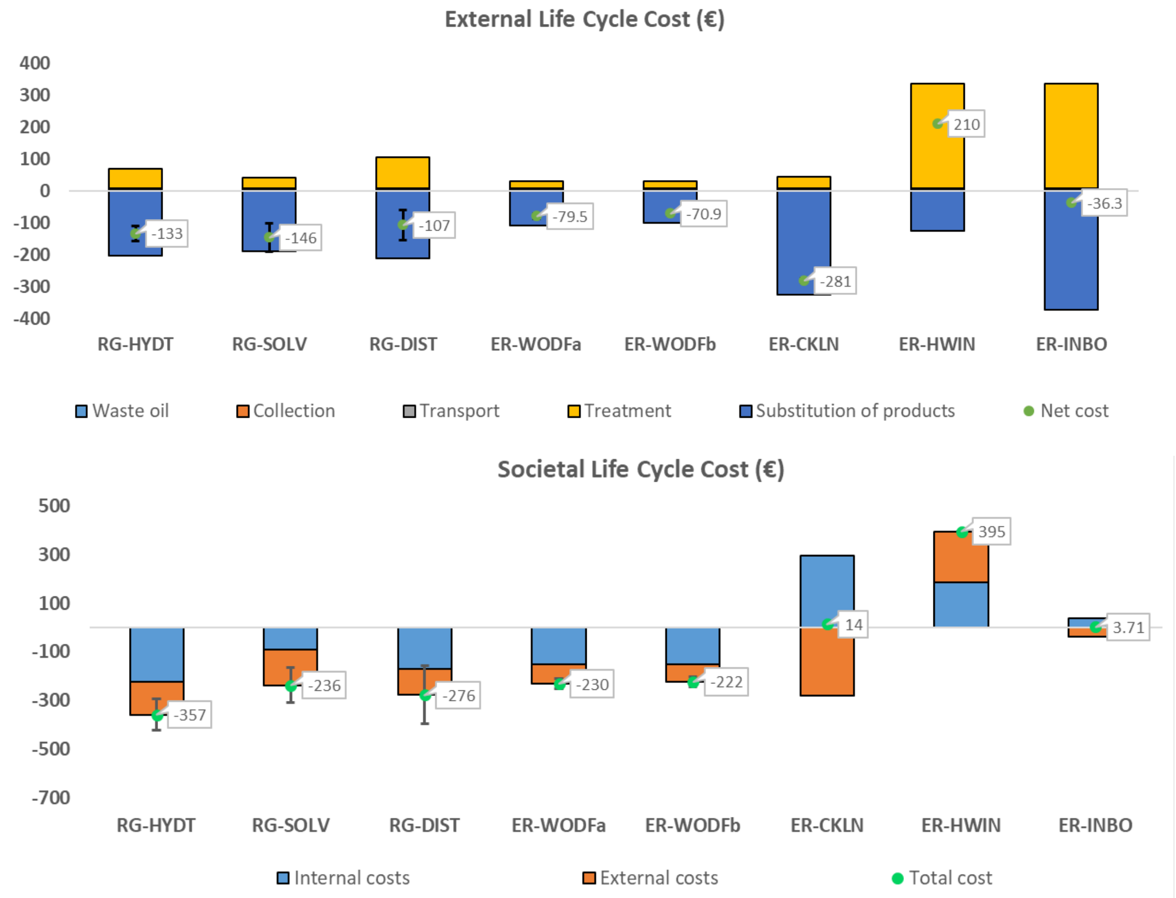


Figure 10 Effects on the Internal, External and Societal life cycle cost indicators associated with the management of 1 tonne of waste lubricant oil in the EU. Negative values represent savings, while positive ones represent costs. The 'Net cost' at scenario level is obtained as the sum of costs and savings. The error bars represent the full extent of the parameters uncertainty (±σ) around the 'Net cost' value (the default one). Refer to Section 3.1.3. for a definition of the different treatment scenarios.

4.3 Sensitivity analyses results

This section reports the results of three of the five sensitivity analyses performed in this study to test important framework assumptions. A detailed description of the sensitivity cases and assumptions can be found in Section 3.3. The sensitivity cases presented here are: SA1 – Energy, SA2 - Waste quality and SA3 – Crude oil price). SA1 and SA2 cases apply to the LCA results, while SA3 only applies to the LCC results.

4.3.1 Energy system and waste oil quality (SA1 and SA2)

The energy mix plays a role in the climate change impact indicator (SA1). As shown in Table 6, for the management options involving regeneration and energy recovery to fuel, the net impact indicator decreases as the de-carbonisation of the energy mix increases. This is explained by the larger portion of energy (electricity and heat) being used in these options, compared to the portion that is exported from the plants. In other words, since these pathways are 'net importers' of energy, they will further improve their footprint with increased decarbonisation of the EU energy system. The opposite applies for the management options involving energy recovery via combustion, i.e. ER-CKLN, ER-HWIN, ER-INBO. They are 'net exporters' of energy, therefore, as the de-carbonisation of the EU energy mix increases their footprint will increase too (less credits obtained for substituting the EU market mix electricity and/or heat). The relative ranking of the different waste oil management pathways do not change due to the conditions of the future (2030) energy system.

Table 6 Effects on the climate change impact indicator associated the management of 1 tonne of waste lubricant oil managed in the EU for a different future energy mix. Negative values represent savings, while positive ones represent burdens. Refer to Section 3.3 for a definition of the different sensitivity scenarios. SA: sensitivity analysis.

SA1 - Climate change in the future energy system (2030)					
	Current EU energy system (baseline)	Ranking	Future EU energy system	Ranking	Change?
RG-HYDT	-393.9	2	-444.5	2	(=)
RG-SOLV	-536.5	1	-586.4	1	(=)
RG-DIST	-343.6	3	-360.1	3	(=)
ER-WODFa	-249.4	4	-333.7	4	(=)
ER-WODFb	-163.8	5	-248.0	5	(=)
ER-CKLN	250.6	6	1003.4	6	(=)
ER-HWIN	2500.5	8	2789.3	8	(=)
ER-INBO	1969.3	7	2700.7	7	(=)

The results in Table 7 show that, for regeneration and energy recovery to fuel, the savings in Climate change are higher when high quality (HQ) waste oil is treated, rather than low quality (LQ) waste oil (SA2). This is due to the additional energy required to remove the excess water from low quality (LQ) waste oil, as well as the extra wastewater produced as a result of the water removal. For the combustion scenarios the net burdens, are generally lower when low quality (LQ) waste oil is treated. This is true despite the additional energy needed to remove the excess water since the lower emissions from combustion of high water content-waste oil compensates the lower energy substitution (lower heating value) in this case. ER-CKLN is an exception to this rule since the additional energy required to remove the excess water of low quality (LQ) waste oil does not compensate and its lower heating value (lower energy substitution) are not compensated by lower combustion emissions from water-rich waste oil. The relative ranking of the different waste oil management pathways do not change due to the conditions of the future (2020) energy system. Similar trends are observed for different quality waste oils under the future (2030) energy system, although changes are observed in the relative rankings of the management scenarios. For instance, ER-WODFa and ER-HWIN increase their ranking one position, whereas the opposite is found for RR-DIST and ER-INBO.

Table 7 Effects on the climate change impact indicator associated the management of 1 tonne of waste lubricant oil managed in the EU for different waste oil qualities (low versus high quality). Negative values represent savings, while positive ones represent burdens. Refer to Section 3.3 for a definition of different the sensitivity scenarios. SA: sensitivity analysis.

SA2 - Climate change for different waste qualities					
Current EU Energy System (baseline)					
	High-Quality waste oil (baseline)	Ranking	Low-Quality waste oil	Ranking	Change?
RG-HYDT	-393.9	2	-85.2	2	(=)
RG-SOLV	-536.5	1	-262.9	1	(=)
RG-DIST	-343.6	3	-70.9	3	(=)
ER-WODFa	-249.4	4	-50.6	4	(=)
ER-WODFb	-163.8	5	113.1	5	(=)
ER-CKLN	250.6	6	593.6	6	(=)
ER-HWIN	2500.5	8	2099.2	8	(=)
ER-INBO	1969.3	7	1744.5	7	(=)
Future EU Energy System (2030)					
	High-Quality waste oil (baseline)	Ranking	Low-Quality waste oil	Ranking	Change?
RG-HYDT	-444.5	2	-328.7	2	(=)
RG-SOLV	-586.4	1	-465.0	1	(=)

RG-DIST	-360.1	3	-219.9	4	(↓)
ER-WODFa	-333.7	4	-220.9	3	(↑)
ER-WODFb	-248.0	5	-190.0	5	(=)
ER-CKLN	1003.4	6	1223.2	6	(=)
ER-HWIN	2789.3	8	2361.7	7	(↑)
ER-INBO	2700.7	7	2419.0	8	(↓)

4.3.2 Crude oil price (SA3)

As shown in Table 8, the crude oil price[28] affects the societal life cycle cost via a change in the internal costs (external costs are unaffected by changes in the selling price of re-refinery products – see Section 3.3). The savings in societal costs are always higher when higher crude oil prices are considered. This effect is more pronounced in the regeneration scenarios (RG-HYDT, RG-SOLV, RG-DIST) than in the energy recovery scenarios that produce distillate fuel, due to the higher yield to petroleum products, e.g. base oil, naphtha, fuels, etc. of the former scenarios. Furthermore, the Societal Life Cycle Costs are always lower (i.e. better off) in the regeneration cases for a given waste oil quality and crude oil price, compared to energy recovery cases.

Table 8 Effects on the Societal Cost indicator associated the management of 1 tonne of waste lubricant oil managed in the EU for different crude oil prices (low versus high price). Negative values represent savings, while positive ones represent burdens. Refer to Section 3.3 for a definition of different the sensitivity scenarios. SA: sensitivity analysis.

SA3 - Societal cost for different crude oil prices					
		High Quality Waste Oil (baseline)			
	Low crude oil price (baseline)	Ranking	High crude oil price	Ranking	Change?
RG-HYDT	-357.4	1	-749.4	1	(=)
RG-SOLV	-235.9	3	-557.0	3	(=)
RG-DIST	-276.5	2	-608.9	2	(=)
ER-WODFa	-230.3	4	-497.2	5	(↓)
ER-WODFb	-221.8	5	-488.7	4	(↑)
ER-CKLN	270.9	7	270.9	7	(=)
ER-HWIN	395.4	8	395.4	8	(=)
ER-INBO	3.71	6	3.71	6	(=)
		Low Quality Waste Oil			
	Low crude oil price (baseline)	Ranking	High crude oil price	Ranking	Change?
RG-HYDT	-377.6	1	-896.9	1	(=)
RG-SOLV	-337.9	2	-704.0	3	(↓)
RG-DIST	-272.1	3	-756.3	2	(↑)
ER-WODFa	-243.7	5	-644.7	4	(↑)
ER-WODFb	-246.2	4	-636.2	5	(↓)
ER-CKLN	-77.9	6	-77.9	6	(=)
ER-HWIN	250.2	8	250.2	8	(=)
ER-INBO	-2.8	7	-2.8	7	(=)

[28] SA3 considers a crude oil price change from 65 €/barrel (baseline) to 120 €/barrel (high crude oil price).

4.3.3 Intra- versus extra-EU emissions and EU ETS (SA4 and SA5)

Regarding sensitivity scenarios four and five we come to the following conclusions: In scenario four, where we only consider emissions that take place within EU countries, the relative ranking of the different pathways in terms of life cycle costs does not change except between pathways that incinerate waste oil directly (i.e. cement kilns, HWI and industrial boilers). It can be seen in Table 9, that the net social savings of all pathways are reduced, because benefits associated with lower impacts outside the EU are not taken into account. Depending on the extra-EU share of total emissions in each pathway, some pathways' benefits decrease more than others, which leads to cement kilns outperforming industrial boilers, but for all other pathways, the relative ranking is preserved.

In sensitivity scenario five, we assume that 100% of all GHG emissions are already covered (either by the EU ETS or by effort sharing regulations). In Section 3.3, where the design of the sensitivity analysis is described, we discuss the rationale behind SA5: GHG emissions from all waste oil treatment pathways are in some form covered either by the EU ETS or by the Effort Sharing Regulation, but for conversion to fuel and regeneration pathways only a share of the GHG emissions are covered. We lack data on how large this share actually is and thus have to make assumptions. In our baseline scenario, avoided GHG emissions are counted as sLCC savings. In SA5, avoided GHG emission are not counted as sLCC savings, as we assume that they are fully covered by existing EU policies.

In SA5, the ranking does indeed change and the regeneration pathway RG-Solv has higher societal life cycle costs than the fuel production pathway ER-WODFa. This is the case because the GHG share of the sLCC savings for the pathway RG-Solv is larger than the GHG share in the sLCC of ER-WODFb. Hence, when GHG emissions are not accounted for in both pathways, the sLCC savings of ER-WODFb decrease less than the sLCC savings of RG-Solv. As a consequence, if one views the climate change impact as 'taken care of' by other policies, regeneration and conversion-to-fuel pathways partially overlap in terms of their societal LCC performance. These results are summarised in Table 9.

Table 9 Sensitivity analysis SA4 (only EU-internal emissions are accounted for) and SA5 (only GHG emissions not covered by the EU ETS or effort sharing mechanisms are accounted for). Pathways are ranked according to their societal life cycle cost.

	Baseline results		Scenario SA4: only emissions within the EU are accounted for		Scenario SA5: GHG emissions assumed to be covered by EU ETS or effort sharing mechanisms	
Technology	**Total cost (€)**	Ranking	**Total cost (€)**	Ranking	Total cost **(€)**	Ranking
RG-HYDT	-357	1	-285	1 (=)	-315	1 (=)
RG-DIST	-276	2	-203	2 (=)	-240	2 (=)
RG-SOLV	-236	3	-159	3 (=)	-187	4 (↓)
ER-WODFa	-230	4	-152	4 (=)	-133	5 (↓)
ER-WODFb	-222	5	-152	5 (=)	-206	3 (↑)
ER-INBO	4	6	29	7 (↓)	40	6 (=)
ER-CKLN	14	7	44	6 (↑)	293	8 (↓)
ER-HWIN	395	8	401	8 (=)	203	7 (↑)

4.4 Discernibility analysis

This section reports the discernibility analysis results for the Climate Change and Societal Life Cycle Cost indicators. The discernibility analysis is limited to these two indicators only due to their particular relevance in the context of waste oil management policy. Refer to Section 3.4.2 for more details on the discernibility analysis methodology.

Table 10 and Table 11 report the Climate Change and Societal Life Cycle cost indicator results of the discernibility analysis performed via a pair-wise comparison of all scenarios investigated. This means e.g. comparing the scenario RG-HYDT versus each of the other investigated scenarios, for each Monte Carlo run. The discernibility analysis reveals that RG-SOLV is the only scenario that is superior in over 50% of the occurrences to all the remaining scenarios with regard to Climate Change. This is followed by RG-HYDT which is superior to the rest for over 50% of the occurrences, except in comparison to RG-SOLV. Regeneration scenarios are superior to scenarios of energy recovery via fuel (ER-WODFa and ER-WODFb) in terms of Climate Change in 58-85% of the occurrences. Both regeneration and energy recovery via fuel scenarios are superior to direct waste oil combustion scenarios in 70-100% of the occurrences. Among the combustion scenarios, ER-CKLN is superior to both ER-HWIN and ER-INBO in 98% and 95% of the occurrences, respectively.

In terms of Societal Life Cycle Costs, RG-HYDT is the only scenario that is superior in over 50% of the occurrences vis-a-vis all other scenarios, with a probability ranging between 60-100% of the occurrences. This is followed by RG-SOLV which is superior to the rest in over 50% of the occurrences, except with regard to RG-HYDT. RG-HYDT and RG-SOLV are superior to energy recovery to fuel scenarios (ER-WODFa and ER-WODFb) in terms of Societal Life Cycle Costs in 53-69% of the occurrences. This contrasts with RG-DIST, which is only better off than energy recovery to fuel scenarios in 46-48% of the occurrences. Both regeneration and energy recovery to fuel scenarios are superior to direct waste oil combustion scenarios in 85-100% of the occurrences. Among the combustion scenarios, ER-INBO is superior to both ER-CKLN and ER-HWIN in 69% and 99% of the occurrences, respectively.

Table 10 Discernibility analysis results for the Climate Change indicator. Pairwise comparisons are carried out by running 1000 Monte Carlo simulations, in which all parameters are varied in each iteration. The percent indicates the number of occurrences (over 1000) in which one scenario (row) is better than the other (column).

Climate Change							
↓Better than→	RG-SOLV	RG-DIST	WODFa	WODFb	ER-CKLN	ER-HWIN	ER-INBO
RG-HYDT	35%	52%	66%	73%	79%	100%	100%
RG-SOLV		63%	79%	85%	84%	100%	100%
RG-DIST			58%	65%	74%	100%	99%
WODFa				64%	73%	100%	100%
WODFb					70%	100%	100%
ER-CKLN						98%	95%
ER-HWIN							32%

Table 11 Discernibility analysis results for the Societal Life Cycle Cost indicator. Pairwise comparisons are carried out by running 1000 Monte Carlo simulations, in which all parameters are varied in each iteration. The percent indicates the number of occurrences (over 1000) in which one scenario (row) is better than the other (column).

Societal Life cycle Costs							
↓Better than→	RG-SOLV	RG-DIST	WODFa	WODFb	ER-CKLN	ER-HWIN	ER-INBO
RG-HYDT	60%	65%	69%	69%	99%	100%	99%
RG-SOLV		56%	53%	53%	95%	99%	93%
RG-DIST			46%	48%	86%	89%	85%
WODFa				52%	99%	100%	100%
WODFb					99%	100%	100%
ER-CKLN						78%	31%
ER-HWIN							1%

5 Socio-economic analysis of policy instruments for waste oil management

The results from the life cycle assessments indicate that waste oil regeneration outperforms direct incineration (incineration, cement kiln, industrial boiler) in almost all the environmental impact categories investigated and conversion to fuel in most of them. Notably, regeneration stands out as the preferred management pathway when considering only the effects on global warming. When looking at societal life cycle costs, the advantage of regeneration over conversion to fuel prevails in most cases but becomes smaller. However, around 39% of collected waste oil in the EU is still going to combustion, be it in the form of processed fuel oil (24%), via direct incineration in, e.g., cement kilns and power plants (11 %) or via other unspecified incineration pathways (Stahl and Merz, 2020). This implies that a higher share of regeneration, especially when based on the best-performing regeneration technology (RG-HYDT), could generate gains in terms of avoided societal life cycle costs. This also is the stance taken by several Member States, which have set up policies to increase regeneration rates (Stahl and Merz, 2020). The relatively high share of waste oil going into energy recovery also is at odds with the EU's waste hierarchy and circular economy ambitions.

Currently there is a large heterogeneity in how waste oils are treated in the EU: While Denmark, Greece and Italy report regeneration rates close to 100%, other countries do not regenerate their waste oil at all. This suggests that there is room for expanding regeneration (note also that the EU has around 1.5 million tonnes of regeneration capacity, of which currently only 1 million is utilised, according to Stahl and Merz, 2020). In 2018, the EU-28 on aggregate had a regeneration rate of 61% (see Figure 3).

In Section 5.1, we review a comprehensive set of policies that could be applied to increase the share of regenerated waste oil. We discuss the arguments in favour and against each policy in detail, from the perspective of *ex-ante* expected effectiveness. We evaluate them in terms of the following criteria: legal, technical and political feasibility, coherence with other EU policy objectives, effectiveness and efficiency, proportionality and identifiability. Note that not all criteria can be assessed for all policies. For each policy, we decide whether:

- (i) it has sufficient potential and is selected for in-depth analysis,
- (ii) to discuss it briefly but refrain from a deeper analysis
- (iii) it is omitted from the analysis because it is either out of scope of this study or we currently lack sufficient information to assess it properly.

In Section 5.3, we perform a socio-economic analysis of those policies that were selected in Section 5.1. The business-as-usual scenario (i.e. the no-policy counterfactual), is outlined in Section 5.2.

5.1 Scoping of possible policies

In general, four categories of policies can be differentiated: Category 1 consists of command and control measures such as restrictions on the use or the blending of waste oils; Category 2 comprises regeneration targets in different forms, for example a regeneration quota for all waste oil collected, or a recycled content target for base oils; Price-based instruments such as levies and subsidies are contained in category 3; Category 4 consists of policies related to the collection of waste oil.[29] The policies selected for in-depth analysis, the way in which they could increase the regeneration share and address other problems associated with waste oils, as well as a qualitative analysis of their specific advantages and disadvantages are described in more detail in Section 5.1.1. The policies that were considered but not analysed in detail, and the main reasons for that are outlined in Section 5.1.2. All policies are summarised in Table 12, where those that are omitted from the detailed analysis are shown in grey font.

[29] Due to data constraints, we cannot analyse collection policies as of now.

Table 12 List of possible policies and proposed level of analysis.

(1) Measures restricting waste oil use for energy recovery		Proposed analysis
1a	Ban on the combustion of waste oil	briefly discussed but omitted (Section 5.1.2)
1b	A ban on the use of waste oil in marine bunker fuels	briefly discussed but omitted (Section 5.1.2)
1c	EU-wide EoW criteria for the conversion of waste oil to fuel oil	briefly discussed but omitted (Section 5.1.2)
1d	A ban on all waste oil exports except for regeneration	briefly discussed but omitted (Section 5.1.2)
(2) Regeneration targets		
2a	A target specifying the share of collected waste oil to be regenerated	in-depth analysis (Section 5.1.1)
2b	A target specifying the share of regenerated base oil on markets	in-depth analysis (Section 5.1.1)
2c	A target specifying the regenerated content for base oil	in-depth analysis (Section 5.1.1)
2d	Generation of regeneration certificates	briefly discussed but omitted (Section 5.1.2)
(3) Price-based instruments		
3a	A production subsidy for regenerators	in-depth analysis (Section 5.1.1)
3b	A charge/levy on virgin base oil that finances a subsidy on regeneration	in-depth analysis (Section 5.1.1)
(4) Collection policies		Not analysed. Not in the scope of this study. See forthcoming study by (RDC Environment, 2023).

5.1.1 Policies selected for in-depth analysis

All policies selected for in-depth analysis fall either into the category of regeneration targets or price-based instruments. The regeneration targets can take the form of country-level minimum percentages of collected waste oil that must be regenerated 2a, or of lubricant or base oils put on markets that must be derived from regenerated waste oil 2b[30]. In contrast to policies 2a and 2b, which leave some room for the exact way in which they are implemented, policy 2c - a mandatory minimum percentage of regenerated content in every lubricant product – already specifies the implementation of the target, but is otherwise similar to policy 2b. Whereas policy 2a regulates the supply of regenerated waste oil, policies 2b and 2c affect its demand. In that sense, policy 2a "pushes" waste oil towards regeneration, while 2b and 2c represent "pull" measures, i.e. they create increased demand for regenerated base oils. With regards to price-based instruments we analyse a subsidy on regeneration financed through the general budget (policy 3a) and a subsidy financed via a levy on virgin-based base oil (policy 3b). In the following, we will go through each selected policy in detail.

[30] This target could be set at EU or MS levels and it could either refer to a subselection of base oil groups or to all base oil groups. For details see the discussion below on policies 2b and 2c.

Policy (2a) A policy prescribing the minimum percentage share of all collected waste oil that must be regenerated, with reference to a target year (e.g. 2030). Both domestic regeneration and intra-EU movements for the purpose of regeneration[31] would count towards the target, given that some MS are lacking their own regeneration capacities.

How the target is achieved would be left to the Member States. The level of the target could either be uniform or differentiated by MS, e.g. a more moderate target for MSs with currently low regeneration rates and more ambitious for MSs with already high regeneration rates, based on the *status quo* and specific circumstances. Reported regeneration rates in the EU in 2018 range between 0% in eight EU countries and 100% in Denmark, Greece and Luxemburg (Stahl and Merz, 2020). The target should be phased in gradually in order for the Member States to build up regeneration capacities.

Arguments in favour of this policy:

- With the implementation left to MS, this is the most flexible policy, in the sense that it can be achieved through different means.
- This policy directly addresses the issue of low regeneration rates, as well as problems about which we do not have sufficient data, such as the use of waste oil for the production of marine fuels. In that sense, a percentage target for regeneration is robust to some uncertainties in the data.
- The target can be set independently of the base oil groups which are produced through regeneration, which reduces complexity.
- The data needed for monitoring the compliance with this policy is relatively clear and available (amount of waste oil regenerated, regeneration capacities, imports/exports for regeneration).
- By directly setting the percentage of collected waste oil that is regenerated, there is little uncertainty in the environmental outcome (similar to an emission standard), which makes it the most tangible policy option in that sense.

Arguments against this policy:

- There is large heterogeneity between countries, so targets would need to be country-specific. Alternatively, there may be intermediate options, like a minimum target and a maximum time to reach it and an ambitious target, for those that already meet the minimum target (although such a distinction might decrease the political feasibility of the policy).[32]
- It is debated whether, due to quality conditions and technical constraints, a residual share of the collected waste oil cannot be regenerated and would thus need to be treated in other ways. This would have to be taken into account when setting the target.
- The policy is rigid compared to more flexible policies such as pricing instruments. If, for example, regeneration capacities are not built up on time, the policy might need to be revised to avoid favouring informal or illegal waste oil disposal.[33]

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[31] Waste oil is classified as a hazardous waste, and thus cannot be exported from an OECD to a non-OECD country, according to the Amendment to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. The proposal for the EU Waste Shipment Regulation would ensure consistency in the implementation of the Basel Convention by each Member State. As a result it aims at avoiding obstacles to the shipments of waste within the EU or impediments to the good functioning of the EU internal market. It also goes beyond the Basel Convention by prohibiting the export of waste for disposal outside EU and European Free Trade Association (EFTA) countries, and the export of some non-hazardous waste outside the OECD.

[32] The ambitious target could, for instance, be the average regeneration rate of the countries that are above the 50th percentile (in terms of waste oil regeneration), which would imply a target of 85%. The less ambitious target could be the current EU average regeneration rate (61%). Note, that in the analysis below, we do not specify the targets at the MS level, but instead analyse an EU-wide target. However, the caveat discussed in the paragraphs just above Figure 3 still applies, namely that regeneration rates are not always calculated in the same way in different Member States.

[33] It appears that there is spare capacity for regeneration in the EU, although not sufficient for handling an immediate shift to regeneration of all waste oil currently used for the production of WO-derived fuels. Such a policy should also include the possibility of shipping waste oil to other EU countries for regeneration.

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

- The percentage of the collected waste oil that is unsuitable for regeneration is unclear and depends on the collection system and on the waste oil accounting, which can differ between Member States (see also the point made on waste oil accounting in the paragraphs just above Figure 3). Although some estimates refer to a range of 5-15%. This aspect might improve once better data are available.

Overall assessment:

Expected effectiveness: This option leads directly to an increase of regeneration and is thus consistent with the waste hierarchy and EU circular economy objectives. It also addresses some identified issues for which there are too many data gaps to address them otherwise such as the abovementioned marine fuel issue.

Expected efficiency: Only a moderate effort is required as Member States already have an obligation to report these figures. Member States themselves can choose the most efficient means – adopted to their circumstances - to achieve targets.

Technical/legal feasibility: Both feasible.

Political feasibility: Depending on how it is implemented, the policy might face critique from negatively affected stakeholders (e.g. consumers, if prices of lubricant products rise).

Conclusion: Policy 2a directly prescribes an increase in regeneration and therefore is suited to meet the objective. It also does not suffer from issues related to data gaps (such as the abovementioned marine fuel problem). However, it might face resistance from consumers if it leads to an increase in the price of lubricant oils, as well as from waste oil-based fuel producers as it diverts waste oil away from this use. In sum, given the high effectiveness and the other arguments in favour of the policy, the policy is analysed in depth.

Policy (2b) A policy setting a minimum percentage share of total base oil put on EU markets that must be derived from regenerated waste oil (possibly distinguished by base oil group).

Since policy 2b would apply to the market as a whole, it is up to lubricant producers to decide which specific lubricants to put on the market with a lower (or higher) regenerated content, as long as the average regenerated content on the market is in line with the target.

Surveillance and enforcement would be left to Member States. However, in order not to distort competition in lubricant markets, the targets themselves would need to be harmonised and set at an EU-wide level, possibly distinguished by base oil group and be applied to imports as well.

Arguments in favour of this policy:

- The target would not need to be country specific and could be set at the EU level.
- Instead of creating supply without increasing demand, as does the regeneration target, the policy would create the demand for regenerated base oil and would thus provide a powerful pull measure. The pull measure would directly incentivise producers to regenerate more, thus addressing both the supply and the demand side.

Arguments against this policy:

- In certain market situations, e.g. due to shocks in the supply chain, there might not be enough regenerated base oil, even when all collected waste oil is regenerated, to meet the demand. Unless the policy is then temporarily suspended, this could lead to an artificial restriction of lubricant supply.
- Base oil demand between groups is continuously shifting, which would require the policy to be adjusted over time.

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

- The content of regenerated base oil in imported base oil is not clear, thus leaving an important variable unknown. According to Stahl and Merz (2020), 0.5 to 0.6 million tonnes of lubricants are imported into the EU. As 4.3 million tonnes are placed on the market, this amounts to 11 to 14%.

Overall assessment:

Expected effectiveness: Regarding the expected effectiveness, the assessment is similar to option 2a. The measure creates a demand for regenerated base oil, which makes it conceptually quite effective. However, there are uncertainties regarding the dynamics on the base oil market, which might reduce this effectiveness to some extent.

Expected efficiency: The effort to enforce and monitor the policy in the EU is expected to be similar to policy 2a, as it would mostly rely on aggregate statistics.

Political feasibility: This policy might face criticism from consumers as it might increase the price of lubricant oils.

Conclusion: This policy is analysed in-depth.

Policy (2c) A policy setting a minimum percentage share of base oil from regenerated waste oil that must be contained in every unit of a lubricant product put on EU markets ('recycled content target'). Similar targets exist already in the EU for other product categories.

The key difference between policies 2b and 2c is that policy 2b would apply to the market as a whole, leaving it up to lubricant producers to decide which specific lubricants to put on the market with a lower (or higher) regenerated content, as long as the average regenerated content on the market is in line with the target. Policy 2c is stricter, as it regulates the content of regenerated waste oil in each unit of lubricant sold.

Similar to policy 2b, surveillance and enforcement would be left to Member States. However, in order not to distort competition in lubricant markets, the targets themselves would need to be harmonised and set at an EU-wide level, possibly distinguished by base oil group and be applied to imports as well.

Arguments in favour of this policy:

In addition to the arguments that apply to policy 2b, the following argument applies.

- Similar targets exist already in the EU for other product categories (e.g. 25% of recycled PET in PET bottles in 2025 or the German "Treibhausgasquote", which specifies the content of biofuels in conventional fuels).[34]

Arguments against this policy:

In addition to the arguments that apply to policy 2b, the following argument applies.

- The target would very likely depend on the base oil group. Since there are only six regeneration plants in the EU producing Group II base oils, only one regeneration plant producing Group III base oil and none producing Group IV, the outcome of this policy would potentially depend on a very small set of companies. Possibly, such a target could be only reasonably set for base oil Group I.
- Base oil demand between groups is continuously shifting, which would require the policy to be adjusted over time.
- Monitoring compliance is difficult and costly, as it would require regular controls at the product level, as opposed to analysing aggregate statistics for policies 2a and 2b.
- The technical feasibility of recycled content in base oil would need to be verified, given that some equipment manufacturers (e.g. in the car industry) work with narrowly defined technical specifications for authorised lubricant products. It is a priori not clear whether all product specifications are compatible with a high recycled content, which is

[34] See here.

due to a lack of data and sometimes differential statements from lubricant producers and regenerators

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

- Similar to policy 2b.

Overall assessment:

Expected effectiveness: Regarding the expected effectiveness, the assessment is similar to option 2a. The measure creates a demand for regenerated base oil, which makes it conceptually quite effective. However, there are uncertainties in the technical feasibility of a recycled content target and the dynamics on the base oil market, which might reduce this effectiveness to some extent.

Expected efficiency: The effort to enforce and monitor such targets in the EU is expected to be rather high.

Political feasibility: This policy might face criticism from consumers as it might increase the price of lubricant oils.

Conclusion: Despite the complexity of the base oil market and the high implementation costs, this policy is analysed in-depth, as it would be a very strong pull measure.

Policy (3a), a subsidy for regenerators financed via the general budget.

This subsidy could be temporary, until sufficient capacity has been built up. It could be linked to the price of crude oil (or another market variable that is linked to the profitability of regeneration), in order for regenerated waste oil to be competitive even with fluctuating crude oil prices.

Arguments in favour of this policy:

- There is a successful precedent in EU agricultural subsidies and a similar policy is in place in California (an increase in the subsidy is analysed in CalRecycle (2016).
- A subsidy might face less resistance compared to other price instruments, particularly taxes.
- This policy option is robust to the previously mentioned uncertainty about the share of the collected waste oil that is unsuitable for regeneration.

Arguments against this policy:

- There is strong heterogeneity at the MS level: Some countries already have a 100% regeneration rate (even without a subsidy) – should they also receive the subsidy?
- There could be undesirable interactions of the subsidy with existing Member State level policies, including with existing subsidy schemes.
- The cost of such a policy might be relatively high (at least equal to quantity of waste oil x subsidy + administrative costs): In 2018, around 1 million tonnes of waste oil were already regenerated and a total of 1.64 million tonnes of waste oil were collected in the EU. Evidence from Italy suggests that to approach a 100% regeneration rate, subsidy levels would need to be between 69 and 208 €/t of waste oil. For reaching a 100% regeneration rate in the EU, this would imply yearly subsidy spending of 113-341 million € (*ceteris paribus*).

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

- Economic parameters that determine dynamics on the waste oil market (e.g. demand elasticities of regenerators and (waste oil-based) fuel producers with regard to the price of waste oil) and on the base oil market (substitution elasticity between regenerated and virgin base oil) could not be obtained through the data collection and need to be estimated or taken from the literature (when available).

Overall assessment:

Expected effectiveness: This option leads directly to an increase in regeneration and is thus in line with the waste hierarchy and circular economy objectives. It also addresses problems on which there are too many data gaps to address them otherwise, such as the abovementioned marine fuel issue, the uncertainty on the share of waste oil that cannot be regenerated and the uncertainty regarding the shift in demand for the different base oil groups.[35]

Expected efficiency: The effort to establish an EU-wide subsidy for regeneration of waste oil is expected to be high. The policy is also expected to be costly.

Technical/legal feasibility: Legal feasibility somewhat unclear, since subsidies, especially EU-wide subsidies can only be granted under narrowly defined conditions and might even raise WTO compatibility concerns.

Political feasibility: This policy might face less resistance than other policies as the associated costs are diffuse, but the benefits are concentrated (i.e. regenerators benefit), as outlined in Olson (1965) .

Conclusion: Despite the high costs (which this policy shares with most others), the policy is robust to most uncertainties that affect other policies and also has precedent in other jurisdictions (California). However, its legal feasibility is unclear.[36]

A further reason to analyse this policy is because a subsidy is a crucial part of policy 3b, which is considered more feasible from the legal point of view. Quantifying policy 3a hence provides a benchmark against which the results from option 3b can be compared.

Policy (3b) A charge/levy on virgin base oil sales used to support regenerators. As in the case of policy 3a, this policy could be temporary and the levels of the levy and the subsidy could be linked to the price of crude oil, for the same reasons.

This policy is more feasible in a legal sense, as there are precedents in the EU ETS. However, the main argument against it is that regeneration facilities only exist in 11 Member States, which would imply cross-border subsidies, which are likely to represent major political and implementation challenges.

As in the case of option 3a (only a subsidy), this policy could be temporary and the levels of the levy and the subsidy could be linked to the price of crude oil, for the same reasons.

Arguments in favour of this policy:

- The policy might face less resistance compared to other price instruments, as the revenue is earmarked and does not simply “disappear” into the general budget (see (Baranzini & Carattini, 2017), for instance, who find evidence of this earmarking effect in the context of carbon pricing).
- This policy option is robust to the previously mentioned uncertainty in the percentage of the collected waste oil that is unsuitable for regeneration.
- Successful precedents exist: The EU-ETS, for instance, comprises a levy and earmarked spending of the revenues. A similar policy is in place in Italy, where just below 100% of waste oil is regenerated. Regenerators received subsidies between 110 and 329 €/t regenerated base oil between 2009 and 2019, paid for by lubricant producers through an EPR scheme. This roughly translates into 69 -208 €/t of waste oil.[37]

Arguments against this policy:

- There is strong heterogeneity at the MS level and some countries already have a 100% regeneration rate – how would the policy be implemented in these countries?

[35] Demand for different base oil groups has shifted over the last years and is expected to shift further from Group I to Groups II and III (Lubes’n’Greases, 2022). However, whether and if so to what extent this process will continue in the future is unclear.
[36] This policy could instead be suggested as one (optional) element of a mandatory national EPR.
[37] Australia also has a similar policy in place, see here.

- There could be undesirable interactions of the policy with existing policies, in particular subsidies.
- Regeneration facilities only exist in 11 MS, which could imply cross-border subsidies, which are likely to represent major political and implementation challenges.

Aspects that hinder the analysis of this option, e.g. knowledge or data gaps:

- [same as 3a]

Overall assessment:

Expected effectiveness: [same as 3a]

Expected efficiency: The effort to establish this policy is expected to be high.

Technical/legal feasibility:

Political feasibility: On the one hand, this policy might face less resistance from the general public than other policies as the revenues are earmarked for a specific purpose (although resistance from virgin base oil producers is likely higher compared to other policies). On the other hand, as regeneration facilities only exist in 11 MS, this would imply cross-border subsidies, which would make the policy less politically feasible.

Conclusion: This policy is more feasible than 3a in a legal sense. On the one hand, this policy might face less resistance than other policies as the revenues are earmarked for a specific purpose (Baranzini & Carattini, 2017). On the other hand, regeneration facilities only exist in 11 MS, which would imply cross-border subsidies, which are likely challenging from the political and implementation point of view.

5.1.2 Policies considered but not further analysed

Policies of category 1 - direct legal restrictions on the use of waste oil for energy recovery – were not further analysed for several reasons, mainly due to a low expected efficiency and legal feasibility concerns or due to a lack of specific information on the blending of waste oil into marine fuels (see Section 1.4.2). Specific policies in this category included a full ban of waste oil combustion for energy recovery (1a), a ban or a restricted use in certain sectors (e.g. marine bunkers, 1b), or mandatory quality and treatment requirements before waste oil can be used for combustion or blending in marine fuels (e.g., EoW protocol for waste oil-based fuel, 1c) and a ban on waste oil export for energy recovery (1d). In terms of scope, all the options in this category would be applied EU-wide, in the interest of consistency.

Policy (1a) A ban on the combustion of untreated or treated waste oil, except in HWI plants for qualities of waste oil that are deemed unsuitable for regeneration. The main reason for leaving out this policy from further analysis is that it is rather radical in the sense that it prohibits all energy recovery pathways except for HWI, although some of them (conversion to fuel) are much less harmful than others (combustion in cement kilns/boilers), in terms of most types of pollutant emissions as well as societal life cycle costs and all of them have lower societal life cycle costs than HWI. This would affect 35% of all collected waste oil in the EU and might lead to excessive adjustment costs (low expected efficiency), as 35% of waste oil treatment capacity has to be replaced by regeneration plants, which might prove technically difficult and uneconomic, particularly given the lower waste oil qualities used in combustion. Not all waste oil has the sufficient quality needed for regeneration so it would need to be burned (at an economic loss) in HWIs. These adjustment costs might appear particularly high when compared to the expected benefits calculated in the LCC (Section 4.2). Taken together, this might lead to resistance from MS (low political feasibility). There also is a lack of data on the different qualities of waste oil on the market, which leads to uncertainty as to what percentage of the collected waste oil can be regenerated (at least at a reasonable cost).

This policy would affect around 640,000 tonnes of waste oil per year in the EU. According to estimates from several stakeholders active in waste oil regeneration and hazardous waste treatment 5-15% of collected waste oil is not suitable for regeneration (at least with current collection practices), but only around 4% is burned in HWIs.. Such a policy seems to be in place in Brazil (DeMarco, 2012; Trenceti, 2019).

Arguments in favour of this policy:

- If all waste oil that previously went to combustion (treated or untreated) could be redirected to energy recovery and the amount of waste oil going to HWI remained unchanged, it would be the most consistent translation of the findings from the LCA/LCC and the EU's circularity and waste hierarchy goals into regulation. However, if this policy increased the amount of waste oil going to HWI, there might be net losses in terms of sLCC (see arguments against this policy below).

- Depending on whether the waste oil diverted to regeneration is replaced by something with a lower import dependence than crude oil, it could contribute to lower EU imports (and dependence) of crude oil.
- Surveillance and enforcement seems relatively simple: it must only be ensured that the collected waste oil goes either to regeneration or hazardous waste incineration.

Arguments against this policy:

- The black/white nature of this policy makes a smooth transition difficult given the regulator needs exact knowledge on EU regeneration and HWI capacities before enacting such a policy and having it enter into force. This knowledge is obtainable in theory but would need to be monitored on a regular basis as it changes dynamically.
- Eliminating energy recovery would leave the lower-quality waste oil with few treatment options beyond HWI, as it is generally unsuitable for regeneration. The current share of waste oil that is unfit for regeneration is not known. From communications with several stakeholders active in waste oil regeneration and hazardous waste treatment, estimates range from 5 to 15% of all collected waste oil with current collection practices. According to GEIR, there is a techno-economic threshold at 5% below which waste oil cannot be regenerated, at least not in an economically viable fashion. Given that hazardous waste disposal is costly, this could create an economic incentive for illegal disposal with risk of environmental damage or it could incentivise exports outside the EU, which would be illegal.[38]
- Depending on whether the waste oil diverted to regeneration is replaced by something with a higher import dependence than crude oil, it could contribute to increase EU import dependency of such resources (e.g. natural gas, coal, or biomass).
- This is a special case of option 2a (which is a target of X% of waste oil going to regeneration – in this case X would equal 100% minus the lower quality waste oil deemed unsuitable for regeneration).

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps.

- We do not know exactly what percentage of waste oil is suitable for regeneration today, i.e. with current collection practices.
- We do not know whether a logistical problem might arise when large additional amounts of waste oil need to be shipped across the EU (or outside) to be matched with free regeneration capacities.

Overall assessment:

Expected effectiveness: The option is using command & control to achieve maximum regeneration. However, as the sensitivity and discernibility analyses in sections 4.3 and 4.4 point out, regeneration

[38] Waste oil is classified as a hazardous waste, and thus cannot be exported from an OECD to a non-OECD country, according to the Amendment to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. Under EU waste shipment law, shipping hazardous waste to non-OECD countries outside the EU is illegal. Shipments to OECD countries, are generally subject to the prior notification and consent procedure which requires the prior written consent of all relevant authorities of dispatch, transit and destination. The proposal for the EU Waste Shipment Regulation would ensure consistency in the implementation of the Basel Convention by each Member State. As a result it aims at avoiding obstacles to the shipments of waste within the EU or impediments to the good functioning of the EU internal market. It also goes beyond the Basel Convention by prohibiting the export of waste for disposal outside EU and European Free Trade Association (EFTA) countries, and the export of some non-hazardous waste outside the OECD.

is not the preferred option to energy recovery in 100% of the cases and hence there is a risk that the measure could, at least in some cases, be considered unjustified or disproportionate.[39]

Expected efficiency: the option is radical and might create excessive adjustment costs.

Technical/legal feasibility: Technically, this would be feasible except for a small share of the collected waste oil, which is too contaminated for regeneration at a viable cost.

Political feasibility: This policy might be met by low acceptance from MS.

Policy (1b) A ban on the use and preparation for use of waste oil in marine bunker fuels. There is only anecdotal evidence on the quantitative significance of waste oil being used, after minimal treatment, as marine fuel. Justifying such a policy – and especially why it should single out the marine sector – might be difficult due to this lack of data. Furthermore, we lack technical data on the process used to convert waste oil to marine fuel and such a policy might interfere with existing national EoW schemes, which might render it legally infeasible at EU level.

Arguments in favour of this policy:

- General coherence with EU's waste hierarchy and circular economy ambitions, since burning waste oil, including as marine fuel, goes against these principles.
- Policy would effectively address legal, and illegal use of waste oil-based fuel as marine fuels, including cases where the legal status is unclear (see Section 1.4.2 for a detailed description of these uses).
- Puts an end to less ambitious EoW protocols that do not require a distillation process to convert waste oil to fuel (as exemplified by the UK PFO protocol, see UK Environment Agency, 2011) which allow presence and release of waste oil-typical harmful contaminants by ships.[40]
- Removing marine bunkers as potential destination for processed waste oil would reduce demand for and price pressure on waste oil, which would make it more likely that more of it goes to regeneration.
- This policy would put an end to the practice of waste oil-based fuel producers buying low quality waste oil and thus maintaining a market for this type of waste oil which might incentivise poor collection practices.

Arguments against this policy:

- There is only anecdotal evidence on the quantitative significance of the waste oil-to-marine-fuel situations/practices a), b), c) described in Section 1.4.2 so justifying this policy – and especially why it singles out the marine sector from all possible waste oil-to-fuel uses – might be difficult.
- Benefits in terms of reduced EU fossil fuel consumption and less import of crude oil seem unlikely, since waste oil diverted away from marine bunker markets will be replaced by virgin fossil fuels[41].

[39] As our LCA represents a technology average, some individual regenerators might still be below that average. This could lead to a less favourable environmental outcome for these regenerators compared to some of the environmentally above-average energy recoverers.

[40] The UK quality protocol for processed fuel oil, specifies the conditions under which waste oil can be converted to a non-waste product called "processed fuel oil" (see UK Environment Agency (2011). For several reasons, among them the fact that the processes outlined in the protocol did not include a distillation step, the European Commission was concerned that the fuels produced via this protocol would have higher contamination levels than comparable "virgin" fuels and that this would lead to adverse environmental and health impacts. This matter was assessed under infringement case number 2012/2081.

[41] A similar effect can be observed in our LCA results for the distilled fuel processes WODFa and WODFb: the environmental savings from using waste oil derived fuels are large because of the displacement of virgin fossil fuels (heavy and light) that would otherwise be used. However, even if all 24% of current waste oil that is converted to fuel would go into the marine fuel market this would be less than 0.2% of the global market in 2020 (see IMO, 2021).

- Waste oil might not be diverted from marine bunkers to regeneration, but also to cement kilns, incineration, etc., which might have a worse environmental impact than the use – with adequate treatment – as marine fuel. The unavailability of legal ways to produce marine fuels from waste oil might also reinforce the illegal practice of doing so (situation b ii. From Section 1.4.2).
- Monitoring and enforcement to prevent that waste oil enters marine bunker markets could be difficult, due to their international character.
- It is challenging for the Commission to prevent MSs from enacting national EoW criteria for waste oils to be used as fuel. At best these could be overridden by possible EU-wide EoW criteria, which are currently not under consideration for waste oils for fuel use.

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

- Lack of usable data on total volumes of waste oil going into marine fuels, and on the shares corresponding to the legal and illegal as well as the channels where the legal status is unclear, see cases a) b) c) described in Section 1.4.2.
- We also do not have reliable data on the technical process of 'low quality waste oil-based fuel', meaning that the potential benefits from reducing this scenario cannot be robustly computed in our LCA.

Overall assessment:

Expected effectiveness: although this policy might impede some undesired waste-to-fuel practices, and also the import and (illegal) use of unsuitable waste oil-based fuel as marine fuel, it would also stop EoW transformation of waste oil into higher quality marine fuels (e.g. as currently done in Spain). The latter is not seen as particularly harmful (see LCA results; this option incurs significant environmental benefits compared to energy recovery via direct incineration but is still outperformed by regeneration in terms of environmental benefits), and therefore it would seem unjustified and disproportionate to phase-out this practice while continuing other EoW protocols for use of treated waste oil outside the marine sector. In addition, this option does not intrinsically lead to an increase of regeneration.

Technical/legal feasibility: Legal feasibility unclear – in particular the possibility to prevent a Member State from adopting a certain EoW protocol is uncertain.

Policy (1c) Developing EU harmonised End-of-Waste (EoW) criteria for the conversion of waste oil to fuel oil and marine bunker after adequate treatment. Not further analysed, as it would go against the objective of reducing the environmental and societal impacts of waste oil treatment, as the LCA and LCC analyses in previous sections demonstrate that regeneration of waste oil generally has lower impacts in these categories compared to conversion to fuel (and, additionally, due to the lack of data on the use of waste oil for blending with marine fuels).

Arguments in favour of this policy:

- This practice valorises waste oil to a higher level than when it is incinerated in power plants/kilns and HWI facilities and thus could provide an intermediate solution until sufficient regeneration capacity is built up.
- It would prevent the uncontrolled release of some pollutants when waste oils are used as ship fuels after milder treatments. There are no specifications – in particular no upper limits – for some of these pollutants in marine fuels as these pollutants are not present in virgin fuel, so without an EoW protocol, these emissions would be in fact legal.

Arguments against this policy:

- The LCA/LCC shows in a large majority of cases a superiority of regeneration compared to waste oil-based fuel production – so why make a new and reinforcing policy for the latter?
- Also, there is a clear risk that EoW criteria, if not formulated carefully, incentivise this use of waste oil, drawing away waste oil from the regeneration sector.

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

The same arguments related to the knowledge and data gaps around the use of waste oil as marine bunker fuel as in policy 1b apply here as well.

Overall assessment:

Expected effectiveness: This policy does not intrinsically lead to an increase of regeneration, and thus goes against the waste hierarchy. By increasing demand from the waste oil to fuel sector, it might even increase the price of waste oil and thereby reduce the share of waste oil that is regenerated, which might be a problem in terms of coherence with other EU policy objectives (circularity, climate change). On the positive side, this policy might impede some of the undesired practices with an unclear legal status[42], and also the import and (illegal) use of unsuitable waste oil-based fuels as marine fuel. It could provide an intermediate solution until sufficient regeneration capacity is built up – but in this case it would need to be accompanied by policies that increase the regeneration share and would need to be phased out over time, which raises issues of proportionality.

Expected efficiency: The effort to establish an EU-wide EoW scheme for the conversion of waste oil to marine fuel is expected to be high. Since this would likely be a temporary policy, this raises issues of proportionality. In addition, this policy does not, in principle, follow the waste hierarchy.

Policy (1d) A ban on all waste oil exports from EU countries to OECD countries, except for the purpose of regeneration.[43] This is in fact already an option at the Member State level under the WFD, where member states have the option to restrict waste oil exports for the purpose of (co-)incineration. The exact wording in Art. 21 of the WFD is that MSs can "*where Articles 11 or 12 of Regulation (EC) No 1013/2006 apply, restrict the transboundary shipment of waste oils from their territory to incineration or co-incineration facilities in order to give priority to the regeneration of waste oils*." This policy would make this option mandatory. Due to this and to the fact that this would only affect less than half a percent of all waste oil in the EU, we did not further analyse this policy.

Overall assessment:

Expected efficiency: For the year 2018, this would only affect 7000 tonnes of waste oil, less than half of a percent of all collected waste oil in the EU. This low quantity would not meet the principles of efficiency and proportionality.

In category 2, we analyse all policies in-depth, except for policy (2d), the generation of regeneration certificates, which would need to be acquired by suppliers of Base Oil or Lubricant Oil products, as a share of their total output.[44] This policy is not further analysed, mainly due to relatively high expected costs related to the monitoring and setting up of the envisaged necessary infrastructure and associated regulatory body.

Arguments in favour of this policy:

[42] See Section 1.4.2.

[43] As waste oil is classified as a hazardous waste, it cannot be exported from an OECD to a non-OECD country, according to the Amendment to the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal. This is also already envisaged in the Waste Shipment Regulation proposal, which would prohibit the export of waste for disposal outside European Free Trade Association (EFTA) countries.

[44] The policy would work as follows: Assuming that a government would like ensure X% of the total base oil on the market (or used in products) from a regenerated source, rather than obliging all base oil producers to comply with this percentage individually, they could establish a certificates market as follows. If a base oil producer achieves a regeneration rate of less than X%, it needs to buy regeneration certificates on the market. The amount of certificates (in tonnes) can then be added in this producer's computation of the regeneration share: (actual output of regenerated base oil + acquired certificates) / total output. If, by contrast, the producer achieves more than X% of regenerated base oil, it can sell regeneration certificates to other producers. The price of the certificate would reflect the cost differential between a tonne of base oil produced from virgin oil and a tonne of base oil produced through regeneration of WO.

- This policy is similar to an instrument used in the Swedish and Norwegian market for renewable electricity (Hustveit et al., 2017).
- This policy is more efficient than obliging each base oil and lubricant producer to comply with the percentage target, as only those producers who can do this most cost-efficiently would increase the amount of regenerated base oils in the lubricants they place on the market.
- The target would not need to be country specific and could be set at the EU level.

Arguments against this policy:

- In certain market situations, there might not be enough regenerated base oil, even when a 100% regeneration rate is achieved. This could gravely distort the market by artificially restricting the base oil supply. To avoid this the regulator would need regularly updated data to be able to set a reasonable volume that can be served by the current regeneration facilities and have some way of correcting the target upwards in the future.
- The target would depend on the base oil group. Since there are only six regeneration plants in the EU producing Group II and only one regeneration plant producing Group III base oil, the outcome of this policy would depend on a very small set of companies.
- Total base oil demand and demand between groups is continuously shifting (Lubes'n'Greases, 2022), which would require the policy to be adjusted over time.
- The system to implement and control this certificates trading system requires infrastructure, a supervisory body, etc. and thus results in high costs and could be considered disproportionate to address the relatively small market represented by waste oils.

Aspects that hinder the analysis of this policy, e.g. knowledge or data gaps:

- The content of regenerated base oil in imported base oil is not known, thus leaving an important variable unknown. According to Stahl and Merz (2020), 0.50 to 0.6 million tonnes of waste oil are imported from outside the EU. As 4.3 million tonnes are placed on the market, this amounts to 11 to 14% of the demand.

Overall assessment:

Expected effectiveness: This policy leads directly to an increase of regeneration and is thus in line with the waste hierarchy and circular economy objectives. It also addresses issues on which there are too many data gaps to address them otherwise such as the abovementioned marine fuel issue.

Expected efficiency: The effort to set up and monitor a regeneration certificate scheme is expected to be high.

Political feasibility: This policy might face resistance from consumers as it might increase the price of lubricant oils.

Some additional price-based measures (category 3) have been omitted for reasons of legal feasibility and are therefore not contained in Table 12. These policies include a VAT reduction for lubricant oil produced from regenerated waste oil, as well as special excise duties on the combustion of waste oil or the production of virgin base oil. These policies will not be discussed further in this report.

5.2 Definition of the business-as-usual scenario (no policy intervention)

In order to assess and compare the different policies, we establish a baseline (or "business-as-usual") scenario of base oil demand, the resulting waste oil generation and the different uses of the waste oil (regeneration, conversion to fuel and energy recovery) until 2045. For these projections we extend projections from Bau et al. (2018) on lubricant oil demand to the year 2045. We use EUROSTAT's [wasgen] database to validate the projections on waste oil.

The objective of Bau et al. (2018) is to estimate the general effect of electric vehicles on future lubricant oil demand, and so they only provide numbers at a global scale. We use the EU's share of global base oil in 2019

(16.9%; Stahl and Merz (2020)) to scale the numbers down to EU-level. We apply the annual lubricant market growth rates from Bau et al. (2018) to European base oil demand taken from Stahl and Merz (2020), so as to obtain a projection of base oil demand and waste oil generation in the EU, and collection rates from earlier years are used to derive projections for the collected waste oil. In accordance with a study by (RDC Environment, 2023) on waste oil collection, we also take EU emission standards for cars into account.[45] As a result, the annual lubricant market growth rates are equal to Bau et al. (2018) until 2035. Starting from 2036, it is assumed that the waste oil generation coming from the automotive sector decreases gradually from its 2035 level to 32.5 % in 2050 due to EU regulations aiming to ban combustion engine cars from 2035 onwards. For more details see (RDC Environment, 2023). The resulting business-as-usual collected and regenerated waste oil quantities are shown in Figure 11 (together with the quantities of waste oil used for regeneration in the policy scenarios).

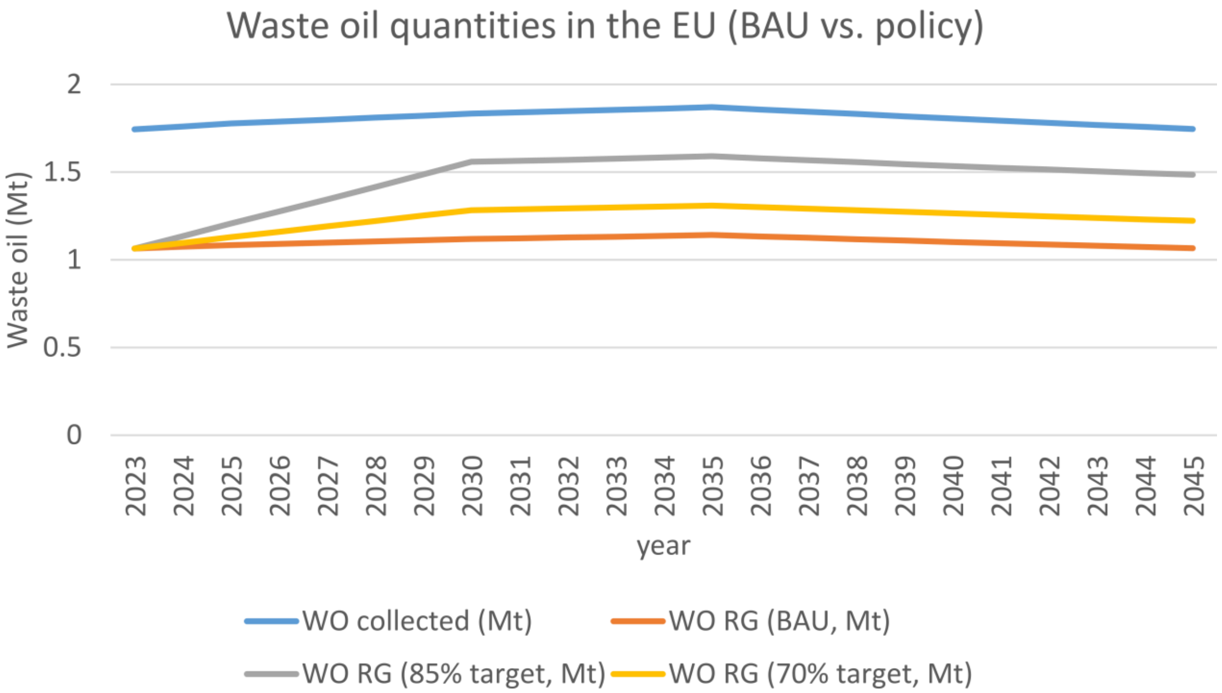

Figure 11 Regenerated (RG) waste oil (WO) in the EU: policy versus baseline (BAU). Source: JRC modelling, building on RDC Environment (2023).

5.3 Socio-economic analysis of policies to regulate waste oil

This report focuses on three main types of impacts: environmental, economic and social. Environmental impact analysis is based on the LCA results and calculates the savings in different types of emissions (such as greenhouse gases, heavy metals and particulate matter) which translates into savings in impact categories (Global Warming Potential, Eco- and Human Toxicity, Particulate Matter, etc.) related to different policy fields. The economic analysis is partially based on the LCC results and estimates benefits and costs associated with different policies. In the analysis of the social effects, net effects on job creation are analysed, as well as different types of distributional effects.

Since the single objective of all policies is to channel waste oils towards regeneration, we render the policies comparable with regard to their economic impacts by calibrating them such that they all lead to the same outcome with respect to regeneration.[46] We specifically analyse two targets. The less ambitious target corresponds to an increase in collected waste oil that goes to regeneration from 61 to 70% until 2030. In the more ambitious scenario, regeneration increases from 61 to 85% until 2030. Note that 85% also corresponds to our conservative estimate of the upper limit of regeneration that could be achieved with current waste oil

[45] Amending regulation 2021/0197(COD) on CO_2 emission standards for cars and vans.

[46] For the sake of this analysis we assume that this implies homogenous environmental impacts across all policies.

qualities and collection practices (see Section 1.1). The policies hence only differ in their economic and social impacts. Table 13 summarizes the corresponding targets for each policy and the methods used to derive them.

Table 13 Policy targets and their equivalents for each policy option, as well as the methods used to derive them. All values corresponding to the 85% target are given in parentheses.

Policy	Target and equivalent targets	Method
2a	70% (85%) of collected waste oil regenerated in 2030	Increasing the regeneration rate by 1.3% (3.4%) a year starting in 2024.
2b	Share of regenerated base oil on markets increased from 11.3 to 13.0% (15.8% for 85% target)	Share of regenerated base oil on market is calculated with data from Stahl and Merz (2019); Data from IFEU (2021) is used to translate base oil into waste oil quantities.
2c	Share of regenerated base oil in Group I base oil increased from 20.7 to 24.1% (29.9% for 85% target)	Share of regenerated base oil in Group I base oil is calculated with data from Stahl and Merz (2019); Data from IFEU (2021) is used to translate base oil into waste oil quantities.
3a	Implementing a subsidy that increases from 5.5 to 34.5 (14.2 to 76.6 for 85% target) €/t of waste oil put to regeneration between 2024 and 2030 between 2024 and 2030	The subsidy is calculated using the elasticity of substitution between virgin and regenerated base oil from CalRecycle (2016).
3b	Implementing a levy that increases from 0.6 to 4.6 (1.7 to 12.5 for 85% target) €/t virgin base oil between 2024 and 2030 and a corresponding subsidy from 5.0 to 31.0 (13.6 to 68.0 for 85% target) €/t of waste oil put to regeneration	Similar to 3a, but the model has feedback effects because levy and subsidy act on the same variables and thus needs additional iterations at each time step to converge.

5.3.1 Policy 2a: A target specifying the share of collected waste oil to be regenerated

This policy sets a minimum percentage of the collected waste oil that has to be regenerated. For the sake of this comparative analysis, we set two targets: a less ambitious one corresponding to 70% of all waste oil collected in the year 2030 and a more ambitious target of 85%. Both targets are gradually phased in starting in 2024.

The results in terms of environmental, economic and social effects are summarized in Table 14 and are discussed at length in the corresponding subsections below.

Table 14 Summary of environmental, economic and social impacts for regeneration rates of 70% and 85% of all collected waste oil (sLCC= societal life cycle cost; FTE= full time equivalent) Avoided GHG emissions, sLCC savings and administrative costs are summed over the period 2024 to 2045. Employment creation refers only to the final year, 2045.

Target	Avoided GHG emissions (Mt CO2-eq.)	s**LCC savings (M€)**	Administrative **cost (M€)**	Employment Creation (FTEs in 2045)
70%	0.6	124	11-213	124

85%	1.7	330	11-213	329

Environmental effects

Between 2024 and 2045, a 70 (85)% regeneration target would move an additional 3.11 (8.29) Mt of waste oil from fuel generation into regeneration, which would avoid 0.6 (1.7) Mt of CO_2-eq. emissions over the whole time period. This equals around 3 (8) % of Estonia's total GHG emissions in 2018.[47] This value is calculated as the difference between the average CO_2-eq. emissions across regeneration technologies, weighted by each specific regeneration technology's share of waste oil treated via regeneration, and the CO_2-eq. emissions from waste oil-based fuel production. This is a lower-end estimate of the savings, as we assume that only waste oil that was going to fuel production is diverted to regeneration. We believe that this is the most reasonable assumption in light of the fact that waste oil going towards incineration has higher levels of contamination, which makes it less suitable for regeneration (at least without further treatment).

Figure 11 shows the comparison of the policy scenario with the business-as-usual (BAU) baseline in terms of regenerated waste oil.

Environmental benefits (in all impact categories) might be asymmetric in the sense that if waste oil is not burned locally, but instead refined in other regions or countries, the exporting region would avoid pollution altogether while the importing region would face additional pollution through increased regeneration activity, even though on aggregate, environmental impacts would be reduced.

Economic effects

The monetary value of the benefit from avoided pollution is determined in the LCC (see Section 4.2; in the LCC, estimates of the external costs of different pollutants were taken from Bijleveld et al. (2018) except for CO_2 externalities, which were taken from van Essen et al., 2019). Based on this, the additional tonnes of waste oil going to regeneration can be translated into monetary savings. In what follows, we use the concept of societal life cycle costs (sLCC), described in detail in Section 4.2. This measure sums up the internal (such as CAPEX and OPEX) and external costs (related to the emissions of pollutants). Due to the sLCC accounting for all costs (and benefits) to society, it is the most comprehensive measure of gains and losses to society in the context of this analysis. Moving one tonne of waste oil from conversion to fuel to regeneration generates a net saving (in terms of sLCC) of 55.8€. This value is calculated as the difference between the sLCC of conversion to fuel (ER-WODFa) and the average sLCC of all regeneration technologies, weighted by each specific regeneration technology's share of waste oil treated (via regeneration).[48] Summing up the savings from 2024 until 2045 for the 70 (85)% target yields a net present value of 124 (330) M€, using a social discount rate of 3%.

The effect on the government budget is not clear ex ante as the implementation of policy 2a would be left to Member States. The costs could be relatively high for a subsidy on regeneration (see also policy 3a) or a certificate scheme (2d), and comparatively lower for recycled content targets (2c) or a subsidy financed via a levy on virgin production (3b). Regarding administrative costs, we have little data to work with, but some insights can be obtained from countries that have comparable schemes in place. Based on an Australian levy and subsidy scheme, we estimate in Section 5.4 that over the 2024-2045 period and discounted with a social discount rate of 3% the administrative costs would amount to a range of 11 to 213 million €. We see no principle reason for why the administrative costs should differ between a 70% and an 85% target.

Regarding the effect on small and medium enterprises (SMEs), both waste oil-based fuel producers that use (processed) waste oil and waste oil regenerators fall generally into the SME category. A policy that shifts more waste oil from the former to the latter hence affects mostly SMEs.[49] In 2019, there were 27 enterprises

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[47] Source.

[48] According to IFEU (2021), of the quantities of waste oil that are regenerated and that are accounted for in their data collection, approximately 32% go towards hydro-treatment, 46% towards solvent extraction and 22% towards distillation. These data represent 82% of all waste oil going towards regeneration. Although there is some uncertainty due to the unaccounted 18%, we assume that the percentages treated via the individual regeneration pathways are a sensible approximation of the fate of all waste oil treated via regeneration and we use them as weights to calculate average values across technologies.

[49] A secondary effect is that refiners using crude oil as a feedstock would face lower demand. However, as base oil production is only a small part of crude oil refiners' business and these enterprises are usually very large, this effect might be negligible.

active in the field of regeneration, most of them SMEs (Table 7-2 in Stahl and Merz (2020)). Further, IFEU (2021) identified 11 companies that were active in the processing of waste oil to fuel in 2019 (mostly SMEs), most of them located in the UK (see Table 8, IFEU (2021)). Energy recoverers are not directly affected by the policy options and only treat around 11% of the waste oil, arguably of inferior quality and not suitable for other uses. Also, in most cases they are large companies and not SMEs. For these reasons we omit them in this discussion on SMEs. There might be potential impacts on the virgin refiners, but they also do not fall under the SME category.

Social effects: Employment

According to the LCA (see Section 4.1), each 1000 tonnes of waste oil diverted from conversion to fuel to regeneration are associated with a net employment effect of 0.783 jobs, which we measure in Full-time Equivalents (FTEs).[50] For the 70 (85)% target, this translates into 18 (47) additional FTEs in 2024, the year the policy is first put into place. Over the analysed period, the number then increases to 124 (329) FTEs across the EU, by the year 2045. These numbers can be interpreted as number of jobs created through this policy.

Since the use of waste oil for energy recovery, including conversion to fuel, often takes place locally, while high quality waste oil suitable for regeneration is quite often exported to places with regeneration facilities, this net job creation implies a shift of jobs between regions and countries: Of the 27 waste oil regeneration facilities in the EU27+UK, six are located in Germany, five in Spain, three in Italy, with the remaining thirteen facilities distributed over Greece, France, Poland, Portugal, the UK, Bulgaria, Denmark and Finland (see Figure 12; Stahl and Merz, 2020). Therefore, implementing regeneration targets likely increases intra-EU movements of waste oil for regeneration from countries without regeneration facilities to countries with existing facilities (and spare capacity), which would imply job losses for waste oil-based fuel producers in the former and job gains for regenerators in the latter regions. This might raise distributional concerns, if no measures are taken to counteract this, such as creating incentives for building local regeneration.

[50] FTE is a unit indicating the workload of an employed person. An FTE of 1.0 corresponds to one full-time worker. In our case, FTEs are determined via the yearly capacities of the different treatment pathways and are thus FTEs per year.

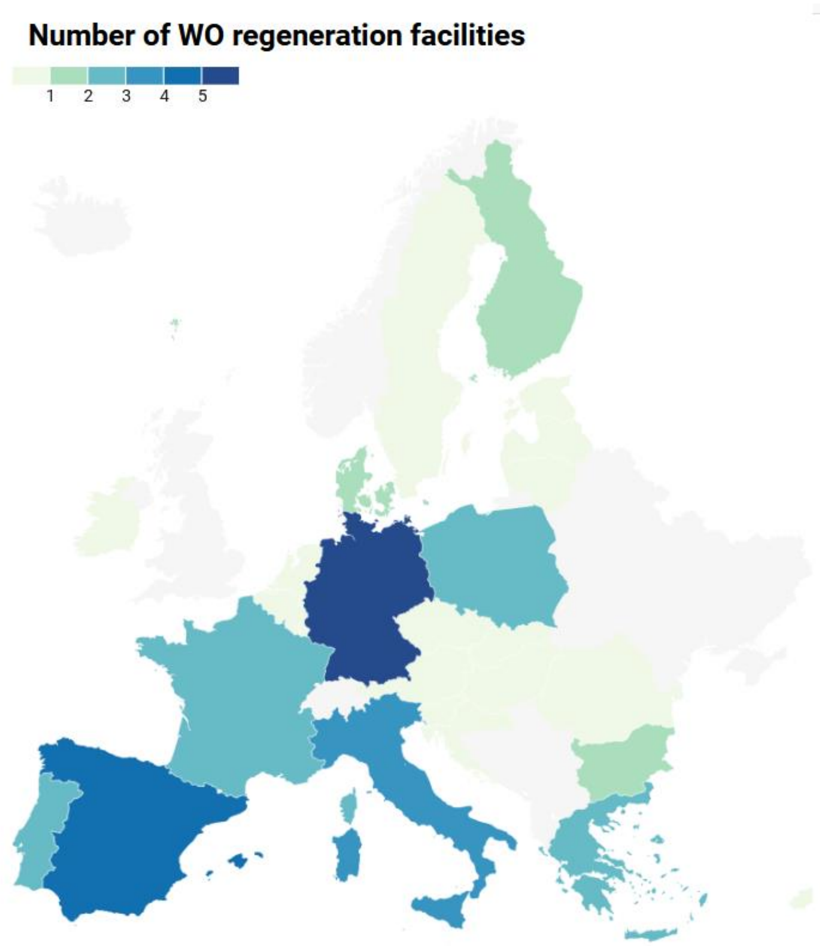

Figure 12 Waste oil regeneration facilities in the EU-27 (absolute number). Source: Stahl and Merz (2020).

We estimate the distributional effects as follows: spare regeneration capacities in the EU are calculated using Tables 9-1 and 27-4 in Stahl and Merz (2020). The country share of the spare regeneration capacity is shown in Figure 13. We then assume that the jobs created through increased regeneration accrue to the different countries according to their share of regeneration capacities. We determine each country's share of the total EU waste oil-based fuel production and assume that jobs lost in waste oil-based fuel production are proportional to this share. The results are displayed in Figure 14.

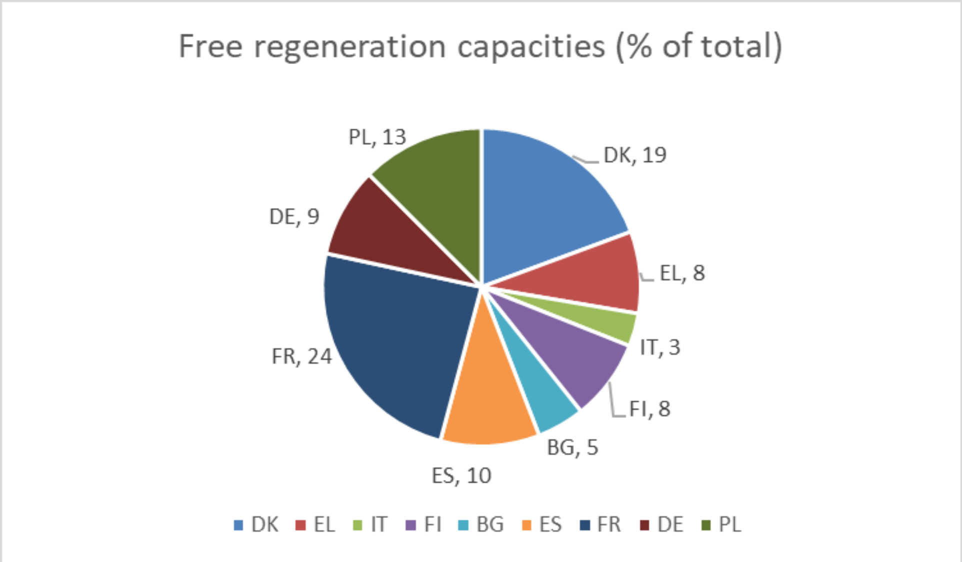

Figure 13 Free regeneration capacities in the EU as a percentage of the total spare capacity.

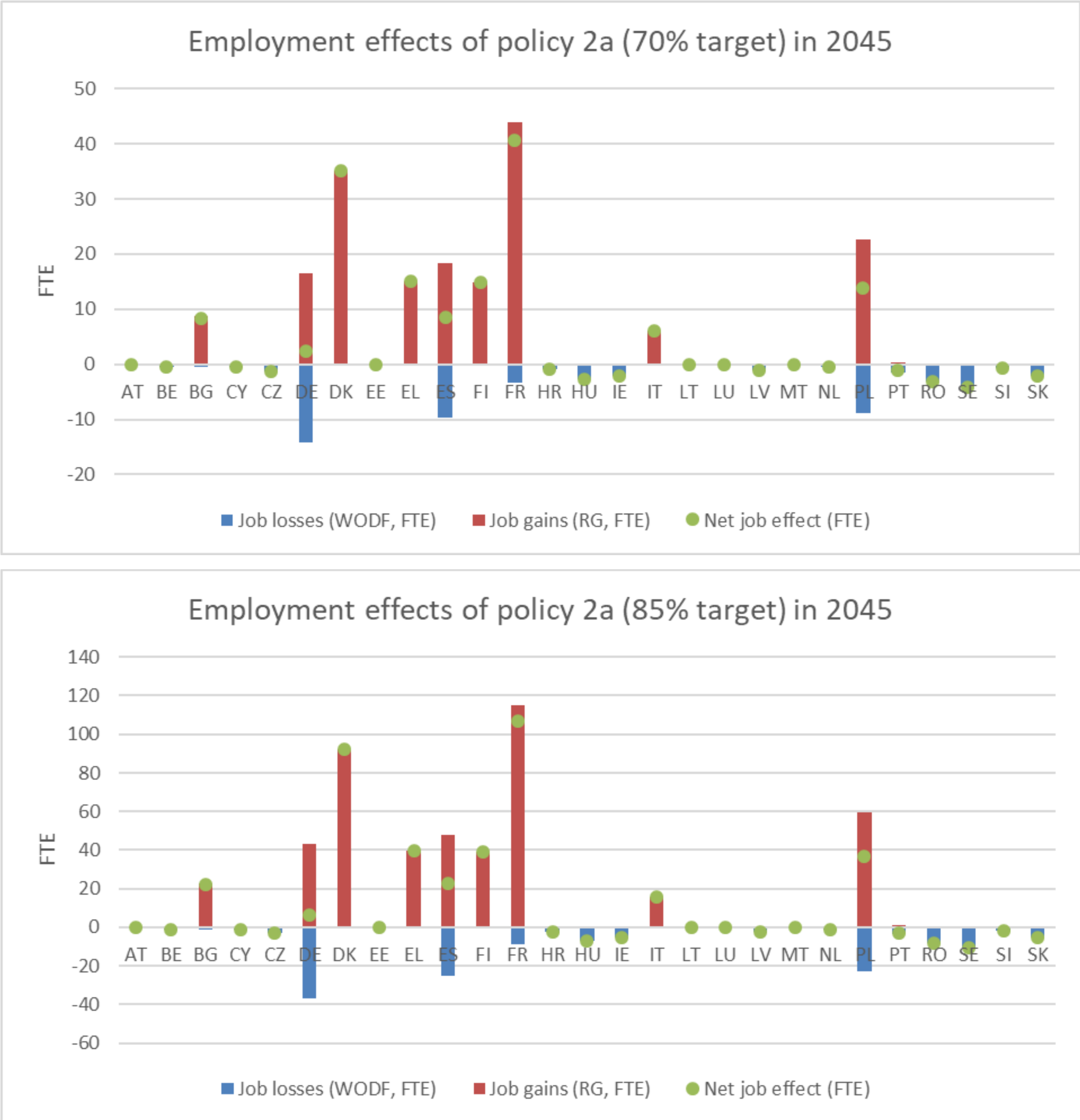

Figure 14 Employment effects of policy 2a in terms of FTEs in 2045 for different EU countries. We assume that the regeneration target set in policy 2a shifts waste oil from waste oil-based fuel producers to regenerators in countries with spare regeneration capacities. FTE stands for Full Time Equivalent. FTE by 2045 can roughly be interpreted as the number of jobs lost over the course of the period 2024-2045. Top panel: 70% regeneration target. Bottom panel: 85% regeneration target.

It can be seen that the aggregate job creation on the EU level outweighs job losses significantly. Looking at the country level, however, shows that some countries, such as France, Denmark, Poland and Greece would benefit strongly, while others, like Romania and Sweden would incur job losses.[51] In the remaining countries,

[51] Sweden and Romania would be the countries with the highest net job losses amounting to 4 and 3 FTEs, respectively, for the 70% target and 11 and 8 FTEs for the 85% target by 2045. FTE by 2045 can roughly be interpreted as the number of jobs lost over the course of the period 2024-2045.

job losses are either offset by gains in regeneration (Spain, Germany), or, if countries do not have regeneration facilities, job losses do occur, but are rather small (Czechia, Croatia, Slovenia).[52]

Social effects: Cost pass-through, distributional impact

Another social issue is related to the question of who pays for the increase in waste oil regeneration. This is illustrated via the supply and demand partial equilibrium model in Figure 15. In economics, these models are used to illustrate how total output and price levels are determined in (partial) equilibrium in well-functioning markets. The equilibrium is partial in the sense that it only considers one product (in our case base oil), assuming that all other prices and quantities remain constant. In the case of base oils, the supply curves of regenerators and virgin producers are summed up (since the product they produce is almost identical) into an aggregated supply curve S_{Agg}. The demand curve is denoted by D.[53] The market equilibrium is given by the intersection of the aggregate supply curve and the demand curve in the point (Q_0,P_0), where Q_0 goods are sold at price P_0 (see the left panel in Figure 15).

The right panel of Figure 15 depicts the supply curve of regenerators. Regenerators are price takers, because the price for base oil is determined by the production costs of virgin refiners, due to the much larger volumes they produce. Therefore, the equilibrium (Q_0,P_0) is the same as in the left panel. According to the regenerators' supply curve, they sell the quantity $q_0 << Q_0$ at price P_0 and they are characterised by a steeper supply curve than the virgin refiners (i.e. they face capacity and supply constraints more quickly). If a policy such as the 70% regeneration target increases the amount of regenerated base oil sold on the market from q_0 to q_1, regenerators face higher costs (p_1) and would, at least in theory, be forced to sell below cost at the equilibrium market price, if they do not receive a higher compensation for their increased production – e.g. through a subsidy from the regulator.[54] This minimum compensation is approximated by the pink triangle in the right panel.

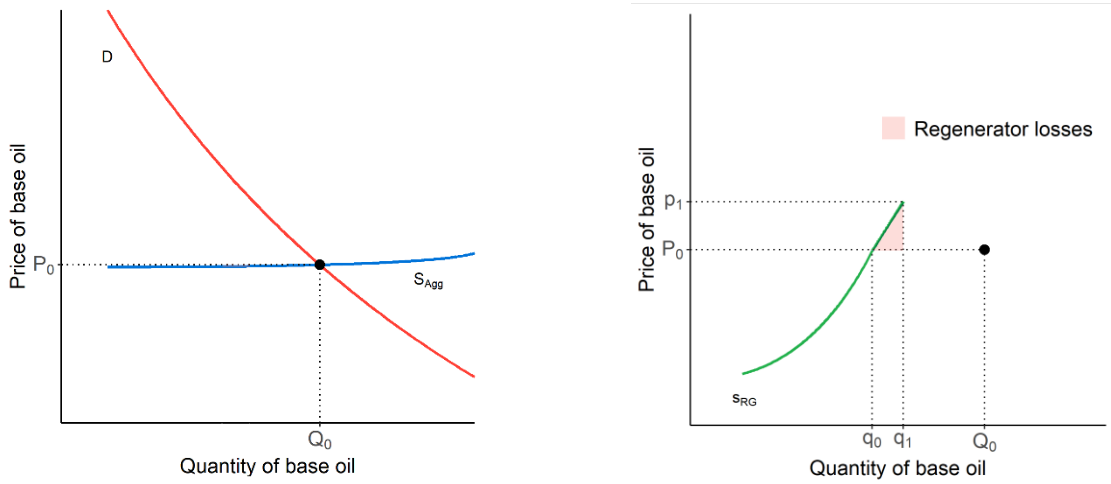

Figure 15 The effect of a quantity target on the base oil market. Left panel: S_{Agg} is the aggregated supply of regenerated and virgin base oil (in blue). D is the demand curve. The market equilibrium is given by the intersection of the aggregate supply curve and the demand curve in the point (Q_0,P_0), where Q_0 goods are sold at price P_0. Right panel: A quantity target increases the supply of regenerated base oil S_{RG} (in green) from q_0 to q_1. Regenerators are price takers because virgin refiners' production costs set the price for base oil, due to the larger volumes they produce. The equilibrium (Q_0,P_0) is the same as in the left panel. According to the regenerators' supply curve (S_{RG}), they sell the quantity $q_0 << Q_0$ at price P_0. If a

[52] One caveat of this finding is that the expansion of regeneration would, at least in the beginning, take place by using spare capacities. This might not have the full employment effect as calculated in the LCA. However, limited reductions of volumes of waste oil-based fuel production most likely would also not directly lead to a firing of personnel. So perhaps both job gains and losses are exaggerated, but the net effect might still be a sensible approximation of reality.

[53] We assume that demand for lubricants is relatively inelastic (i.e. it does not react much to price changes), because it is mostly tied to existing capital such as cars and people are unlikely to change their lubricant spending in response to a small price increase. To reflect this, the demand curve D should be relatively steep, almost vertical. However, in Figure 15 we used a less-steep demand curve for the sake of better illustration of the effects at play.

[54] This equilibrium price might change due to the policy, but this change would be rather small due to the comparatively low volume of regenerators compared to virgin producer and to relative flatness of the aggregate supply curve. Also, increased base oil quantities would be sold at the pre-policy equilibrium price and would push the aggregate supply curve (a little bit) downwards, thus increasing regenerator losses.

policy (such as the 70% regeneration target) now increases the amount of regenerated base oil sold on the market from q_0 to q_1, regenerators face higher costs (p_1), and therefore need a cost compensation of at least the area corresponding to the pink triangle in the right panel.

This situation would not be economically viable in the long run without additional policy support. We analyse the example of a subsidy for regenerators in Section 5.3.4.

The effect of this policy on consumer prices and related distributional effects cannot be assessed without knowing the way in which regenerators would react to the increased waste oil load (and the related costs). With the current policy setting, regenerators cannot pass the cost on to consumers through higher prices, because the price of base oil is set by the larger group of virgin oil refiners. Therefore, financial support for regenerators or additional policies that ensure that lubricant producers buy regenerated base oil at higher prices would be necessary. The distributional impacts would differ, depending on the policy chosen: A subsidy would affect the consumer price only very little (and, if so, it would push them downwards) and thus not have much distributional implications between households. If, by contrast, lubricant producers would be obliged to buy regenerated base oil at increased prices (e.g. under a recycled content obligation), at least some of the price increases would be passed on to consumers.

5.3.2 Policy 2b: A target specifying the share of regenerated base oil on markets

Policy 2b – a percentage target of regenerated base oil as a market average - is a measure designed to 'pull' regenerated base oil into the base oil market (as opposed to the 'push' measure in policy 2a). The policy is calibrated such that its effect on regeneration of waste oil is equivalent to policy 2a (a regeneration target of either 70% or 85% of all waste oil collected in the year 2030). For policy 2b, this means that the share of regenerated base oil on markets increases from 11.3 to 13.0 % for a 70% target and to 15.8% for an 85% target between 2024 and 2030. The share of regenerated base oil on the market is calculated using data from Stahl and Merz (2020); Data from (IFEU, 2021) is used to translate base oil quantities into their waste oil equivalents.

Environmental effects

Although the environmental impact of the policy is designed to be equivalent to that of policy 2a, there is a higher uncertainty of the effect of policy 2b on the regeneration rate. While policy 2a affects the regeneration rate directly, policy 2b is an indirect approach that only acts on a proxy of the regeneration rate. For example, it would be conceivable that the mandated increase of regenerated base oils on EU markets is to some extent covered by imports, rather than by increased waste oil regeneration in the EU itself. In this case, the effect of policy 2b on the EU regeneration rate would be lower than anticipated.

Economic effects

While the overall economic effects in terms of societal life cycle costs are similar to policy 2a, there is a key difference in who pays the burden of the policy: For policy 2b, the responsibility of ensuring that the targets are met is placed on the lubricant market and, consequently, on the producers of these products, who have to buy and incorporate more regenerated base oil, which under normal economic conditions increases the price of the latter and hence their production costs. If lubricant producers do not receive additional financial support, they most likely pass on parts or all of this cost increase to consumers (see social effects). The effect on small and medium enterprises (SMEs), is identical to policy 2a.

Social effects

In addition to the employment effects discussed for the previous policy (2a), the following additional distributional effects need to be taken into account: Setting targets in terms of the market share of regenerated base oil (as in policy 2b)[55] shifts the regulatory burden onto the lubricant producers. As they increase their purchases of regenerated base oil, prices rise and allow regenerators to produce the increased quantities in a profitable way. Looking at the right panel in Figure 15, lubricant producers increased costs would be approximated by $(p_1-P_0)*q_1$.

[55] In the case of a price-based target (as in 2b), some mechanism would need to be implemented to ensure that a price equilibrium exists in the lubricant market. Tradable regeneration certificates could provide a solution for this.

Lubricant producers would pass at least part of their increased costs on to consumers, which would increase the price of lubricant products. Whether or not this price increase has a regressive impact in EU MS depends on structural factors, such as widespread car ownership among low-income households. Using the EU Household Budget Survey for the reference year 2015, we find that spending on lubricant products is very heterogeneous across EU Member States. Unfortunately, the relevant data is rather noisy and does not allow for a full distributional analysis of price increases in lubricant products. However, the data shows that in general spending on lubricants makes up a tiny fraction of total spending (usually below 1%). Taken together with the fact that a subsidy that is equivalent to a target of 70 (85)% of waste oil going to regeneration would be on the order of magnitude of 1-6% (2.5-13.5%) of the price of base oil (see the section on options 3a and 3b), we conclude that a small price increase would have only a negligible distributional effect, particularly when compared to the comparatively large price changes induced by the recurrent fluctuations of crude oil prices.

5.3.3 Policy 2c: A target specifying the recycled content for base oil

Policy 2c - a recycled content target for base oil - resembles policy 2b in being designed to 'pull' regenerated base oil into the base oil market (as opposed to the 'push' measure in policy 2a). It is calibrated such that its effect is equivalent to policy 2a (a regeneration target of either 70% or 85% of all waste oil collected in the year 2030). For policy 2c, this means that the share of regenerated base oil in Group I base oil[56] used in every unit of lubricant product sold in the EU increases from 20.7 to 24.1% for the 70% target and to 29.9% for the 85% target between 2024 and 2030. The share of regenerated base oil on EU markets is calculated using data from Stahl and Merz (2020); data from (IFEU, 2021) is used to convert base oil quantities into their waste oil equivalents.

Environmental effects

Identical to policy 2b.

Economic effects

Identical to policy 2b.

Social effects

Identical to policy 2b.

5.3.4 Policy 3a: A production subsidy for regenerators

The policy consists of a unit subsidy given to regeneration facilities for each ton of processed waste oil. For comparability it is set at level (€/tonne) such that the outcome in terms of additional regeneration is equivalent to policy 2a (regeneration of either 70% or 85% of all waste oil collected in the year 2030). In policy 3a, the funding for this policy is not specified and may be assumed to be financed out of the general budget.

Environmental effects

For the same reason as in policies 2b and 2c, there is higher uncertainty on the environmental outcome of policy 3a compared to policy 2a, because the policy is indirect. E.g., in the case of an oil price shock, the subsidy might lead to an overshooting, i.e. more regeneration than expected (see Section 5.3.2 for more details).

Economic effects

Similar to policies 2a-2c, the monetary value of the benefit from avoided pollution is determined as follows: Moving one tonne of waste oil from conversion to fuel to regeneration generates a net societal life cycle cost saving of 55.8€ and summing up the savings from 2024 until 2045 yields a net present value (NPV) of 124 M€ for the 70% target and 330 M€ for the 85% target (savings from years after 2024 are discounted to

[56] For policy 2c we only look at Group I base oils for two reasons: First, according to information received from industry stakeholders, the technical feasibility of increasing the content of regenerated base oil in lubricant products employing higher base oil groups is to some extent unclear. Second, the majority of existing regeneration plants in the EU produces Group I base oil.

2024). However, the total spending on the subsidy (plus the costs for administrating the scheme) has to be subtracted from the external cost savings.

For the 70% target, the subsidy would start at 5.5€ per t of waste oil regenerated in 2024 and would gradually increase to 34.5€ in 2030.[57] For the 85% target the subsidy increases from 14.2 €/t to 76.6 €/t. The subsidy is calculated such that the specified regeneration rate of all collected waste oil in the EU is reached in 2030. Using the elasticity of substitution between regenerated and virgin base oil from CalRecycle (2016), we can estimate the changes in the relative quantities in response to changes in the relative prices and infer the corresponding waste oil subsidy, knowing that, according to (IFEU, 2021), in a quantity weighted average across regeneration technologies one tonne of waste oil is regenerated into approximately 0.63 tonnes of base oil. Since the subsidy would be paid to every unit of regenerated waste oil - also to that part that would have been regenerated even without the subsidy - the total sum of the subsidy payments is comparatively large: The NPV of all subsidies until 2045 is 595 M€ for the 70% target and 1604 M€ for the 85% target, roughly four times the NPV of the societal life cycle savings. This would render a subsidy financed out of the government budget inefficient. It also risks generating excess profits for regenerators, as they receive a subsidy for waste oil that would have been regenerated already in the baseline.

Compared to policy 2a, policy 3a has an additional effect on SMEs: The subsidy in option 3a benefits regenerators which are in most cases SMEs, while refineries, which are in most cases large enterprises would lose some of their share in the base oil market.

Social effects

The social effects of policy 3a in terms of employment are equivalent to that of option 2a. The regional distributional effects (jobs shifted from regions without regeneration facilities to regions that have regeneration facilities) are also similar to those of option 2a.

One crucial difference, however, occurs with regard to who pays for the additional regenerated base oil. This is left open in option 2a, while lubricant producers initially pay the burden in options 2b and 2c (and eventually pass at least part of it on to consumers). In option 3a, the subsidy would be financed out of the general budget which would have largely negligible distributional effects and no direct ('first-order') effects on the price of lubricant products. This is illustrated in the left panel of Figure 16, where the main effect of the subsidy is a shift of the regenerators' supply curve to the right.[58]

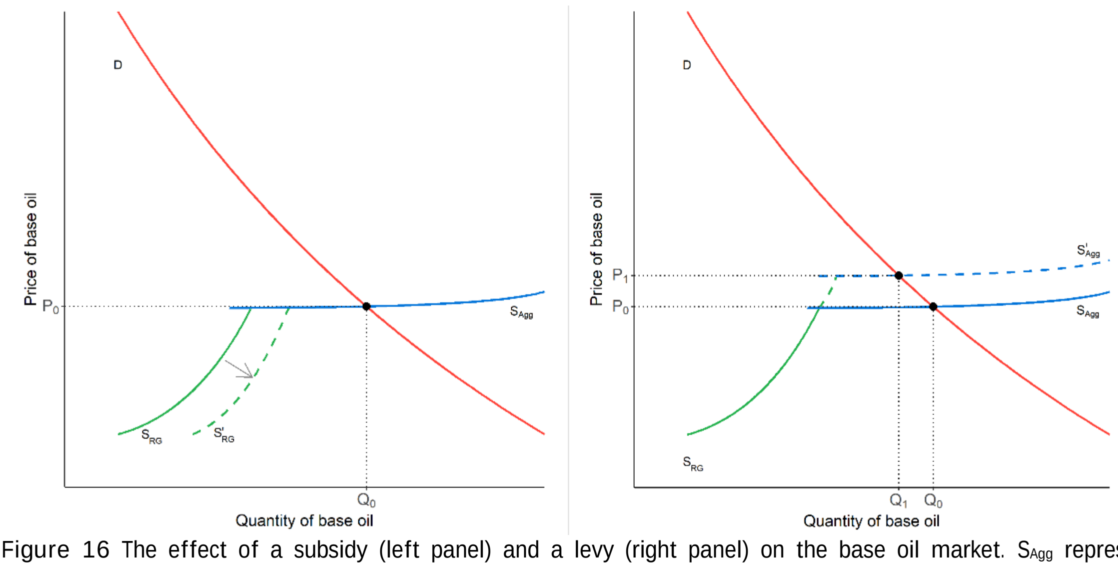

Figure 16 The effect of a subsidy (left panel) and a levy (right panel) on the base oil market. S_{Agg} represents the aggregate supply curve (in blue), which is the sum of the virgin refiners' and the regenerators' supply curves. For illustrative purposes, the regenerators supply curve S_{RG} is also shown separately (in green). D is the demand curve (in red).

[57] One tonne of waste oil can be regenerated into around 0.63 tons of base oil (averaging over different technologies see IFEU (2021)). The subsidy for one tonne of regenerated base oil can hence be calculated by dividing the subsidy per tonne of waste oil by 0.63. The subsidy per tonne of regenerated base oil would hence increase from 8.7€ to 54.8€ over the period 2024 to 2045.

[58] As the price of base oil is determined by the costs of the virgin base oil producers, even though regenerated base oil might become cheaper, the overall price level is unlikely to be affected, but the share of regenerated base oil is increased.

Left panel: The effect of a subsidy for regeneration on the ratio of RG to virgin-based base oil. The supply curve for regenerators is shifted to the right (from S_{RG} to S_{RG}'), but the aggregated supply curve (S_{Agg}) hardly shifts, due to the much larger volume of virgin base oil (we therefore do not include a shifted aggregate supply curve in the left panel). Right panel: The effect of a levy on virgin-based base oil on aggregate base oil supply. The aggregated supply curve (S_{Agg}) shifts upwards (to S'_{Agg}) due to the increased cost for virgin refiners, making regeneration more economic for regenerators, as they can sell at a higher price. Policy 3a is represented in the left panel, while policy 3b is the sum of the effects displayed in both panels.

5.3.5 Policy 3b: A charge/levy on virgin base oil that finances a subsidy on regeneration

As in policy 3a, a subsidy for regeneration is set at such a value that the policy is equivalent to policy 2a (regeneration of either 70% or 85% of all waste oil collected in the year 2030). In contrast to policy 3a, the funding for the subsidy comes from a levy on virgin base oil. Due to the negative effect of the levy on the competitiveness of virgin base oil, the necessary regeneration subsidy for reaching the 70% and 85% target is lower than in policy 3a.

Environmental effects

Identical to policy 3a and, with some additional uncertainty, as 2a

Economic effects

Similar to policy 3a, except for the following points.

If the subsidy is financed out of the general budget as in policy 3a, the total spending on the subsidy (plus the costs for administrating the scheme) has to be subtracted from the external cost savings which leads to net costs of the policy. From the general budget's perspective, policy 3b has the advantage that it "pays for itself" by means of the levy on virgin-produced base oil. However, the costs of the subsidy do not disappear in policy 3b (albeit becoming somewhat lower), but are financed by lubricant product consumers. .

For the 70 % target, the levy would increase from less than 0.6€ to 4.6€ per tonne of virgin-based base oil between 2024 and 2030 (a magnitude of less than 1% of the market price) and the subsidy would increase from 5.0€ to around 31.0€ per tonne of waste oil regenerated.[59] Until 2045, the NPV of the sum of all levies (which is equivalent to the sum of all subsidies) is 361 M€. For the 85% target the levy increases from 1.7€ to 12.5€, the corresponding subsidy from 13.6€ to 68.0€ and the NPV of the sum of all levies equals 954 M€. Since the levy by itself already induces an increase in the ratio of regenerated to virgin-based base oil quantities, the subsidy for achieving a specific regeneration rate can be lower than in the case of a government budget-financed subsidy (option 3a). However, as in policy 3a, there is a risk of generating excess profits for regenerators, from receiving a subsidy for waste oil that would have been generated also in the baseline.

The effects on SMEs discussed for policy 3a carry over to policy 3b.

Social effects

The social effects of option 3b in terms of employment are equivalent to that of option 2a. The regional distributional effects (jobs shifted from regions without regeneration facilities to regions that have regeneration facilities) are also similar to those of option 2a.

As for policy 3a, a crucial difference, however, is who pays for the additional regenerated base oil. In option 3b, the initial burden falls on virgin refiners of base oil in the form of the levy, which shifts the virgin refiners' (and hence the aggregate) supply curve up (see the right panel in Figure 16), while regenerated base oil becomes cheaper as a result of the subsidy. The overall effect of policy 3b is hence the sum of the effect from the left and the right panel in Figure 16. It is likely that the price increase caused by the levy is passed on to consumers, but due to the low level of the levy, it likely has a small effect on households' budgets.[60] We assume that demand for lubricants is relatively inelastic (i.e. it does not react much to small price changes),

[59] One tonne of waste oil can be regenerated into around 0.63 tons of base oil (averaging over different technologies, see IFEU (2021)). The subsidy for one tonne of regenerated base can hence be calculated by dividing the subsidy per tonne of waste oil by 0.63.

[60] For the 70% target, the levy in 2024 makes up less than 0.1% of the total price of base oil, increasing to 0.6% in 2030. For the 85% target, the levy increases from 0.3% to 2.5% of the price of base oil over the same period.

because it is mostly tied to existing capital such as cars, and people are unlikely to change their lubricant spending in response to a small price increase.[61]

5.4 Summary and discussion of socio-economic analysis of policy impacts

The policies compared in the previous sections are calibrated such that they are all consistent with the same target: An EU-wide increase in the regeneration rate from 61% to either 70% or 85% by 2030, depending on the specific scenario. The policies build on different means to achieve the target: Policy 2a simply sets the target and leaves it up to Member States to achieve it; Policies 2b and 2c are indirect and set targets for regenerated base oil in total base oil put on EU markets, either in the form of an average market-wide quota (2b) or a recycled content target applied to each lubricant product unit (2c). Policies 3a and 3b consist of subsidies for waste oil regeneration, either financed from the general budget (3a) or via a levy on virgin oil-based lubricants (3b).

The main results are summarised in Table 15. As intended, environmental effects are the same for all policies, as they are all designed to meet the same target. Some economic, social and distributional effects differ, however. In terms of economic effects, apart from the 124 M€ of avoided societal life cycle costs until 2045 for the 70% target and the 330 M€ for the 85% target, which are identical under all policies, the following differences arise. While the financial burden that might be incurred by policy 2a is undefined (implementation left to Member States), the main burden of policies 2b and 2c initially falls on lubricant producers, and ultimately on lubricant consumers. In policy 3a it would fall on the government's budget (and ultimately on taxpayers) and in policy 3b initially on virgin base oil producers and eventually on lubricant consumers. Spending on subsidies by far exceeds benefits from avoided external costs for policies 3a and 3b, while costs are expected to be more moderate for the other policies.

Regarding social effects, there are several factors to consider. First, for all policies (except 3a) it can be expected that all or at least a part of the burden is passed on to consumers via higher lubricant prices. However, given the fact that these price increases are quite small and as spending on lubricants is very low in relation to household income, the social effects of this price increase are expected to be minimal. Policy 3a would not necessarily lead to such a price increase, it could even decrease prices to a small extent. However, as for the price increases, the distributional effects of this are largely negligible. Second, regarding the distributional effects of the environmental effects, there could be a regional shift in emissions from regions without regeneration capacity to regions that possess sufficient free capacities. Third, a similar shift could be expected for jobs, which would decrease in regions without regeneration capacities and increase in regions with available capacities. Hence, although all policies lead to an overall increase in jobs, some regions would benefit while others would lose.

Regarding the total savings in societal life cycle costs – 124 M€ until 2045 for the 70% target and 330 M€ for the 85% target – they are relatively low, particularly compared to the implementation costs of the policy under discussion, which we estimate by analysing the administrative cost of countries that have comparable schemes in place. One such case is Australia, where a levy and subsidy scheme, similar to policy 3b is in place. According to Deloitte (2020), the administrative costs are on the order of magnitude of 1 million Australian dollars per year (or about 0.65 million €, using 2022 exchange rates). The Australian lubricant oil market is around 20 times smaller than the European market, so administrative costs would be higher in the EU, but due to economy-of-scale effects they are likely below twenty times the Australian costs (i.e. somewhere between 0.65 and 13 million € per year).[62] Over the 2024-2045 period and discounted with a social discount rate of 3% this would amount to a range of 11 to 213 million €. We see no principle reason for why the administrative costs should differ between a 70% and an 85% target. The main reason for the relatively low sLCC savings, particularly when compared to the administrative costs, is that the societal cost difference between regeneration and conversion to fuel is simply not that large (around 55.8€ per tonne of processed waste oil). Moreover, the total amount of waste oil is also limited (2 Mt per year are estimated to be collectible) compared to other waste streams (e.g. municipal waste generation is more than 220 Mt per year).

[61] This inelastic demand is not immediately evident from Figure 15 and Figure 16, where we used a less-steep demand curve to illustrate the effects at play.

[62] Around 680,000 tonnes of regenerated base oil have been produced in the EU in 2018 (Stahl and Merz, 2020) at an average price of around 630 €/tonne (IFEU, 2021), which leads to a total regenerated base oil market size of 428 million €. Comparing the administrative costs against the size of the regenerated base oil market or against the expected benefits of a policy that increases regeneration, they appear rather high, as will be shown below.

There are two factors that limit the amount of waste oils that can be regenerated: First, once all free EU regeneration capacities are utilised, additional investment has to take place to increase total capacity, which might be difficult to mobilise, particularly in view of the expected decline of total lubricant use and waste oil generation (see the Business-As-Usual scenario in Section 5.2). Second, as discussed in Section 1.1, evidence suggests that the quality of the waste oil that currently undergoes incineration might generally be lower and less suitable for regeneration. Hence, it might be the case that only waste oil used for conversion to fuel could be directly diverted to regeneration, which amounts to 24% of all collected waste oil. This would imply an upper limit on the EU regeneration rate of 85%. However, with improved collection practices that better preserve waste oil quality, higher regeneration rates could become attainable.[63]

Table 15 Comparison of environmental, economic and social effects of the different policies until 2045 at EU level. All monetary values are given in 2024 NPV.

Policy	Environmental effects (until 2045 at EU level)	Economic effects (until 2045 at EU level)	Social effects (until 2045 at EU level)
2a (a target specifying the share of collected waste oil to be regenerated)	waste oil diverted to regeneration: 70% target: 3.11 Mt 85% target: 8.29 Mt	societal life cycle cost savings: 70% target: 124 M€ of 85% target: 330 M€	Net employment creation: 70% target: 124 jobs 85% target: 329 jobs
	CO_2 emissions avoided: 70% target: 0.6 Mt 85% target: 1.7 Mt	Cost incidence: depending on exact implementation	Regional disparity in job creation
	Significant reductions in other pollutants	Economic actors: shift from waste oil-based fuel production to RG (both SMEs)	
	Possibly a regional shift in emissions	Cost of regulation depends on specific implementation chosen by Member States	
2b (a target for the share of regenerated base oil on markets and 2c (a recycled content target for Group I base oil)	Identical to 2a	Avoided societal costs and econ. activity shift as in 2a	Job creation and regional disparity as in 2a
	Indirect target: higher uncertainty regarding effect on regeneration rate	Shift of burden from regenerators to lubricant producers	Lubricants price increase: distributional incidence small
		Lubricant producers (partially) pass through cost burden to consumers	
3a (a subsidy for waste oil regeneration financed out of the	Identical to 2a	Avoided societal costs and econ. activity shift as in 2a	Job creation and regional disparity as in 2a
	Indirect policy: higher uncertainty regarding	Expensive; costs of subsidy: 595 M€ (70% target) and	No direct effects on price of lubricants

[63] Analysing waste oil collection is beyond the scope of this study but see (RDC Environment, 2023).

general budget)	effect on regeneration rate	1604 M€ (85% target)	
			Distributional effects at household level negligible
3b (a subsidy for regeneration financed by a levy on virgin base oil	Identical to 2a	Avoided societal costs and econ. activity shift as in 2a	Job creation and regional disparity as in 2a
	Indirect policy: higher uncertainty regarding effect on regeneration rate	Burden shift to virgin-based base oil producers via levy with the total cost: 361 M€ (70% target) and 954 M€ (85% target)	Lubricants price increase (small, paid by consumers). Distributional incidence small
		Government: no additional spending on subsidy	

Looking at the different policies in Table 15, no clear ranking emerges. Policies 3a and 3b – subsidies for regeneration financed either out of the general budget or via a levy on virgin base oil – lead to relatively high costs in terms of subsidies, which already exceed expected sLCC savings by a big margin even when administrative costs are not taken into account (see Table 14). This is due to the fact that the subsidies would be paid not only for the additional quantities of regenerated base oil but also for the base oil that is already regenerated even before the implementation of the policy. This makes the subsidy less efficient than e.g. a recycled content target, which would provide the minimum incentive needed to supply the incremental quantities of regenerated base oil for complying with the target. Answering whether policies 2a to 2c lead to a net benefit or a net loss is less straightforward, since the expected benefits in terms of sLCC savings (124 M€ for the 70% target and 330M€ for the 85% target) are of the same order of magnitude as the administrative costs, which we estimate to be between 11 and 213 M€. In any case, the net benefits after accounting for the costs are expected to be rather small (and in some cases negative) and would not be sufficient to justify a policy intervention, particularly in view of the uncertainties involved.

A final aspect is the possibility or problem of integrating different policies: Policy 2a (a regeneration target) is the least specific policy. It would not be sufficient as a standalone policy and would need to be accompanied by policies that specify the details of its implementation at the Member State level. A scenario would be conceivable in which policy 2a is set at the EU level and Member States choose more specific policies at the national level to reach the regeneration target. Policy 2b is more specific – it sets the share of base oil on the market that needs to come from regenerated sources – but it still does not define how this target is reached. Both 2a and 2b would hence need to be complemented by policies that specify the implementation at the national level, such as policies 2c (a recycled content target), 3a (a subsidy for regeneration financed out of the government budget) or 3b (a subsidy for regeneration financed via a levy on virgin base oil).

As an additional complication, in all these cases it would have to be ensured that the individual implementations by Member States do not create barriers for the Single Market. For instance, recycled content targets should be harmonised across Member States to avoid confusion on the base oil market. From this point of view, it would be preferable to opt for a policy that already defines a specific implementation, such as policy 2c, directly set at the EU level.

6 Conclusions

In this report we compare different pathways for treating waste oil in terms of their environmental, economic and social impacts. Building on this, we compare policy options that aim at increasing waste oil flows towards the most beneficial pathways. Our main methods are life cycle assessment, life cycle costing and socio-economic analysis.

For most individual impact categories, as well as in the societal life cycle costing, the three regeneration pathways perform best among all waste oil treatment options. However, while this is a rather clear-cut conclusion when only considering greenhouse gas emissions, the results become more nuanced when considering the societal life cycle costing, which are given by the sum of internal and external costs (i.e. the monetised environmental emissions). In societal life cycle costing terms, the least performing regeneration pathway (solvent-based) only has a small benefit over the treatment to fuel (via distillation) and, under some conditions, can even fall behind this treatment. The discernibility analysis also shows that in terms of societal life cycle costing, solvent-based and distillation-based regeneration are not robustly superior to treatment to fuel (but neither the opposite). Direct incineration pathways (cement kilns, hazardous waste incineration and industrial boilers) are clearly inferior options. In sum, regeneration - depending on the specific technology and context – is superior or comparable to treatment to fuel and superior to direct energy recovery, from a societal cost perspective.

At first glance, these conclusions appear to contradict earlier studies (reviewed in Section 2) that find a clear benefit of regeneration over energy recovery in all its forms. The reason why our results appear to differ from these studies, is that we go beyond previous studies in several ways: First, instead of only analysing greenhouse gas emissions, we look at 14 different impact categories related to different kinds of pollutants. In order to obtain a single metric from the 14 categories, we monetize the impacts using a societal life cycle costing approach, according to up-to-date estimates of the external costs of pollutants. As a consequence, the results become more nuanced in the following sense: in terms of societal life cycle costing, the advantage of regeneration over energy recovery prevails, but it becomes less striking and the worst-performing regeneration technology only has a 5€/t advantage over the best performing energy recovery technology, which is conversion to fuel. Considering greenhouse gas emissions in isolation, however, our results confirm earlier studies.

Despite the uncertainties involved and the relatively small comparative advantage of regeneration over conversion to fuel, at least in terms of societal life cycle costs, we analysed different policies that could be employed to increase waste oil regeneration, in terms of their socio-economic impacts. All policies are calibrated to lead to the same regeneration target: We consider a less ambitious target that corresponds to an increase in the share of collected waste oil from the current 61% to 70% in 2030 and a more ambitious target corresponding to an increase to 85% over the same period. The different policies thus have a similar environmental impact (such as avoiding 0.6 Mt of CO_2-eq. emissions until 2045 for the 70% target and 1.7 Mt for the 85% target).

We find that implementing these policies would yield a cumulative benefit of 124 M€ between 2024 (the year the policy is phased in) and 2045 (the end point of the analysis) in terms of avoided societal costs for the 70% target and 330 M€ for the 85% target. Particularly when the estimated cumulative administrative costs of 11-213 M€ are factored in, this rather small benefit is unlikely to justify regulatory intervention. All policies lead to a small net gain in employment of 124 jobs over the whole of the EU in the year 2045 for the 70% target and 329 jobs for the 85% target, but gains and losses are distributed unequally across regions.

Apart from policies 3a and 3b – subsidies for regeneration financed by different means – which lead to high costs in terms of subsidies that already exceed expected savings by a big margin, all policies perform similarly. They differ, however, in how their costs are initially allocated to the different economic actors. Ultimately, this cost increase will at least partially be passed on to lubricant consumers. However, on the product level, the cost increase will be hardly noticeable and lubricant spending makes up only a negligible share of household spending, which also makes the distributional effects negligible. Some of the policies are less specific than others regarding their implementation, which is why it is probable that the final policy package might be a combination of various policies.

One key caveat to this result is that the benefits of regeneration are not guaranteed for all regeneration technologies and under all circumstances, which would be a prerequisite for generic regeneration targets or similar policies, i.e. some regeneration technologies do not show benefits over processing to distillate fuel in some impact categories and in some of the robustness checks. Additional analysis and in particular better data on the waste oil qualities used in different pathways could help to develop more fine-tuned policy interventions, under which an inadvertent support of less beneficial treatments would be avoided.

Regarding the treatment options that have been identified as clearly inferior, namely direct incineration, they absorb a relatively small share of EU waste oils (around 11%, see Figure 3) and seem to mostly process low quality (i.e. contaminated) waste oils that are less suitable – both technically and economically - for other treatments. This suggests that, given current waste oil qualities, there is no case for a policy intervention that would induce a deterrent effect with regard to these treatment options.

Instead, supporting the exhaustive collection of waste oils, with separation of different qualities according to their recyclability, could be a plausible way forward. Stepping up the enforcement of existing waste oil regulation, which stipulates separate collection, should complement this, as well as surveillance to verify and – if necessary – counteract the illegal practice of channelling waste oils without appropriate end-of-waste treatment into marine bunker markets.

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List of abbreviations and definitions

API	American Petroleum Institute
BO	Base oil
CBA	Cost-benefit analysis
DIM	Direct impacts model (refers to model used in CalRecycle, 2016)
EF	Environmental footprint
EFTA	European Free Trade Association
EoL	End of life
EoW	End of waste
EPR	Enhanced Producer Responsibility
ETS	Emissions trading scheme
FTE	Full-time equivalent
FU	Functional unit
GEIR	Groupement Européen de l'Industrie de la Régénération
GHG	Greenhouse gas
GWP	Global warming potential
HWI	Hazardous waste incineration
IMO	International Maritime Organization
ISO	International Organization for Standardization
LCA	Life cycle assessment (or analysis)
LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability analysis (or assessment)
MARPOL	International Convention for the Prevention of Pollution from Ships
MDO	Marine diesel oil
NPV	Net present value
OPEX	Operational expenditures
PAH	Poly-aromatic hydrocarbon
PCB	Polychlorinated biphenyl
PFC	Perfluorocarbon
PFO	Processed fuel oil (UK EoW specification for a waste oil-based fuel)
RDF	Refuse-derived fuel
RFO	Recovered fuel oil
RGBO	Regenerated base oil
RRBO	Re-refined base oil
SA	Sensitivity analysis
SEA	Socio-economic assessment
sLCC	Societal LCC
SRF	Solid recovered fuel
WFD	Waste Framework Directive
WO	Waste oil
WODF	Waste oil derived fuel
WSR	Waste Shipment Regulation

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Annex 1. Inventory tables of the modelled regeneration scenarios for waste oil management

Table A1- 1 Inventory of the regeneration and energy recovery to fuel scenarios

Inventory flow	Quantity (per functional unit*10^{-3})					
	RG-HYDT	RG-SOLV	RG-DIST	ER-WODFa	ER-WODFb	Unit
Process inputs						
Waste oil (incl. water)	1	1	1	1	1	kg
Hydrogen	1E-02-1E-01	0	0	0	0	kg
Nitrogen	1E-03-1E-02	1E-04-1E-03	1E-04-1E-03	0	0	Nm^3
De-emulsifier	0	0	0	1E-03-1E-02	1E-03-1E-02	kg
Nitric acid	0	0	0	1E-02-1E-01	1E-02-1E-01	kg
Ammonia	0	0	0	1E-03-1E-02	1E-03-1E-02	kg
Sodium hydroxide	1E-03-1E-02	1E-03-1E-02	1E-03-1E-02	0	0	kg
Sodium carbonate	0	1E-04-1E-03	0	0	0	kg
Potassium hydroxide	1E-03-1E-02	1E-02-1E-01	1E-03-1E-02	0	0	kg
Filter aid	0	1E-01-1	0	0	0	kg
Solvent	0	1E-04-1E-03	0	0	0	kg
Propane	1E-04-1E-03	0	0	0	0	kg
Catalyst	1E-04-1E-03	0	0	0	0	kg
Cooling water	1-1E01	1-1E01	1E-01-1	-	-	kg
Deionized water	1E-01-1	1E-02-1E-01	1E-01-1	1E-01-1	1E-01-1	kg
Water (unspecified)	1-1E01	0	1-1E01	1-1E01	0	kg
Electricity from grid	1E-02-1E-01	1E-02-1E-01	1E-01-1	1E-01-1	1.77E-01	kWh
Electricity from on-site plant	E-02-1E-01	0	0	0	01	kWh
Thermal energy, imported fuel	E-02-1E-01	1E-01-1	1E-01-1	1E-01-1	1E-01-1	kWh
Thermal energy, from co-products	1E-01-1	0	1E-01-1	0	0	kWh
Process outputs – Products and co-products						

Base oil, regenerated (API Group I)	1E-01-1	1E-01-1	1E-01-1	0	0	kg
Base oil, regenerated (API Group II)	1E-01-1	0	0	0	0	kg
Base oil, regenerated (API Group III)	1E-01-1	0	0	0	0	kg
Light ends	1E-02-1E-01	1E-03-1E-02	1E-02-1E-01	1E-02-1E-01	1E-02-1E-01	kg
Naphtha	1E-02-1E-01	0	1E-02-1E-01	0	1E-02-1E-01	kg
Gasoil	1E-02-1E-01	1E-02-1E-01	1E-02-1E-01	1E-01-1	1E-01-1	kg
Heavy fuel oil	1E-02-1E-01	1E-02-1E-01	1E-03-1E-02	1E-01-1	1E-01-1	kg
Bitumen, secondary	1E-02-1E-01	1E-01-1	1E-01-1	0	0	kg
Sludge	0	0	0	E-02-1E-01	E-02-1E-01	kg
Process emissions to air						
Non-methane volatile compounds	1E-07-1E-06	1E-07-1E-06	1E-07-1E-06	1E-04-1E-03	1E-04-1E-03	kg
Methane	1E-08-1E-07	1E-08-1E-07	1E-08-1E-07	1E-05-1E-04	1E-05-1E-04	kg
Process emissions to water						
Waste cooling water	1-1E01	1E-08-1E-07	1E-08-1E-07	0	0	kg
Waste water from process	1E-01-1	1E-01-1	1E-01-1	1E-01-1	1E-01-1	kg
Solid waste from process						
Waste to hazardous waste incinerator	1E-03-1E-02	1E-02-1E-01	1E-02-1E-01	0	0	kg
Waste to landfill	1E-04-1E-03	0	0	1E-02-1E-01	1E-02-1E-01	kg

Table A1- 2 Transfer factors to air of the waste-to-energy process used to model the energy recovery from waste oil via direct incineration (scenarios ER-CKLN, ER-HWI, ER-INBO)

Substance	**Transfer factor (%)**		
	ER-CKLN	**ER-HWIN**	**ER-INBO**
Carbon	1.00E+02	1.00E+02	1.00E+02
Chlorine	1.50E+00	3.00E-02	3.00E-02
Sulphur	5.00E-01	6.00E-02	6.00E-02
Antimony	3.00E-02	0.00E+00	0.00E+00
Arsenic	2.00E-02	1.00E-06	1.00E-06
Cadmium	2.00E-01	5.51E-03	5.51E-03
Chromium	1.00E-02	7.00E-06	7.00E-06
Cobalt	1.00E-02	7.00E-02	7.00E-02
Copper	1.00E-02	7.00E-02	7.00E-02
Lead	7.00E-02	3.71E-03	3.71E-03
Manganese	1.00E-02	1.00E-06	1.00E-06
Mercury	2.50E+01	3.00E-06	3.00E-06
Nickel	1.00E-02	7.00E-02	7.00E-02
Thallium	1.00E+00	1.00E-01	1.00E-01
Tin	7.00E-02	1.33E-01	1.33E-01
Vanadium	1.00E-02	1.00E-02	1.00E-02
Zinc	7.00E-02	7.00E-02	7.00E-02

Table A1- 3 Inventory of the waste-to-energy process used to model the energy recovery from waste oil via direct incineration (scenarios ER-CKLN, ER-HWI, ER-INBO)

Inventory flow	Compartment	Amount (per tonne of waste oil incinerated)	Unit
Process inputs			
Deionised water	Technosphere	0.8	kg
Wastewater	Technosphere	0.175	m^3
Hydrochloric acid	Technosphere	1.5	kg
Calcium carbonate	Technosphere	3.2	kg
Quicklime	Technosphere	1.04	kg
Iron (III) chloride	Technosphere	0.021	kg
Process outputs			
VOC, volatile organic compounds, unspecified origin	air	1.08E-05	kg
Particulates, < 2.5 um	air	1.81E-06	kg
Particulates, > 2.5 um, and < 10um	air	1.63E-05	kg
Carbon monoxide, fossil	air	1.08E-04	kg
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	air	1.40E-13	kg
Ammonia	air	9.39E-05	kg
Nitrogen oxides	air	1.69E-03	kg
Cyanide	air	3.60E-07	kg
Sulfur dioxide	air	3.74E-06	kg
Ammonia	air	4.80E-08	kg
Phosphorus	air	5.60E-09	kg
Hydrochloric acid	air	3.21E-08	kg
Hydrogen fluoride	air	8.05E-09	kg

Dinitrogen monoxide	air	4.59E-05	kg
Sulfate	water	8.95E-03	kg
Phosphate	water	3.75E-07	kg
Chloride	water	1.04E-04	kg
Aluminium	water	1.75E-09	kg
Silver	water	6.94E-11	kg
Arsenic	water	8.00E-11	kg
Cadmium	water	1.76E-11	kg
Chromium	water	1.53E-08	kg
Cobalt	water	9.03E-07	kg
Copper	water	6.86E-07	kg
Iron, ion	water	7.71E-05	kg
Lead	water	1.49E-10	kg
Manganese	water	3.20E-11	kg
Mercury	water	4.19E-10	kg
Nickel, ion	water	3.27E-07	kg
Antimony	water	7.29E-11	kg
Tin	water	3.19E-11	kg
Vanadium, ion	water	8.00E-12	kg
Zinc, ion	water	5.90E-06	kg
Boron	water	6.03E-06	kg
Fluor	water	3.19E-05	kg
Iodine	water	1.60E-06	kg
Selenium	water	1.34E-10	kg

Annex 2. Detailed results for life cycle assessment and life cycle costing of recycling and energy recovery scenarios: breakdown of impact contributions for individual impact categories

This annex provides the detailed numerical results of the life cycle assessment with regard to the fourteen impact categories considered in this study, i.e.: Climate Change (CC), Ozone Depletion (ODP), Human toxicity, cancer (Htox_c), Human toxicity, non-cancer (Htox_nc), Particulate Matter (PM), Ionising Radiation (IR), Photochemical Ozone Formation (POF), Acidification (AC), Eutrophication, terrestrial (TEU), Eutrophication, freshwater (FEU), Eutrophication, marine (MEU), Ecotoxicity, freshwater (Ecotox), Resource use, minerals and metals (MRU), Resource use, fossils (FRU). The results are expressed per functional unit, i.e. management of one tonne (t) of waste oil input to each of the compared scenarios.

a) Environmental impact categories

Climate change (kg CO_2 eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-3.94E+02	-5.36E+02	-3.44E+02	-2.49E+02	-1.64E+02	2.51E+02	2.50E+03	1.97E+03
Collection	9.72E+00	9.72E+00	9.72E+00	9.72E+00	9.72E+00	9.72E+00	9.72E+00	9.72E+00
Transport	3.95E+01	3.95E+01	3.95E+01	3.95E+01	3.95E+01	3.95E+01	3.95E+01	3.95E+01
Treatment	4.90E+02	2.35E+02	5.17E+02	1.75E+02	1.75E+02	2.92E+03	2.94E+03	2.94E+03
Substitution of products	-9.33E+02	-8.21E+02	-9.10E+02	-4.74E+02	-3.88E+02	-2.72E+03	-4.92E+02	-1.02E+03
Ranking	2	1	3	4	5	6	8	7

Ozone depletion (kg CFC-11 eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-7.78E-04	-7.54E-04	-7.99E-04	-6.86E-04	-6.91E-04	-1.65E-04	1.28E-05	1.29E-05
Collection	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06	2.15E-06
Transport	8.97E-06	8.97E-06	8.97E-06	8.97E-06	8.97E-06	8.97E-06	8.97E-06	8.97E-06
Treatment	1.35E-05	2.57E-05	7.88E-06	2.24E-06	2.24E-06	0.00E+00	1.80E-06	1.80E-06
Substitution of products	-8.02E-04	-7.91E-04	-8.18E-04	-6.99E-04	-7.04E-04	-1.76E-04	-7.87E-08	-8.55E-11
Ranking	2	3	1	5	4	6	7	8

Human toxicity, cancer (CTUh)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-2.26E-05	-1.47E-07	8.08E-07	-1.03E-07	-1.06E-07	-3.02E-07	5.75E-07	4.55E-07
Collection	4.29E-09	4.29E-09	4.29E-09	4.29E-09	4.29E-09	4.29E-09	4.29E-09	4.29E-09
Transport	1.52E-08	1.52E-08	1.52E-08	1.52E-08	1.52E-08	1.52E-08	1.52E-08	1.52E-08
Treatment	3.35E-08	1.21E-07	1.10E-06	3.49E-08	3.49E-08	2.22E-08	6.53E-07	6.53E-07
Substitution of products	-2.27E-05	-2.88E-07	-3.10E-07	-1.57E-07	-1.61E-07	-3.44E-07	-9.75E-08	-2.17E-07
Ranking	2	3	8	5	4	1	6	7

Human toxicity, non-cancer (CTUh)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-7.05E-06	-4.17E-06	-5.40E-06	-3.34E-06	-3.41E-06	-5.97E-08	-1.86E-07	-7.51E-06
Collection	1.06E-07	1.06E-07	1.06E-07	1.06E-07	1.06E-07	1.06E-07	1.06E-07	1.06E-07
Transport	4.46E-07	4.46E-07	4.46E-07	4.46E-07	4.46E-07	4.46E-07	4.46E-07	4.46E-07
Treatment	9.17E-07	2.22E-06	1.84E-06	6.15E-07	6.15E-07	1.81E-06	3.97E-06	3.97E-06
Substitution of products	-8.52E-06	-6.95E-06	-7.79E-06	-4.51E-06	-4.58E-06	-2.42E-06	-4.70E-06	-1.20E-05
Ranking	2	4	3	6	5	8	7	1

Particulate matter (Disease incidence)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-5.43E-05	-6.02E-05	-6.59E-05	-1.59E-05	-1.67E-05	-1.81E-05	-1.20E-05	-3.60E-05
Collection	6.66E-07	6.66E-07	6.66E-07	6.66E-07	6.66E-07	6.66E-07	6.66E-07	6.66E-07
Transport	3.18E-06	3.18E-06	3.18E-06	3.18E-06	3.18E-06	3.18E-06	3.18E-06	3.18E-06
Treatment	3.61E-06	5.38E-06	4.84E-06	2.89E-06	2.89E-06	2.91E-06	3.35E-06	3.35E-06
Substitution of products	-6.17E-05	-6.95E-05	-7.46E-05	-2.26E-05	-2.35E-05	-2.49E-05	-1.92E-05	-4.32E-05
Ranking	3	2	1	7	6	5	8	4

Ionising radiation (kBq U^{235} eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-1.87E+02	-1.94E+02	-1.93E+02	-1.67E+02	-1.68E+02	-4.57E+01	-8.93E+01	-7.28E+00
Collection	6.42E-01	6.42E-01	6.42E-01	6.42E-01	6.42E-01	6.42E-01	6.42E-01	6.42E-01
Transport	2.63E+00	2.63E+00	2.63E+00	2.63E+00	2.63E+00	2.63E+00	2.63E+00	2.63E+00
Treatment	2.59E+01	1.60E+01	2.40E+01	1.87E+01	1.87E+01	0.00E+00	8.20E-01	8.20E-01
Substitution of products	-2.16E+02	-2.13E+02	-2.21E+02	-1.89E+02	-1.90E+02	-4.89E+01	-9.34E+01	-1.14E+01
Ranking	3	1	2	5	4	7	6	8

Photochemical ozone formation (kg NMVOC eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-3.13E+00	-3.27E+00	-2.42E+00	-2.14E+00	-2.09E+00	-7.33E-01	1.74E+00	7.13E-01
Collection	2.23E-02	2.23E-02	2.23E-02	2.23E-02	2.23E-02	2.23E-02	2.23E-02	2.23E-02
Transport	9.46E-02	9.46E-02	9.46E-02	9.46E-02	9.46E-02	9.46E-02	9.46E-02	9.46E-02
Treatment	5.60E-01	3.04E-01	1.35E+00	5.06E-01	5.06E-01	2.10E+00	2.14E+00	2.14E+00
Substitution of products	-3.81E+00	-3.69E+00	-3.89E+00	-2.76E+00	-2.72E+00	-2.95E+00	-5.20E-01	-1.55E+00
Ranking	2	1	3	4	5	6	8	7

Acidification (mol H^+ eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-7.21E+00	-7.69E+00	-5.64E+00	-4.32E+00	-4.35E+00	-1.44E+00	6.56E-01	-1.28E+00
Collection	2.68E-02	2.68E-02	2.68E-02	2.68E-02	2.68E-02	2.68E-02	2.68E-02	2.68E-02
Transport	1.10E-01	1.10E-01	1.10E-01	1.10E-01	1.10E-01	1.10E-01	1.10E-01	1.10E-01
Treatment	6.21E-01	4.92E-01	3.04E+00	3.15E-01	3.15E-01	1.90E+00	1.96E+00	1.96E+00
Substitution of products	-7.97E+00	-8.32E+00	-8.81E+00	-4.77E+00	-4.80E+00	-3.48E+00	-1.44E+00	-3.38E+00
Ranking	2	1	3	5	4	6	8	7

Eutrophication, terrestrial (mol N eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-7.20E+00	-7.69E+00	-4.22E+00	-5.54E+00	-5.25E+00	-1.26E+00	9.63E+00	6.76E+00
Collection	5.89E-02	5.89E-02	5.89E-02	5.89E-02	5.89E-02	5.89E-02	5.89E-02	5.89E-02
Transport	2.49E-01	2.49E-01	2.49E-01	2.49E-01	2.49E-01	2.49E-01	2.49E-01	2.49E-01
Treatment	1.90E+00	1.07E+00	5.05E+00	8.03E-01	8.03E-01	1.05E+01	1.06E+01	1.06E+01
Substitution of products	-9.41E+00	-9.07E+00	-9.58E+00	-6.66E+00	-6.37E+00	-1.20E+01	-1.31E+00	-4.18E+00
Ranking	2	1	5	3	5	6	8	7

Eutrophication, freshwater (kg P eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-3.35E-03	5.89E-04	-3.01E-03	-1.17E-03	-1.21E-03	-7.04E-01	-1.79E-03	-7.58E-03
Collection	8.26E-05	8.26E-05	8.26E-05	8.26E-05	8.26E-05	5.89E-02	8.26E-05	8.26E-05
Transport	2.92E-04	2.92E-04	2.92E-04	2.92E-04	2.92E-04	2.49E-01	2.92E-04	2.92E-04
Treatment	1.11E-03	4.81E-03	1.86E-03	1.37E-03	1.37E-03	1.05E+01	9.27E-04	9.27E-04
Substitution of products	-4.84E-03	-4.59E-03	-5.24E-03	-2.92E-03	-2.95E-03	-1.15E+01	-3.10E-03	-8.88E-03
Ranking	3	8	4	7	6	1	5	2

Eutrophication, marine (kg N eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-6.56E-01	-7.04E-01	-3.86E-01	-5.25E-01	-5.02E-01	-1.14E-01	7.18E-01	3.91E-01
Collection	5.28E-03	5.28E-03	5.28E-03	5.28E-03	5.28E-03	5.28E-03	5.28E-03	5.28E-03
Transport	2.24E-02	2.24E-02	2.24E-02	2.24E-02	2.24E-02	2.24E-02	2.24E-02	2.24E-02
Treatment	1.78E-01	9.71E-02	4.66E-01	4.85E-02	4.85E-02	8.24E-01	8.42E-01	8.42E-01
Substitution of products	-8.61E-01	-8.28E-01	-8.80E-01	-6.01E-01	-5.78E-01	-9.66E-01	-1.52E-01	-4.79E-01
Ranking	2	1	5	3	4	6	8	7

Ecotoxicity, freshwater (CTUe)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-2.64E+04	3.78E+02	-1.26E+04	-2.03E+04	-2.06E+04	-1.10E+04	-4.65E+02	-1.18E+03
Collection	1.21E+02	1.21E+02	1.21E+02	1.21E+02	1.21E+02	1.21E+02	1.21E+02	1.21E+02
Transport	4.80E+02	4.80E+02	4.80E+02	4.80E+02	4.80E+02	4.80E+02	4.80E+02	4.80E+02
Treatment	4.44E+03	2.43E+04	1.22E+04	9.06E+02	9.06E+02	5.78E+01	1.39E+03	1.39E+03
Substitution of products	-3.15E+04	-2.45E+04	-2.54E+04	-2.19E+04	-2.21E+04	-1.17E+04	-2.46E+03	-3.17E+03
Ranking	1	8	4	3	2	5	7	6

Resource use, minerals and metals (kg Sb eq.)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-1.03E-04	5.81E-04	1.24E-04	1.53E-04	1.43E-04	-6.30E-04	2.21E-04	2.02E-04
Collection	4.20E-05	4.20E-05	4.20E-05	4.20E-05	4.20E-05	4.20E-05	4.20E-05	4.20E-05
Transport	1.32E-04	1.32E-04	1.32E-04	1.32E-04	1.32E-04	1.32E-04	1.32E-04	1.32E-04
Treatment	1.50E-04	7.86E-04	3.37E-04	3.48E-04	3.48E-04	0.00E+00	1.32E-04	1.32E-04
Substitution of products	-4.27E-04	-3.79E-04	-3.88E-04	-3.68E-04	-3.79E-04	-8.04E-04	-8.53E-05	-1.04E-04
Ranking	2	8	3	5	4	1	7	6

Resource use, fossils (MJ)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-4.01E+04	-4.44E+04	-4.73E+04	-3.98E+04	-4.01E+04	-2.05E+04	-9.99E+03	-2.31E+04
Collection	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02
Transport	6.00E+02	6.00E+02	6.00E+02	6.00E+02	6.00E+02	6.00E+02	6.00E+02	6.00E+02
Treatment	7.61E+03	2.41E+03	1.81E+03	2.38E+03	2.38E+03	0.00E+00	1.69E+02	1.69E+02
Substitution of products	-4.84E+04	-4.76E+04	-4.98E+04	-4.29E+04	-4.32E+04	-2.13E+04	-1.09E+04	-2.41E+04
Ranking	3	2	1	5	4	6	8	7

b) Life cycle costing

Internal costs (€)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-2.24E+02	-9.00E+01	-1.69E+02	-1.51E+02	-1.51E+02	2.95E+02	1.85E+02	4.00E+01
Waste oil	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02
Collection	3.00E+00	3.00E+00	3.00E+00	3.00E+00	3.00E+00	3.00E+00	3.00E+00	3.00E+00
Transport	2.80E+00	2.80E+00	2.80E+00	2.80E+00	2.80E+00	2.80E+00	2.80E+00	2.80E+00
Treatment	1.35E+02	2.05E+02	1.35E+02	9.46E+01	9.44E+01	2.90E+02	8.33E+01	0.00E+00
Revenue from products	-5.13E+02	-4.48E+02	-4.57E+02	-3.99E+02	-3.99E+02	-1.48E+02	-5.17E+01	-1.13E+02
Ranking	1	3	2	4	5	8	7	6

External costs (€)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-1.33E+02	-1.46E+02	-1.07E+02	-7.95E+01	-7.09E+01	-2.81E+02	2.10E+02	-3.63E+01
Waste oil	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Collection	1.59E+00	1.59E+00	1.59E+00	1.59E+00	1.59E+00	1.59E+00	1.59E+00	1.59E+00
Transport	6.62E+00	6.62E+00	6.62E+00	6.62E+00	6.62E+00	6.62E+00	6.62E+00	6.62E+00
Treatment	6.08E+01	3.38E+01	9.58E+01	2.16E+01	2.16E+01	3.50E+01	3.28E+02	3.28E+02
Revenue from products	-2.02E+02	-1.88E+02	-2.11E+02	-1.09E+02	-1.01E+02	-3.24E+02	-1.26E+02	-3.73E+02
Ranking	3	2	4	5	6	1	8	7

Societal costs (€)

Process	RG-HYDT	RG-SOLV	RR-DIST	ER-WODFa	ER-WODFb	ER-CKLN	ER-HWIN	ER-INBO
Total	-3.57E+02	-2.36E+02	-2.76E+02	-2.30E+02	-2.22E+02	1.42E+01	3.95E+02	3.71E+00
Waste oil	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02	1.47E+02
Collection	4.59E+00	4.59E+00	4.59E+00	4.59E+00	4.59E+00	4.59E+00	4.59E+00	4.59E+00
Transport	9.42E+00	9.42E+00	9.42E+00	9.42E+00	9.42E+00	9.42E+00	9.42E+00	9.42E+00
Treatment	1.96E+02	2.39E+02	2.31E+02	1.16E+02	1.16E+02	3.25E+02	4.12E+02	3.28E+02
Revenue from products	-7.15E+02	-6.36E+02	-6.68E +02	-5.08E+02	-4.99E+02	-4.73E+02	-1.78E+02	-4.86E+02
Ranking	1	3	2	4	5	7	8	6

Annex 3. Summary of reviewed LCA studies

Study	Year	Geography	Scope	Reference system(s)	Boundary	LCI	Functional unit	Final product quality
Abdalla, N. and Fehrenbach, H.	2017	Europe	Comparative LCA of a regenerated base oil via Avista, LPC, Hylube and Viscolube processes and regeneration to fuel oil and refinery base oil	Treatment to fuel oil and refinery base oil	G-G[1]	Yes, in the original study from 2005	Entire volume of regenerated waste oil in the EU	*Minimum: corresponding to Group I base oil *Presumed achievable optimum: corresponding to a mix of 70 % Group I base oil and 30 % Group IV base oil.
Abdalla, N., Fehrenbach, H. and Theis, S.	2022	Europe	Updated LCA for regeneration of waste oil to base oil – Final Report	Treatment to fuel oil and refinery base oil	G-G[1]	Yes, in the original study from 2005	Entire volume of regenerated waste oil in the EU	*Minimum: corresponding to Group I base oil *Presumed achievable optimum: corresponding to a mix of 70 % Group I base oil and 30 % Group IV base oil.
Botas, J.A., Moreno, J., Espada, J.J., Serrano, D.P., Dufour, J.	2017	Spain	Comparative LCA of a regenerated base oil via propane extraction and refinery base oil	Refinery base oil	G-G	Yes	1 tonne base oil	Not specifically stated. Likely Group I
Boughton, B., Horvath, A.	2004	CA, USA	Comparative LCA of a regenerated base oil and i) recycled fuel oil; ii) regenerated marine diesel fuel	i) recycled fuel oil; ii) regenerated marine diesel fuel	G-Gr	Partial; only process for metal emissions	1 l dry used oil	Not specifically stated. Likely Group I
California Department of Resources Recycling and Recovery (CalRecycle)	2013	CA, USA	Comparative LCA of a regenerated base oil and i) recycled fuel oil; ii) regenerated marine diesel fuel	i) recycled fuel oil; ii) regenerated marine diesel fuel	G-Gr	Yes	1 l dry used oil	Not specifically stated. Likely Group I

[1] Gate-to-Gate
[2] Gate-to-Grave

Study	Substituted processes	IA method	Impact categories	Uncertainty/Sensitivity analysis	Main results
Abdalla, N. and Fehrenbach, H.	*Production of base oil from crude oil via waxy distillates Group I; *Production of oly-alphaolefins (PAO, base oil Group IV) from natural gas via i-decene synthesis	Unknown; mid-point	Resource depletion, CED[2], GWP, AP, EP, HTP	Sensitivity	Environmental advantage (all impact categories) of regeneration of waste oil to base oil when: i) group, and ii) a mix of I-IV are substituted
Abdalla, N., Fehrenbach, H. and Theis, S.	*Production of base oil from crude oil via waxy distillates Group I; *Production of oly-alphaolefins (PAO, base oil Group IV) from natural gas via i-decene synthesis	Unknown; mid-point	Resource depletion, CED[2], GWP, AP, EP, HTP	Sensitivity	Environmental advantage (all impact categories) of regeneration of waste oil to base oil when: i) group, and ii) a mix of I-IV are substituted
Botas, J.A., Moreno, J., Espada, J.J., Serrano, D.P., Dufour, J.	None; mass and economic allocation used	Unknown; mid-point	CED, GWP, HTP, EP, AP	None	The production of base oil by propane extraction is more environmentally friendly than the conventional refinery process
Boughton, B., Horvath, A.	Not specifically stated	Unknown; mid-point	TETP, HTP, EP, FETP, ODP, POCP, GWP, AP	None	Re-refined waste oil results in significantly lower impacts than combustion of regenerated fuel oil and virtually the same as regenerated marine diesel fuel
California Department of Resources Recycling and Recovery (CalRecycle)	Not specifically stated	Unknown; mid-point	TETP, HTP, EP, FETP, ODP, POCP, GWP, AP	Sensitivity	No single "best" option among the three formal disposition routes: re-refining, distillation into marine distillate oil (MDO), and use as a heavy fuel (recycled fuel oil, or RFO). Some environmental benefits could be achieved if more used oil was processed into a distilled fuel or as re-refined lubricating oil rather than used as RFO.

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Study	Year	Geography	Scope	Reference system(s)	Boundary	LCI	Functional unit	Final product quality
Collins, M., Schiebel, K., Dyke, P.	2017	CA, USA	Comparative LCA of different waste oil management options in the state of California	i) re-refined base oil (RRBO); ii) recycled fuel oil (RFO); iii) regenerated marine diesel oil (MDO); iv) vaccum gas oil (VGO)	G-Gr	Yes	Entire volume of collected waste oil in California in 2010	Not specifically stated. Likely Group I
Du đak, L., Milisavljević, S., Jocanović, M., Kiss, F., Šević, D., Karanović, V., Orošnjak, M.	2021	Serbia	Comparative LCA of waste oil management via i) regeneration; ii) energy recovery in cement kilns; iii) energy recovery in hazardous waste incinerator	Hazardous waste incineration	G-G[1]	Yes	1 l dry used oil	Not specifically stated. Likely Group I
Fehrenbach, H.	2005	Europe	Comparative LCA of a regenerated base oil via Avista, LPC, Hylube and Viscolube processes and regeneration to fuel oil and refinery base oil	Treatment to fuel oil and refinery base oil	G-G	Yes	Entire volume of regenerated waste oil in the EU	*Minimum: corresponding to Group I base oil *Presumed achievable optimum: corresponding to a mix of 70 % Group I base oil and 30 % Group IV base oil.
Grice, L.N., Nobel, C.E., Longshore, L., Huntley, R., DeVierno, A.L.	2014	USA	Comparative LCA of re-refined used oil vs virgin oil	Virgin lubricating oil	C-G	No	1 US gal. of base oil	Not specifically stated. Likely Group I
Kalnes, T.N, Shonnard, D.R., Schuppel, A.	2006	Germany	Comparative LCA of re-refined used oil vs recycled fuel oil	Recycled fuel oil	C-Gr	No	1 kg waste oil	Not specifically stated. Likely Group I

Study	Substituted processes	IA method	Impact categories	Uncertainty/Sensitivity analysis	Main results
Collins, M., Schiebel, K., Dyke, P.	None; use of system expansion w/o substitution	TRACI, CML	ADP el., ADP fossil, AP, EP, ETP, GWP, PM, HTP cancer, HTP non-cancer, ODP, CED fossil	Sensitivity	No single disposition shows consistently lower impacts under all conditions, with greater benefits generally flowing from increasing collection, rather than from changing disposition.
Du đak, L., Milisavljević, S., Jocanović, M., Kiss, F., Šević, D., Karanović, V., Orošnjak, M.	Virgin base oil and refinery products	ReCiPe 2016 (H)	ReCiPe 2016 (H)	None	Environmental advantage of energy recovery in cement kilns. Results strongly depend on substituted local energy mix
Fehrenbach, H.	*Production of base oil from crude oil via waxy distillates Group I; *Production of oly-alphaolefins (PAO, base oil Group IV) from natural gas via i-decene synthesis	Unknown; mid-point	Resource depletion, CED, GWP, AP, EP, HTP	Sensitivity	Environmental advantage (all ICs) of regeneration of waste oil to base oil when: i) group, and ii) a mix of I-IV are substituted
Grice, L.N., Nobel, C.E., Longshore, L., Huntley, R., DeVierno, A.L.	None; mass allocation	PAS 2050	GWP	None	GWP of re-refined oil significantly lower than that of virgin oil
Kalnes, T.N, Shonnard, D.R., Schuppel, A.	None; use of system expansion w/o substitution	Ecoindicator 99	GWP, AP, EP, ADP fossil	None	Re-refining UO in the HyLube process is more environmentally acceptable than UO combustion in cement kilns

Study	Year	Geography	Scope	Reference system(s)	Boundary	LCI	Functional unit	Final product quality
Kanokkantapong, V., Kiatkittipong, W., Panyapinyopol, B., Wongsuchoto, P., Pavasant, P.	2009	Thailand	Comparative LCA of 6 different used oil management options, RRBO vs RFO	RFO via i) small boiler, ii) vaporizing burner boiler, iii) atomizing burner boiler, iv) cement kiln	G-G	No	1 kg waste oil	Not specifically stated. Likely Group I
Nakaniwa, C. Graedel, T.E.	2002	Japan	Comparative LCA of recycled fuel oil (RFO) vs incineration of used oil w/o energy recovery	Incineration of used oil	G-G	Energy consumption and emissions of CO_2, SO_2, and NO_x	1 kg RFO	RFO
Pires, A., Martinho, G.	2012	Portugal	Comparative LCA of RRBO, RFO and expanded clay production	RFO, expanded clay, electricity	G-G	Yes	Entire volume of collected waste oil in Portugal in 2011	Not specifically stated. Likely Group I
Pires, A., Martinho, G.	2013	Portugal	Comparative LCA of 16 waste lubricant oil (WLO) systems (15 management alternatives and a system in use in Portugal)	RFO, expanded clay, electricity	G-G	Yes	Entire volume of collected waste oil in Portugal in 2012	Not specifically stated. Likely Group I

Study	Substituted processes	IA method	Impact categories	Uncertainty/Sensitivity analysis	Main results
Kanokkantapong, V., Kiatkittipong, W., Panyapinyopol, B., Wongsuchoto, P., Pavasant, P.	None	Unknown; mid-point	GWP, AP, EP and heavy metals	None	RRBO results in lower GWP than all of the energy recovery options. For the other impact categories the results vary
Nakaniwa, C. Graedel, T.E.	None; use of system expansion w/o substitution	None; inventory based	None; inventory based	None	Choosing re-refined oil can result in reducing natural resource consumption. Higher electricity use for re-refining oil. NO_x from diesel collection trucks can be a serious problem.
Pires, A., Martinho, G.	Virgin base oil and electricity	IPCC	GWP	None	Overall, the GHG emissions resulting from expanded clay production using treated WOs receives the highest credit in terms of carbon footprint
Pires, A., Martinho, G.	Light expanded clay aggregate (LECA), virgin oil, electricity, heat	Unknown; mid-point	AP, EP, GWP, HTP, FAETP, POCP	None	None of the scenarios had the highest or lowest environmental profile for all environmental impact categories. The management alternative that best performed in the most environmental impact categories was T2R, i.e., where WLO is treated with treatment T2 and then sent for re-refining

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