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Life Cycle Carbon Footprint of Re-Refined versus Base Oil That Is Not Re-Refined

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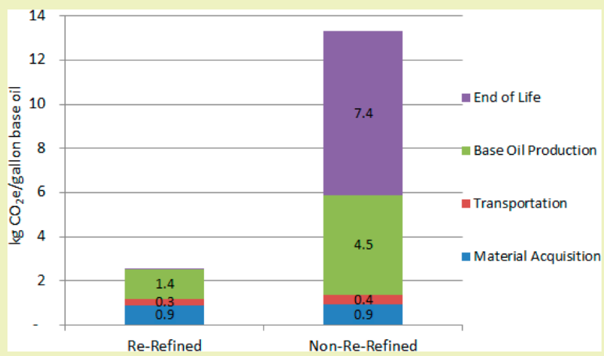

ABSTRACT: Consumers, communities, and regulators are focusing on recycling as a method to potentially reduce environmental impacts. One such recycling approach, the re-refining of used motor oil, is purported to avoid the greenhouse gases (GHG) associated with extracting and processing crude oil, as well as the emissions associated with alternative used oil management methods. This study analyzed the relative GHG reduction benefits of re-refining used motor oil by quantifying the life cycle carbon footprint associated with one gallon of re-refined base oil and contrasting that with the life cycle carbon footprint of an equivalent product derived from virgin stock that is not re-refined. The carbon footprint analysis included the GHG emissions associated with raw material extraction and processing, transportation, manufacturing, and waste management based on Safety-Kleen Systems primary data for re-refining. Safety-Kleen Systems is the largest producer of re-refined oil in North America. All other data was derived from best available secondary sources. The analysis showed that the carbon footprint of re-refined base oil is 81% lower than virgin stock-derived base oil that is not re-refined. This difference is primarily due to differences in emissions associated with base oil production and used oil end of life between the two systems studied.

KEYWORDS: *Green engineering, Sustainability, Life cycle carbon footprint, Recycling, Re-refined oil, Used oil management, Waste oil, Life cycle analysis*

INTRODUCTION

Throughout oil's life cycle: extraction, transport, refining, distribution, use, and disposal, there is potential for negative impacts on the environment.[1] Re-refining used oil into base oil (lubricant without additives) has benefits associated with both reducing the need to produce base oil from crude oil sources as well as avoiding emissions associated with used oil disposal. These potential benefits have motivated legislation such as the California Oil Recycling Enhancement Act[2] in the United States and the Council Directive on the disposal of used oils (75/439/EEC, amended by Directive 2008/98/EC) in Europe[3] that promote the re-refining of waste oil. Previous studies have utilized life cycle assessment to evaluate the environmental impacts of re-refining compared to other used oil end-of-life management methods. Boughton[4] reported that for global warming potential (GWP) impacts re-refining had a near 1:1 ratio to used oil distilled and then combusted for energy. Pires and Marinho[5] showed that re-refining resulted in a lower GWP impact than used oil combusted to produce heat or electric energy. Although these studies examine re-refining, they focus on the waste management phase and do not allocate upstream GHG emissions from crude oil acquisition and processing to the recovered product.

Life cycle cradle-to-gate inventories for lubricant oil produced from crude oil have been developed by Bousted Consulting[6] and Ecoinvent.[7] The National Energy Technology Laboratory[8] developed a comprehensive baseline for the life cycle GHG emissions from petroleum products that includes specific emissions associated with raw material acquisition, transport to the refinery and fuel production.

IFEU/GEIR[9] conducted an assessment of five re-refinery processes compared to base oil produced from crude oil derived from German and European production data. The study showed that global warming potential was lower for all five re-refining techniques considered compared to the production of base oil in standard refineries. This study's boundaries include collection and re-refining (including no upstream burden from the initial base oil generation) compared to the production of base oil from virgin sources. The study presents the impact results on a used oil collected basis.

The study discussed in this article builds on previous studies in that it compares the comprehensive carbon footprint of continuously re-refined oil to oil that is used once and disposed on a per gallon produced basis, rather than exclusively focusing on the waste management path of the used oil or the cradle-to-gate emissions of base oil produced from crude oil. Specifically,

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Table 1. Re-Refined and Base Case Base Oil Process Steps by Life Cycle Stage

life cycle stage	Safety-Kleen re-refined base oil	base oil that is not re-refined
material acquisition	input material acquisition (including used oil and other materials); used oil input includes virgin oil extraction, crude oil and feedstock transport, and initial base oil production.	crude oil extraction (composite crude oil and Canadian Oil Sands mix for the United States)
transportation	Safety-Kleen and third party transport to branches, terminals, and re-rerefinery via branch box trucks, tanker trucks, rail, and barge by both Safety-Kleen and third party vehicles	crude oil feedstock transport to United States refineries, which includes emissions associated with transport via pipeline, tanker ship, railroad, and truck and transport of used oil to disposal
base oil production	re-refinery and terminal operations, including dehydration, vacuum stripping, vacuum distillation, and hydrotreating	heavy end (atmospheric distillation, vacuum distillation) and base oil production (solvent deaphalting, dewaxing, extraction, and recovery; hydrogen treatment)
use	excluded	excluded
transport to customer	excluded	excluded
end-of-life management	continuous re-refining; management of re-refinery solid and liquid waste disposal	used oil combustion with energy recovery (80% of used oil); dumping (20% of used oil)

the boundaries of the carbon footprint for the re-refined oil include the emissions associated with the initial production of the base oil from crude oil, as well as continuous re-refining; the comparative product derived from virgin stock and not re-refined includes end-of-life emissions associated with disposal as well as cradle-to-gate emissions. This study quantifies the relative GHG benefit of re-refining versus the equivalent product derived from virgin stock that is not re-refined on a per gallon base oil basis. The study has been completed to inform consumers and regulators regarding the GHG savings derived from re-refining used oil and using re-refined oil.

■ MATERIALS AND METHODS

This study compares the carbon footprint associated with Safety-Kleen Systems' (Safety-Kleen) base oil re-refining process with the carbon footprint of the alternative processes in which equivalent products are not re-refined. The study was conducted in accordance with ISO 14040[10]and 14044[11] and PAS 2050[12] guidelines as confirmed by a critical review panel.

Functional Unit and System Boundaries. Safety-Kleen, the largest used oil re-refiner in North America, collects and re-refines used oil into approximately 100,000,000 gallons of base oil per year. Base oil (i.e., mineral oil) is a finished petroleum lubricant stock that when blended with additives produces products such as motor oil that protect internal combustion engines. Re-refined base oil has nearly identical properties to base oil that is produced from crude oil at a refinery. Both re-refined and the equivalent product derived from virgin stock must meet the same American Petroleum Institute (API) standards and equivalent volumes to fulfill the same functions.

This study analyzes the life cycle carbon footprint associated with one gallon of continuously re-refined base oil versus one gallon of virgin stock-derived base oil that is not re-refined (subsequently referred to as the "base case"). Table 1 lists the system boundaries and associated processes considered in the life cycle carbon footprints of re-refined and base case base oil. The life cycle stages assessed in this study included raw material acquisition, transportation, base oil production, and end-of-life management. The initial base oil production that results in the input used oil for the re-refined base oil is considered part of the raw material to the re-refinery process and is included in the "Material Acquisition" stage of the re-refined base oil. The use and transport to consumer phase emissions are excluded because they are similar for both re-refined and base case analyses. In the re-refined system, base oil is produced at a refinery, used, collected, continuously re-refined and re-used until it is consumed. As illustrated in ISO 14049,[13] the number of uses of a recycled material is estimated based on the following equation

$$\text{Uses} = 1 + \frac{z \times y}{1 - (r \times y)}$$

where z = the fraction of virgin product that is recovered after a first use and then recycled; y = yield of the recycling (e.g., base oil re-refining) process; and r = the fraction of the recycled product (e.g., re-refined base oil) that is recycled again. z and r are assumed to be 100% based on the analysis boundary conditions (i.e., all of the base oil is re-refined until it is consumed, and the use phase is excluded from the analysis). The re-refining base oil system yield is 86% based on Safety-Kleen's production values. Thus, one gallon of base oil that is continuously re-refined results in the equivalent of 7.14 gallons of use.

In the base case system, base oil is produced, used once, and disposed of via combustion with energy recovery or disposal without energy recovery. This analysis does not include further differentiation of end-of-life scenarios, such as the inclusion of the processes associated with distillation of used oil used for marine diesel oil. The transport to customer and use phases were excluded from the analysis because GHG emissions from both steps are equivalent in both systems.

The Safety-Kleen re-refining process includes the following steps, as illustrated in Figure 1. Safety-Kleen and third party collection firms collect used oil and transport it either to branches for consolidation or directly to Safety-Kleen's East Chicago or Breslau re-refineries. Safety-Kleen transports a portion of the used oil to terminals where it undergoes preprocessing, such as dehydration, and some is sold as fuel. Safety-Kleen re-refines used oil into base oil through dehydration, vacuum stripping, vacuum distillation, and hydrotreating processes.

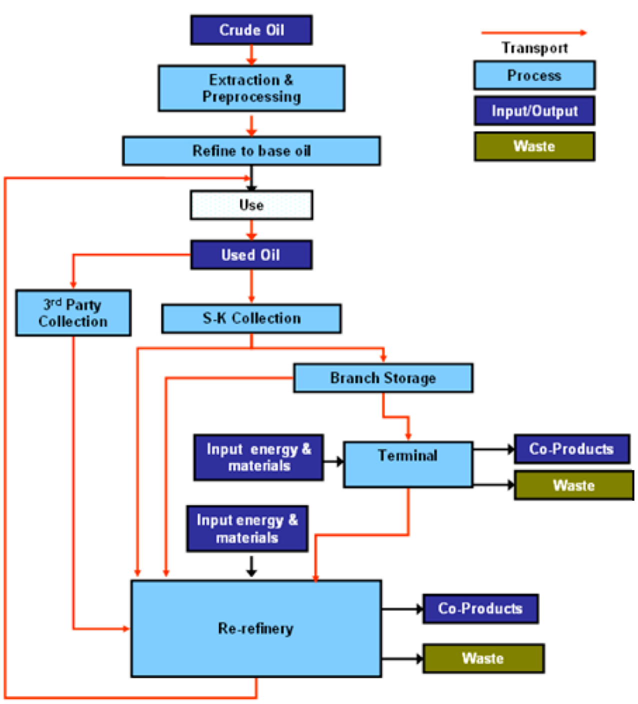

Figure 1. Re-refining system processes.

Table 2. Data Sources and Assumptions Used in Re-Refined Base Oil Analysis

process step	activity data sources	assumptions
initial base oil production burden	see Table 3; crude oil extraction through refine to base oil steps	see description above
collection	Safety-Kleen primary data	Used oil is collected, stored at branches and transferred from storage containers to trucks under the pumping power of the diesel-powered on-truck pumps. Emissions are accounted for and aggregated into the transportation process analysis
Safety-Kleen and third party transport to re-refineries, branches, and terminals	Safety-Kleen Primary Data (Miles traveled and fuel efficiency-trucks; weight transported-rail and barge)	Used oil is transported to the Safety-Kleen re-refineries, branches, and terminals via branch box trucks, tanker trucks, rail, and barge by both Safety-Kleen and third party vehicles. This analysis includes backhauls for SK trucks because all miles traveled are included. Backhauls for third party transport are not included in this analysis. All transportation emissions are allocated to re-refined base oil.
Re-refining preprocessing at terminals	Safety-Kleen primary data (electricity and natural gas consumed)	Approximately one-fourth of the used oil is preprocessed at terminals where a proportion is sent to the re-refineries, and the remainder is sold to be processed into residual fuel oil. Only the used oil sent to re-refining is included in this analysis. Electricity and natural gas usage are allocated to the recycled base oil based on the proportion sent to re-refining by volume.
re-refining and terminal operations: fuel and energy inputs	Safety-Kleen primary data (electricity, natural gas, diesel consumed)	Extraction and production (i.e., embodied emissions) and combustion emissions are included for purchased fuel. Combustion emission is only included for fuel produced on-site. Location-specific combustion factors are used for purchased electricity. Net amounts used at all facilities are included.
re-refining and terminal operations: chemical inputs	Safety-Kleen primary data (amount consumed)	Included are total chemical inputs that are greater than 0.01% of the base oil produced by mass or volume: water, phenol destruct, sulfuric acid, caustic, nitrogen, hydrogen, catalyst, softener salt, and bleach. Applied conservatively, high emission factor of 10,000 g CO_2e/kg material for materials with unavailable emission factors (catalyst and phenol destruct).
re-refining and terminal operations: co-products	Safety-Kleen primary data (amounts produced, burned on-site and sold off-site)	Re-refining produces several co-products from the different re-refining processes. Co-products sold off-site are allocated emissions credits following the PAS 2050 product displacement allocation method. These primarily include vacuum stripping fuel and hydrotreating distillate which displace #2 distillates in the marketplace. Combustion emissions (but not embodied emissions) associated with the displaced products are used for those co-products burned on-site as refinery fuel. No displacement credit is given for fuels burned onsite.
re-refining and terminal operations: additive and other constituents	Safety-Kleen primary data (amount of coproducts produced)	Additive and other constituents (such as ethylene glycol) comprise the "non-base oil" portion of input used oil that is processed at the re-refinery. The re-refined base oil that Safety-Kleen produces includes no additives, thus the additives must exit the re-refining process as co-products or wastes. Co-product credit for ethylene glycol and asphalt extender are not included in the base oil values to conservatively account for the embodied emissions of additives.
re-refining solid and liquid waste disposal	Safety-Kleen primary data (amount of waste disposed)	Wastewater is sent to an off-site wastewater treatment facility. Small amounts of solid waste filter press sludge are disposed of at a landfill. Oily water and some process sludge are sent to cement kilns to be disposed of as waste-derived fuel. To account for energy recovery at cement kilns, emissions associated with the acquisition and combustion of fuel products displaced were subtracted from actual combustion emissions.[12] The actual combustion emissions per quantity combusted are assumed to equal to that of residual fuel oil (RFO) or coke for liquids and solids, respectively. Assumes that these waste-derived fuels displace natural gas at the cement kilns because natural gas is the highest marginal value fuel used, i.e., natural gas is the most expensive fuel used at the time of this study, so it would have been replaced first.

Life Cycle Data and Assumptions. To calculate the emissions from Safety-Kleen base oil re-refining, Safety-Kleen provided 2010 operations data (such as electricity used and miles traveled) for the majority of activity data. This study uses secondary data from academic or industry studies for base case process activity data and emission factors. Base case process activity data from extraction through heavy end production was obtained from NETL,[8] and the data for the additional steps required to produce base oil from heavy end petroleum products was obtained from DOE.[14]

A key element of this analysis is the allocation of "virgin" base oil embodied emissions to the re-refined base oil carbon footprint. On the basis of the derived number of uses (u) of 7.14 from continuous re-refining (as detailed above), the "virgin raw material" (e.g., base oil first use cycle) accounts for the first gallon of use, and the re-refining process generates the subsequent 6.14 gallons of use. Thus, the allocation for the initial (i.e., virgin) contribution and the allocation to the re-refining system are as follows

$$\text{Virgin Allocation} = 1/u = 0.14$$

$$\text{Re-refining Allocation} = (u - 1)/u = 0.86$$

To calculate the Safety-Kleen total emissions per gallon including virgin base oil embodied emissions and continuous re-refining, we apply the following formula

$$0.14 \times (\text{virgin embodied emissions/gallon base oil}) + 0.86 \times (\text{Safety-Kleen re-refining process emissions/gallon})$$

Tables 2 and 3 summarize the additional activity data sources and assumptions used to develop the life cycle emissions inventory for re-refined and base oil that is not re-refined. In the results, we apply a sensitivity analysis to examine the range of impacts due to input values that have a material impact on the results due to their uncertainty and/or variability.

GHG Emissions Calculations. We calculated GHG emissions by first cataloging the amount of material and energy used and wastes produced from each system process included based on the primary data from Safety Kleen and secondary data as described in Tables 2 and 3. We converted this activity data to greenhouse gas emissions by multiplying the values by greenhouse emissions factors within a spreadsheet model. We obtained emission factors from secondary data sources such as the U.S. EPA,[16] The Climate Registry,[17] National Renewable Energy Laboratory (NREL) U.S Life Cycle Inventory Database (USLCI),[18] and Ecoinvent[7] Life Cycle Inventory Database.

This analysis considers the GHGs governed by the Kyoto Protocol and addressed by PAS 2050: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs). GHG emissions are reported throughout this inventory report in metric tons of carbon dioxide equivalents (CO_2e). CO_2 equivalents are the metric used to express the impact of emissions from each individual GHG on a common scale, using each GHG's global warming potential (GWP) value to determine the amount of CO_2 emissions that would cause the same amount of global warming. GHG emissions are converted into CO_2e emissions using the 100-year GWPs from the Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report,[19] as required by PAS 2050 (which requires use of the most recent IPCC Assessment Report).

RESULTS AND DISCUSSION

Table 4 presents the carbon footprint of re-refined base oil and those of base oil that is not re-refined. The carbon footprint of re-refined base oil is 81% less than base case base oil within the boundaries studied. Of the life cycle components, the key emission difference between the two products are the higher emissions associated with base case waste management and base oil production. Re-refined base oil production (including re-refinery and terminal operations) results in 69% less

Table 3. Data Sources and Assumptions Used in the Base Case Base Oil Analysis

process step	activity data sources	assumptions
crude oil extraction and preprocessing	NETL[8] (CO_2e per barrel crude oil)	Composite value used for this analysis includes the GHG emissions consistent with extraction of the composite United States crude oil mix for 2005 that weights the emissions based on the input of crude oil to American refineries from around the world (NETL Report, Tables 2–6). This study did not assess the extent of additional impacts associated with synthetic crude oil production.
transport to refinery	NETL[8] (CO_2e per barrel delivered)	CO_2e emissions from crude oil feedstock transport to United States refineries in 2005, including emissions associated with transport via pipeline, tanker ship, railroad, and truck (NETL report, Tables 3–16).
refine to heavy ends	NETL[8] (CO_2e per barrel refined product, broken out by process)	Includes initial atmospheric distillation and production of "heavy ends", via vacuum distillation, which included emissions sources for refinery fuel combustion, purchased steam and electricity, acquisition of natural gas and coal, acquisition of refinery-produced fuels, hydrogen production, and flaring (venting and fugitive) (NETL report, Tables 4–55).
refine to base oil	DOE[14] (energy use per barrel, broken out by fuel type)	Includes solvent deasphalting, dewaxing, extraction, and recovery, which includes emission sources for electricity, natural gas, and other fuels. (DOE report,[14] Table 9.3).
collection and transport of used oil to disposal	estimated value	Assumes the transport of used oil an average round trip distance of 500 miles by heavy-duty trucks.
waste management	U.S. EPA[15] (used oil management volumes)	Of the accounted for used oil that is not re-refined, this study assumes 80% is used as fuel and 20% is improperly disposed of (i.e., dumped) No additional processing (such as distillation for marine diesel) is included. Used oil combustion with energy recovery: Accounted for the combustion emissions of the used oil (assumed to have emissions similar to RFO) and subtract the embodied and combustion emission of natural gas. Assumes that these waste-derived fuels displace natural gas because natural gas is the highest marginal value fuel used, i.e., natural gas is the most expensive fuel used at the time of this study, so it would be replaced first. The amount of natural gas displaced is determined based on the average heat content input requirement for cement kilns. Improperly disposed: Assumes that all of the carbon in the waste used oil that is improperly disposed of by dumping in the ambient environment is converted into CO_2 during the 100-year time frame considered in the analysis.

Table 4. Comparison of Re-Refined vs Base Case Base Oil Lifecycle Emissions per Gallon by Life Cycle Stage

life cycle stage	re-refined base oil (kg CO_2e/gallon base oil)	base case (kg CO_2e/gallon base oil)
material acquisition: virgin burdencrude extraction	0.90	0.94
transport to refinery	0.26	0.19
base oil production	1.35	4.53
transport to consumers	*excluded from analysis*	
use phase	*excluded from analysis*	
transport to end of life[a]	N/A	0.22
end of life	0.003[b]	7.43
total	2.5	13.3

[a]In the case of re-refining, "transport to end of life" is "transport to refinery". [b]End of life in the re-refining case is management of re-refinery waste.

emissions than those associated with base oil production at a refinery.

Base Oil Re-Refining Results. As presented in Figure 2, the emissions due to re-refinery operations (i.e., re-refinery

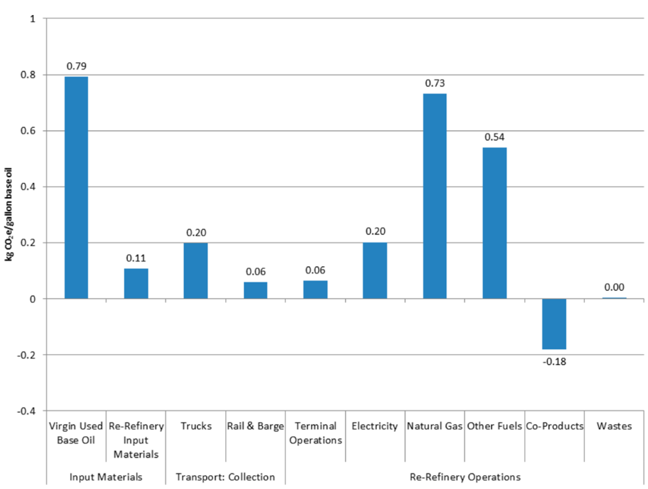

Figure 2. Safety-Kleen re-refined base oil CO_2e emissions by life cycle stage and source.

electricity, natural gas, and refinery fuel) encompass the majority of the carbon footprint, accounting for 57% of the total emissions. Emissions associated with the initial production of the base oil (used oil input) account for 29% of the re-refined base oil carbon footprint.

Base Case Base Oil Results. As presented in Figure 3, the emissions due to disposal via combustion and dumping comprise the largest percentage of the base case base oil footprint (56%), followed by base oil production (34%).

Sensitivity Analysis. Uncertainties can affect the carbon footprint results. Differences in outcomes can vary dependent on the boundaries included in the analysis, allocation approaches, and assumptions applied throughout the analysis. To target parameters to examine in a sensitivity analysis, we reviewed the model inputs to identify those parameters that both were potentially highly variable and have a significant impact on the overall emissions. For example, although re-refining fuel and energy use contribute the majority of re-refining GHG emissions, these values were obtained directly from invoices and do not vary significantly from year to year, so

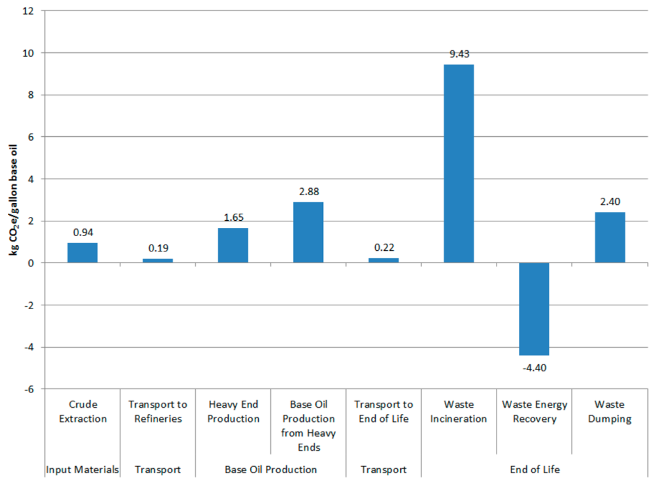

Figure 3. Base case base oil CO_2e emissions by life cycle stage and source.

there is only minor uncertainty and variability. Likewise, although the collection distance of used oil to disposal can be highly variable, transport to end of life is not a significant contributor to the base case carbon footprint. On the basis of this analysis, we identified parameters that could affect the results of the LCA GHG by 10% or more: re-refining system yield/number of uses, amount of used oil disposal energy recovery, and type of fuel displaced for energy recovery.

The re-refining system yield/number of uses affects both the contribution of the input virgin materials and the allocation of the re-refining process emissions. Figure 4 presents the re-refined

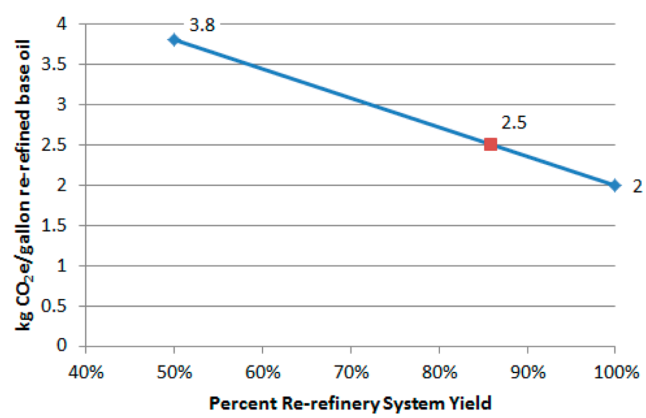

Figure 4. Model results for re-refined base oil when different re-refinery system yields are applied.

carbon footprint-based oil GHG emissions for re-refinery system yields of 50% (equivalent to two gallons of use over a gallon of base oil's lifetime; 50% burden from virgin base oil input) to 100% (infinite re-refining; no burden from virgin base oil input). If production yield increases, emissions are distributed over more gallons of use, resulting in a lower carbon footprint for re-refined base oil. This range in re-refining yield/number of uses results in re-refined base oil results that are 20% lower and 50% higher than the footprint associated with the analysis system's 84% yield assumption. The upper bound of the analysis, which reflects system yields below Safety-Kleen's historical yield values, results in carbon emissions per gallon of base oil that are significantly below the values derived for base oil produced from virgin stock.

Because the disposal phase emissions contribute the largest percentages (56% combined) of the base case carbon footprint results, the allocation approaches applied to these emissions estimations have a large impact on the results. For example, if 100% of the base-oil is assumed to be disposed of with combustion with energy recovery (i.e., excluding the dumping scenario), the total emissions per gallon would be 12.2 instead of 13.3 kg CO_2e/gal base oil. Another key assumption is the emission credit proportioned to the waste base oil that is combusted as fuel. Figure 5 presents the results of a sensitivity analysis for a range of heat contents for the used oil. The used oil heat content assumption determines the amount of equivalent displaced fuel; heat contents evaluated range from no energy recovery (no fuel displaced) to the equivalent heat content of residual fuel oil. The base case results vary approximately 30% from the base case assumption of displacement based on the average heat content of cement kiln input fuels.

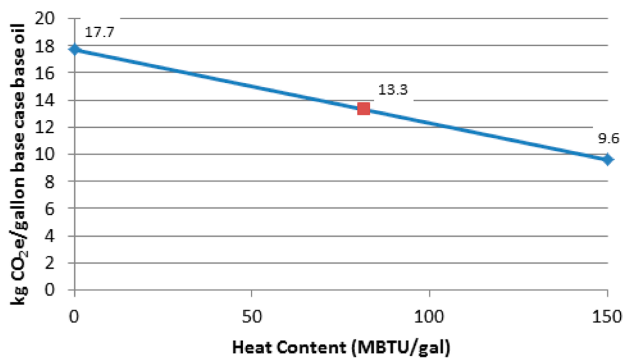

Figure 5. Model results for base case base oil when different used oil heat contents are applied for energy recovery at the end of life.

This analysis assumed that used oil displaces natural gas because it was the highest value fuel at the time of the analysis; Figure 6 presents the results of a sensitivity analysis of the base case carbon footprint assuming that the used oil displaces various fuels or is not burned for energy recovery. The energy recovery credit depends on the displaced fuel's heat content, combustion emissions, and embodied emissions. The type of fuel displacement assumptions result in base case carbon footprint values that range from 22% lower and 30% higher than the footprint associated with displacing natural gas. The model results for the re-refined base oil (even assuming a low re-refinery yield) are less than half of the lower range of the model results for the base case sensitivity analysis evaluations of various heat content and displaced fuels.

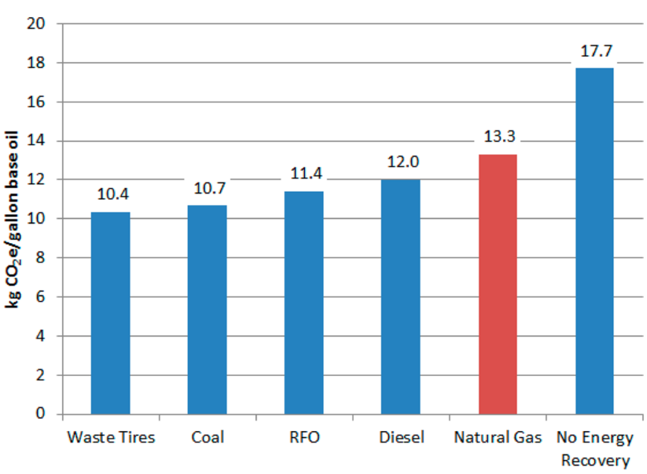

Figure 6. Model results for base case base oil when different fuels are displaced for waste energy recovery at the end of life.

This analysis determined that re-refining and base case carbon footprints can vary significantly depending on model assumptions; however, re-refining results in less than 50% of the GHG emissions than base case base oil in all scenarios evaluated. The results show that the most significant advantages of re-refining occur during the base oil production and waste management life cycle phases. Future work could analyze the relative impact of environmental impacts other than climate change such as resource depletion or human health effects, examine the impact of alternative used oil processing activities such as intermediate processing of used oil into distillates, or examine the impacts of various sources of virgin crude oil. Safety-Kleen is applying these results to target emissions reductions and engage and educate consumers and public policy makers on the potential greenhouse gas emission benefits of re-refined base oil.

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Notes

The authors declare the following competing financial interest(s): Safety-Kleen Systems, Inc. retained ENVIRON International Corporation to conduct an assessment of the life cycle greenhouse gas emissions of its re-refined base oil products compared to the carbon footprint of the alternative "virgin" product.

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■ ABBREVIATIONS

API, American Petroleum Institute; bbl, barrel; CH_4, methane; CO_2, carbon dioxide; CO_2e, carbon dioxide equivalents; DOE, U.S. Department of Energy; GHG, greenhouse gas; GHG LCA, greenhouse gas life cycle analysis; GWP, global warming potential; HFC, hydrofluorocarbns; IPCC, Intergovernmental Panel on Climate Change; ISO, International Organization for Standardization; kg, kilogram; LCA, life cycle analysis; LCI, life cycle inventory; N_2O, nitrous oxide; NETL, National Energy Technology Laboratory; NREL, National Renewable Energy Laboratory; OTR, over the road; PAS, publically available specifications; PFC, perfluorocarbons; RFO, residual fuel oil; SF_6, sulfur hexafluoride; USLCI, U.S. Life Cycle Inventory Database

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