
Critical Review of Used Oil Life Cycle Assessment Study



California Department of Resources Recycling and Recovery

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Introduction

As part of Senate Bill (SB) 546 of 2009, CalRecycle was directed to 1) contract with a third-party consultant with recognized expertise in life cycle assessments (LCA) to coordinate a comprehensive life cycle analysis of the used lubricating and industrial oil management process, from generation through collection, transportation, and re-use alternatives; 2) solicit input from representatives of all used oil stakeholders in defining the scope and design of the LCA; 3) evaluate the impacts of certain components of SB 546; and 4) submit a report to the Legislature on the results and “any recommendations for statutory changes that may be necessary to promote increased collection and responsible management of used oil.”

CalRecycle has contracted with the University of California, Santa Barbara (UCSB) to conduct the LCA (LCA Contractor). UCSB is performing all the steps necessary to perform the analysis. CalRecycle has also contracted with Life Cycle Associates, LLC to be the Critical Review Contractor (Review Contractor) and support the successful completion of the LCA project by assuring that it complies with International Organization for Standardization (ISO) standards and protocols.

Review Background

The Life Cycle Associates approach to satisfying this objective is briefly discussed in the following discussion. The discussion outlines the methods we have employed to satisfy, not only the overall project objective, but also the objectives of each of the project tasks. It specifically describes how each project task will be completed to achieve its individual objective(s).

According to the Work Plan for the project, the study was to proceed in three project tasks, as follows:

- Task 1: Provide Coordinate LCA Study Critical Review Panel.
- Task 2: Coordinate LCA Study Critical Review Panel
- Task 3: Reporting

This report documents the project progress in the first two of those tasks.

Reviewers

To complete later tasks in this project requires assembling a review panel of experts in the life cycle assessment field with particular expertise in the life cycle analysis of energy systems, waste management, and used oil management. The critical reviewers selected by CalRecycle are:

- Christopher Loreti of The Loreti Group
- Dustin Mulvaney of EcoShift Consulting
- Francois Charron-Doucet of Quantis
- Jeffrey Morris of Sound Resource Management Group, Inc.
- Keith Killpack of SCS Global Services
- Gerard Mansell of SCS Global Services
- Stefan Unnasch of Life Cycle Associates

A summary of each reviewer's LCA credentials is given in the following. In addition Mr. Killpack will rely heavily on the experience of Gerry Mansell of SCS Global Services. Dr. Mansell's LCA credentials are also given below.

Christopher Loreti

Christopher Loreti is the founder and principal of The Loreti Group, a sole proprietorship based in Arlington, Mass. He has more than 25 years of environmental consulting experience, focusing on greenhouse gas emissions and energy consumption in industry, primarily the petroleum industry. His consulting experience includes 15 years with Arthur D. Little, Inc., where much of his work focused on the fate and transport of chemicals in the environment, five years with the Battelle Memorial Institute, and seven years with The Loreti Group. He holds B.S. degrees in Chemical Engineering and Environmental Engineering from Northwestern University and an M.S. degree from the Department of Engineering and Policy at Washington University.

Mr. Loreti has considerable experience assessing the energy and emissions associated with the production and processing of oil and petroleum products. For more than a decade, he has assisted the oil industry in quantifying emissions of both conventional air pollutants and greenhouse gases, as well as energy consumption from oil industry operations. He served as project manager for the development of the first widely-used petroleum industry greenhouse gas emissions model.

In addition to deep technical knowledge of the environmental impacts of the oil industry, Mr. Loreti has also reviewed and conducted life cycle assessments. He led or co-led two major assessments of The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET), a life cycle model that has been applied in the evaluation petroleum products and alternative fuels. His work on these studies focused on the refining of oil and the associated energy consumption and emissions. Mr. Loreti has conducted a comparative life cycle assessments following the guidelines of ISO 14040 and 14044.

Dustin Mulvaney

Dustin Mulvaney is a principal for EcoShift Consulting and Assistant Professor of Sustainable Energy Resources in the Department of Environmental Studies, San Jose State University. His life cycle assessment (LCA) work includes research on material and energy flows in the photovoltaic, biofuel, and natural gas energy sectors. LCA clients include Sunoco, BioArchitecture Labs, and BioSynthetic Technologies. LCA projects he has directed and/or contributed to include evaluations of emissions related to photovoltaic (PV) modules, natural gas from shale, corn ethanol, brown seaweed ethanol, poly alpha olefins, and biosynthetic methyl esters. Dr. Mulvaney is also a peer reviewer of several LCAs for solar energy systems including those reported in the following peer viewed journals: the *Journal of Solar Energy*, the *Journal of Integrative Environmental Sciences*, and the *Journal of Environmental Science and Technology*.

Dr. Mulvaney has a B.S. in Chemical Engineering from the New Jersey Institute of Technology and a Ph.D. in Environmental Studies from UC Santa Cruz. Dr. Mulvaney was a National Science Foundation Postdoctoral Scholar at the University of California, Berkeley, where he did research on the life cycle impacts of solar photovoltaics and biofuels and gained experience with unpacking emissions factors. He has previously worked as a process engineer for a Fortune 500 chemical manufacturer.

Dr. Mulvaney also has experience with the design and operation of take-back and recycling systems, and is currently developing a manuscript on the life cycle impacts of extended producer responsibility for PV modules. In reviewing the Used Oil LCA study he will be able to draw on other EcoShift team support including that of Joep Meyer (with more than a decade of LCA experience including work on petroleum-based products) and Rob D'Arcy (with 14 years of

experience in waste management and used oil management through the County of Santa Clara Hazardous Waste Recycling and Disposal Program and the Hazardous Materials Program Manager).

Francois Charron-Doucet

François Charron-Doucet has been active in the field of life cycle assessment (LCA) for the past eight years and has completed many LCA projects. As an approved individual verifier by the International Environmental Product Declaration (EPD) System, he conducted external verifications of several EPDs for North American EPD programs including ICC-ES and UL Environment. He also participated in several critical reviews as chairman or LCA expert. He currently holds the position of Scientific Coordinator at Quantis and his main task is to internally verify Quantis' deliverables. He has reviewed more than 70 LCA studies over the past two years.

Mr. Charron-Doucet graduated with a degree in Engineering Physics in 2004 (Ecole Polytechnique de Montreal) and holds a master's degree in Life Cycle Assessment from the Chemical Engineering Department of the Ecole Polytechnique de Montreal (2006). He earned this diploma in collaboration with the CIRAIG (Interuniversity Research Centre for the Life Cycle of Products, Processes and Services), one of the most important research centers in LCA in the world.

Mr. Charron-Doucet has developed extensive knowledge and understanding of the different standards and guidance related to LCA. Along with adept knowledge of all aspects of LCA, his main fields of expertise are: inventory analysis and LCI databases; attributional, consequential and dynamic LCA; allocation rules; and greenhouse gas (GHG) project quantification and carbon foot-printing (including biogenic emission balances).

Mr. Charron-Doucet also has an in-depth understanding of the environmental models used in prevalent life cycle impact assessment (LCIA) methodologies, including TRACI, IMPACT 2002+ and ReCiPe.

Jeffrey Morris

Jeffrey Morris is an economist (Ph.D.—Economics and M.A.—Theoretical Statistics, from UC Berkeley; M.B.A.— Finance and Operations Research, from Northwestern University) and co-founder of Sound Resource Management Group, Inc. (SRMG) in Olympia, Washington. SRMG was incorporated in 1987 and currently specializes in economic and environmental research and consulting, with an emphasis on economic and environmental life cycle assessment (LCA) for municipal and other solid wastes management systems.

Dr. Morris has more than 20 years of experience conducting life cycle analyses and assessments. Among these is the ground breaking study of life cycle energy conservation from recycling municipal solid waste (MSW) materials compared with energy generation via waste-to-energy (WTE) processes. Results from this study were published in the *Journal of Hazardous Materials* in 1996. In 2005 he published an LCA in the *International Journal of Life Cycle Assessment* on the environmental impacts of waste recycling versus disposal.

The assessment included monetization of impacts to evaluate different trade-offs among environmental consequences and trade-offs between economic and environmental costs or benefits. In 2010 Dr. Morris published an article in *Environmental Science & Technology* detailing the climate impacts of using landfill or waste-to-energy (WTE) for MSW disposal. The innovation in this LCA was to illustrate the conditional and uncertain nature of environmental rankings for waste management MSW disposal options.

Dr. Morris has also served on life cycle study peer review panels, provided peer review on article submissions to several journals, and conducted LCAs and/or LCA literature reviews for the U.S. General Services Administration, Washington State Department of Ecology, Alberta Ministry of the Environment, Ontario Ministry of the Environment, Seattle Public Utilities, Portland Metro (OR), and the City and County of San Francisco.

Keith Killpack

Keith Killpack manages SCS Global Services' Life Cycle Services department. Under his supervision, the department conducts life cycle assessments (LCAs) for a wide range of industries and clients, using advanced methods now being standardized under the American National Standards Institute (ANSI) process (LEO-SCS-002). These studies are conducted to help companies design products and services to minimize environmental impacts, optimize operational efficiencies, satisfy customer requests, engage stakeholders, and support comparative ecolabels and environmental product declarations.

Specializing in biofuels and bioenergy assessments, he has completed dozens of assessments for the U.S. Department of Energy (DOE). Mr. Killpack has also helped develop methods using life cycle assessments to analyze whole buildings including site selection and preparation, design and construction, building occupancy, maintenance and operations, upgrades and decommissioning. He draws from prior experiences in environmental chemistry and applied biology, validation of environmental analytical data, environmental remediation projects, and sustainability, including a Master's thesis reviewing international environmental health and safety and product stewardship practices in the nanotechnology field.

The depth and breadth of his LCA experience are illustrated by the many projects Mr. Killpack has managed and/or performed. For example under contract with the Department of Energy (DOE), he built LCA models and prepared summary reports for over a dozen advanced biofuel and biomass electricity generation projects seeking DOE loan funding. He has overseen the development of an on-line tool to assess all environmental impacts related to buildings.

Mr. Killpack completed the first Environmental Building Declaration (EBD), a whole building life cycle analysis comparing the Caltrans Inland Empire Transportation Management Center to standard construction. He has conducted LCAs and prepared final certification reports for industry trade groups and building and consumer products, trained and provided guidance to employees in LCA methods and software, and performed site investigations including collection of soil and groundwater samples for environmental analysis. He also has experience with hazardous waste site remediation and supervision of drill crews.

Mr. Killpack has a B.S. in Biochemistry and Molecular for MDO Biology and an M.S. in Environmental Science and Management, both from the University of California, Santa Barbara.

Gerard Mansell

Gerard Mansell has been developing, evaluating, and applying emissions, meteorological, and advanced photochemical air quality models for more than 20 years, with extensive experience in various mathematical modeling techniques and numerical analysis methods. As a member of the LCA Services team at SCS, he performs life cycle assessments using various life cycle inventory databases and LCA modeling tools (SimaPro). Additionally, he applies air dispersion models and data analysis techniques to assess the human health and other environmental impacts for clients in a variety of industrial and commercial sectors, as required to meet the advanced impact assessment protocols of the draft standard, LEO-SCS-002.

Prior to joining SCS, Dr. Mansell conducted numerous air quality and emissions inventory modeling studies in an environmental consulting capacity, and was instrumental in the development of several regulatory air quality modeling systems. He has extensive experience in all aspects of the air quality modeling process including development of model input data, model application and evaluation, as well as post-processing and interpretation of modeling results. He also has expertise in the application and evaluation of state-of-the-science regulatory meteorological, air dispersion and emissions models including MM5, WRF, CAMx, CMAQ, UAM-V, AERMOD, SMOKE, CONCEPT, MOBILE6, BEIS and MEGAN.

Dr. Mansell has performed several life cycle impact assessments (LCIAs) for Environmental Product Declarations (EPD) and Environmentally Preferred Product (EPP) certifications, human health and environmental impact assessments for industrial and commercial sectors and air quality and environmental data analysis using standard and customized software applications. He has completed many critical reviews of LCA studies for ISO conformance, applied air dispersion modeling and analysis in support of LCIA studies, developed Gaussian plume dispersion models for large-scale applications of risk assessment and exposure, and developed and applied GIS-based emissions and air dispersion modeling systems and analysis tools using ArcGIS and Python scripting.

Dr. Mansell has B.S., M.S., and Ph.D. degrees, all in Mechanical Engineering and all from the University of California, Santa Barbara.

Stefan Unnasch

Stefan Unnasch is the founder and principal of Life Cycle Associates, LLC, located in Portola Valley, California. Mr. Unnasch has more than 30 years of experience with transportation technologies and life cycle analysis. His consulting experience includes 25 years with Acurex and its successors where he managed heavy-duty vehicle demonstration projects, including engine oil monitoring programs. He has worked on the life cycle analysis of fuels for more than 25 years. Since founding Life Cycle Associates, much of his work focused on transportation products including petroleum fuels and alternative fuels. He holds B.S. degrees in Mechanical Engineering from University of California, Berkeley.

Mr. Unnasch has performed fuel cycle analysis studies since 1987 where he developed analytical approaches that take into account the environmental constraints that apply to California. He develops models of well-to-wheel energy impacts and emissions including criteria pollutants, toxics, greenhouse gases, and global energy inputs. These analyses have included assessing the resource mix and transportation modes for fuel production, process modeling of fuel production plants, and vehicle drive cycle analysis. He has developed spreadsheet and database models that enable the calculation of regional specific emissions as part of a full fuel cycle analysis. His work on California fuel cycle analysis efforts includes serving as the co-chairman of the Societal Benefits Topic Team for the California Hydrogen Highway Blueprint Plan, support of California AB1007, and the Low Carbon Fuel Standard.

Mr. Unnasch was a participant in Annex XI, Life Cycle of Fuels, and Annex XV Fuel Cell Systems for Transportation under the International Energy Agency Operating Agreements. In this effort, he worked with a group of international experts on assessing the life cycle emissions from conventional and alternative fuels. He also was the key U.S. contributor to Annex XV, Fuel Cell Systems for Transportation. Mr. Unnasch has participated in comparative life cycle assessments following the guidelines of ISO 14040 and 14044.

Review Summary

Table 1 provides a summary of the critical review comments provided by the reviewers, and outlines the UCSB responses to these comments that will be included in the LCA study's revised Final Report. The remainder of this report discusses these comments and other aspects of the critical review of the study.

Table 1. Critical review panel draft LCA study report summary

Issue	Resolution
Major issues	
Air emission metals valence state: assumes all Cr is all Cr(VI)	Current model assumes 20% Cr(VI) for all fuels
Emission factors for NO _x and PM need alignment with combustion sources	Data for combustion emissions was evaluated in more detail. Explanatory discussion added to final revision
Retention rates are based on simple averages	UCSB reexamined retention rates. Explanatory discussion added to final revision
Transport energy intensity: data doesn't make sense on a Btu/ton-mi basis	UCSB modified the transportation energy intensity to align with factors in the GREET model that reflect the hauling of fuels
PE data on refining: refinery CO ₂ seems low compared to other LCA studies	UCSB reviewed PE data and added explanatory discussion on rationale for PE data. UCSB added crude oil transport to the LCA model. Extensive sensitivity discussion added to final revision
OEHHA factors on toxics are different than TRACI 2.0	UCSB discussed options for impact assessment, identify OEHHA factors, and point out limitations in assigning particulate emissions as diesel particulate.
Environmental justice, spatial limitations, and marginal emissions are not completely addressed	Environmental justice was not discussed in the Final Report, and should definitely be included as a study limitation. Spatial limitations should also be described as the LCA is intended to inform public policy. Average emissions instead of marginal were used per PE report
There is no interpretation for the scenarios results section.	Comprehensive interpretation of scenario results was not in the LCA study scope; CalRecycle will provide interpretation in their report to the Legislature

Table 1. Concluded

Issue	Resolution
Other issues	
Refinery emissions should be CA-specific	Average U.S. refinery data used per PE report; substituting a specific refinery has marginal effect on impact calculations
A given year impacts not related to past year emissions/discharges such as oil disposed to landfill	Timing issues regarding landfill disposal and LFG emissions and leachate composition were discussed in final revision
Freshwater/marine aquatic impacts are not differentiated	Differentiation has been clarified in the Final Report
Abiotic depletion and terrestrial ecotoxicity are not considered	Explanatory discussion added to final revision
ISO reporting standards are not rigorously followed regarding cut off criteria and sensitivity analysis	Cut-offs and exclusions section have been added to final revision. Sensitivity analysis section was added. Consistency and completeness checks were discussed. UCSB reviewed all ISO requirements.
Treatment of non-detects is incompletely justified	Final revision sensitivity discussion examined non detects in data
Lack of non-fossil electricity generation data in electricity model	Non fossil electricity is discussed. Study makes no attempt to examine marginal power or oil refining. This is beyond the LCA study scope.
More detail on limitations is needed	Detailed discussion of study limitations added to final revision. Discussion includes limitation on the consistency of the consequential modeling approach and completeness of the LCIA (HC speciation in air emissions in particular)
Emission/discharge data should be based on actual process use not capacity	Explanatory discussion added to final revision. Average emissions used instead of marginal per PE report
LFG emission capture efficiency used differs from GaBi	Clarification and any needed rationalization discussion added to final revision
Improper disposal fate data used need to be better clarified	The Final Report discusses improper disposal in sufficient detail

Goal and Scope

Critical Review Project Objective

The overall objective of this project is to provide technical assistance to the CalRecycle project team in coordinating the overall used oil life cycle assessment (LCA) effort. The project team is comprised of CalRecycle and the University of California, Santa Barbara (UCSB, LCA contractor, Roland Geyer, UCSB Project Manager). The LCA reviewers selected for the project are just noted above. Life Cycle Associates serves as the critical review coordinator, to oversee and coordinate critical review services for the used oil study. This technical assistance was to be focused on the study project coordination and stakeholder interactions.

The aim of the Critical Review oversight and coordination effort assigned to Life Cycle Associates was to conclude whether:

- The methods used to carry out the study are consistent with ISO standards 14040 and 14044
- The methods used to carry out the study are scientifically and technically valid.
- The data are appropriate and reasonable in relation to the goal of the study
- The interpretations reflect the limitations identified and the goal of the study
- The study is transparent and consistent

To satisfy this objective, Life Cycle Associates acted as the Critical Review Panel chair for the used oil study from the beginning of the project through the completion of the final report. This role incorporated coordinating the efforts of the five critical reviewers noted above so they remained “on the same page” with respect to keeping the efforts of the LCA contractor in compliance with ISO standards 14040 and 14044.

Goal and Scope Review

The goal and scope as described in the Final Report and as implemented in the GaBi Envision models provided to the Review Panel seem appropriate for evaluating the overall environmental impacts of the California used oil management system on an annual basis. However, there is a time frame issue implicit in the LCA procedures for evaluating the environmental impacts of landfill disposal of used oil. There is also a timing issue with respect to the evaluation of the environmental impacts of recycling used oil into re-refined base lubricating oil.

This latter issue is also of importance for evaluating relative environmental impacts of the three main pathways for recycling used oil—re-refined base oil (RRBO), recycled fuel oil (RFO), and distillate fuel oil (DFO), or marine distillate oil (MDO) as the DFO is commonly termed in the report. The comparison of changes in environmental impact when a quantity of used oil is handled via each of these pathways for used oil management might be informed through a marginal analysis for environmental impacts.

The timing issue for disposal of used oil in a municipal solid waste (MSW) landfill is discussed in the following section. A discussion of the timing issue for RRBO is provided in the following.

The concern with the environmental impact comparisons among the two combustion and one re-refining options embodied in the LCA’s annual model is that there apparently is no behavioral connection between dispositions for used oil and their environmental impacts in one year versus

following years. For example, the possibility that an increase in purchases of re-refined lube oil might lead to increases in lube oil recycling rates in future years or that a policy change that drives improper disposal down and increases re-refining might motivate increased lube oil recycling.

In the event that behavior is changed in this way used oil that is recycled could have a ripple effect in future years. This ripple or multiplier effect may not be analytically visible in the annual compilations of used oil environmental impacts. This long run multiplier effect for secondary base oil displacement of virgin base oil due to closed loop recycling can be expressed mathematically as the infinite series indicated by Equation [1]:

$$\sum_{n=1}^{\infty} (1 - l)^n = (1 - l)/l, \quad [1]$$

where l is the portion of a gallon of lubricating oil purchased in California that is lost in use, lost to improper disposal, lost to non-re-refining dispositions, and lost during re-refining; and n represents the average time interval over which a gallon of lube oil is used. Intuitively Equation [1] expresses that fact that, on average, the purchase and use of a gallon of lubricating oil in California will yield less than a gallon of re-refined base oil, due to losses in use, improper disposal, dispositions other than re-refining, and re-refining processing losses. This is expressed by the first term $(1 - l)$ in the infinite sum given by Equation [1]. Purchase and use of this $(1 - l)$ gallons of used oil, $(1 - l)$ of which may in turn be sent after use for re-refining, will then yield $(1 - l) * (1 - l) = (1 - l)^2$ gallons of re-refined lube oil in period 2, which is the second term in the infinite sum. This re-refining loop can continue indefinitely, assuming users of re-refined oil always recycle their used oil when they change it themselves, or otherwise take their vehicles to oil change service providers who always recycle used oil.

Fortunately, Equation [1] has a solution that tells us how many gallons of re-refined lubricating oil can potentially be spawned or motivated by re-refining one gallon of used oil in period 1. The infinite sum has the closed form indicated on the right hand side of the equal sign as long as $0 < l < 1$. For example, if $l = 0.2$, then re-refining one gallon of used oil will over time yield 4 gallons of secondary base oil to displace virgin base oil. If $l = 0.4$, then the secondary base oil yield from recycling would be 1.5 gallons. This does not necessarily mean that the base case or extreme scenario calculations for re-refining are incorrect. They could be exactly correct for the first year of the switch from marine distillate oil (MDO), recycled fuel oil (RFO), or illegal disposal to re-refining. But they may understate the long run benefit of the re-refining pathway.

To get an estimate of the excluded multiplier effect, the following estimates from the extreme scenarios GaBi Envision model were used – 65 percent of a gallon of collected used oil that is sent for re-refining ends up as secondary base lube oil, 91 percent of a gallon of collected used oil that is sent for recycling into fuel oil ends up as RFO, and 52 percent of a gallon of collected used oil that is distilled ends up as MDO.

Suppose a gallon of used passenger car motor oil is diverted from improper disposal each year. Given the 65 percent processing yield for re-refining, the displacement of passenger car motor oil production is 0.65 gallons in the first year plus another 0.25 gallons of future displacement motivated by that first year's diversion of a gallon from improper disposal. The 0.25 gallons takes into account the 19 percent use loss for passenger car motor oil (from Table 7 in the UCSB final report) by setting $l = 0.65 * 0.81 = 0.53$ in solving Equation [1]. Hence, eventually 0.90 gallons of

passenger car motor oil production will be displaced from diverting a gallon of used oil from improper disposal. This yields a multiplier of 1.4 ($=0.90/0.65$).

The 0.90 gallons of re-refined oil produced over time from recycling one gallon of used oil in year one compares with the diversion of 0.91 gallons of recycled fuel oil or 0.52 gallons of marine distillate oil. In other words, for this example, re-refining has the additional benefit of diverting an additional 0.25 gallons of lubricating oil production that does not appear to be accounted for in the annual formulation of the life cycle assessment model.

Caveat

According to the system boundary shown in Figure 1 in the Final Report (UCSB 2013), lubricant sales and use are not included in the system boundary used by the LCA. Because of this exclusion one might argue that future years' closed loop re-refining spawned by re-refining a gallon of formerly improperly disposed lube oil or by switching to re-refining from processing for recycled fuel oil or marine distillate oil in a current year are also outside the system boundary. The idea is that the LCA is only intended to measure annual environmental impacts within the system boundary and decreases in virgin lube oil sales and increases in secondary lube oil sales over time are not in the system boundary. Further, one might point out that a lube oil gallon sold in a future year can have the same processing fate regardless of whether the gallon is virgin or secondary.

So why is the future re-refining that might be spawned by current re-refining important? To answer this question it may be important to determine the question(s) that the UCSB model might be asked to answer. Suppose the question is: How will the California used oil management system's environmental impacts evolve over time given likely trends in prices for virgin and secondary used oil and prices and costs for the three processing options? Assuming all processing and combustion emissions parameters are accurate and predictions for parameter changes over time are accurate, the model seems an excellent choice for answering that question when used in combination with economic modeling that accurately portrays the future paths and feedback loops for prices and quantities.

However, if the question is about what processing option would be most beneficial if a policy to decrease improper disposal were instituted, or a policy to direct all passenger and light truck used oil to re-refining, then the concern would be that the UCSB model, even in combination with the economic modeling, may not adequately reflect the environmental impacts of the additional re-refining that is motivated by re-refining in an initial year.

Closed-loop versus open-loop recycling is described in Appendix E. Based on these descriptions, it is clear that a preference between either recycling approach will depend on the system at hand; there is no general rule as to which is better. Nevertheless it is important to hold a high standard for displacement. Products that compete in sectors that suffer from chronic over-production may not displace anything at all and simply constitute a net increase in overall production. More market information would be needed to determine whether there is actually a 1:1 displacement ratio between virgin and recycled base oil. A short justification could strengthen this argument, perhaps in the appendix that describes displacement factors in more detail.

The goal of scope of the Final Report states that this study is being conducted according to the ISO 14040:2006 and ISO 14044:2006. Furthermore, it is mentioned that the results of the study are intended for use in comparative assertions to be disclosed to the public. Consequently, the report shall comply with reporting requirements for comparative assertion described in Sections 5.1, 5.2 and 5.3 of the ISO 14044 standards. A review on the goal and scope section of the Draft Report showed that some requirements had not been fulfilled. For example, omissions of processes or

cut-off criteria for initial inclusion of inputs and outputs were not presented in detail in the Draft Report. The Final Report does include an entire section outlining the cut-off criteria.

A list of omitted processes should indicate whether infrastructures, capital goods, or employee commuting have been included or not. The Final Report notes that infrastructure, water, and land use change have been omitted, suggesting that capital goods and employee commutes have also been excluded. Furthermore, the cut-off criteria are essential to understand the level of completeness of the life cycle assessment (LCA) model. They also describe the level of detail that was sought by LCA practitioners during the data collection phase. In general, a default 1 percent cut-off on mass, energy, and environmental relevance are used when collecting data on subsystems. The authors should mention if they believe that some processes or flows could have been omitted with a contribution above these default criteria and in this case discuss of the potential impact of this omission on the results.

An example of flow that should be documented as a cut-off and more thoroughly discussed is the fact that transfer losses were not assigned any environmental impacts (see Section 4.3.2.4). Because the transfer loss is 1.35 percent, this value is already above the 1 percent that is generally used as default assumption.

Here is an additional list of issues that were identified in the goal and scope and life cycle inventory analysis sections.

- Flows of ethylene glycol are reported for Extreme ReRe scenario in Table 26 of the Final Report. However, Section 1.2.2 indicates that ethylene glycol is actually associated with marine distillate oil (MDO) production. Table 165 indicates that both MDO marine distillate oil and ReRe processes generate ethylene glycol. Finally, neither Figure 2 (MDO) nor Figure 3 (ReRe) in the Final Report present outflow of ethylene glycol. This is quite confusing and would benefit from additional clarification.
- The literature review provides an interesting and relevant summary of previous findings regarding used oil LCA. However, this exercise would be even more useful if the authors would have provided a general conclusion about the main disagreements and similarities between the conclusions of these studies. Another interesting step would be to compare the literature conclusions with the ones of this study.
- In order to avoid any misperception, one reviewer suggests than the scope of the consequential modeling be better explained in the goal and scope (which is essentially limited by the use of the Direct Impacts Model). While system expansion is commonly presented as a consequential approach in the literature, most LCA studies that use this approach for solving system multi-functionality are not defined as consequential LCA. Clarification about the modeling approach is considered important because a more thorough consequential approach would have included marginal data and rippled effects in the long term could have significant impact on the results. This observation could also be discussed in the limitations and the interpretation of the results.

Life Cycle Inventory Modeling

The discussion in this section follows the outline of the UCSB report. As a minor editorial comment, there are some instances in this section in the UCSB report in which an inappropriate use of future tense occurs.

Used Oil Management System

The used oil management system was estimated from the material flow analysis (MFA). This combined data from waste manifests from the California Department of Toxic Substance Control (DTSC) and other organizations. The rationale for the collection assumptions and values seem appropriate. However, more information on how data on load sizes and transport distances were extracted from the manifests would be useful in evaluating assumptions for inter-facility transports.

Overall, the report's MFA seems quite thorough. Potential issues are:

- The fate of improper disposal includes guesstimates that were not clearly identified in the Draft Report, but better detailed in Appendix C of the Final Report.
- The effect of the MFA with changes in oil processing system depends on results from the economics team.

The used oil management system in the advance UCSB Draft Report has a clear and transparent description of the materials flows, which also appears to be consistent with that in the GaBi Envision model. However, better clarification is needed for the data used to identify improper disposal fates and metadata for the various values embedded in Envision would help achieve this goal in the next draft of the UCSB report. The Kline report (Kline 2012) should help clarify many of the questions that arise regarding data sources and assumptions. Appendix C of the Final Report also helps clarify the assumptions.

The section on limitations in the Draft Report needed to be more detailed. For example, what are the actual limitations in data, methodological approaches, and sensitivities over time for changes in the mass balances in the overall product flows within the system boundaries. The limitations were better described in the Final Report.

In addition, sensitivity analyses are missing from the advance UCSB Draft Report. When they are included it will be important to identify the sources of uncertainty for the areas identified.

Material Flow Analysis

In the description of the functional unit in this section, it is noted that data were collected from 2007 to 2010 and that 2010 was chosen as the base year. It would be clearer if a justification were added in the initial discussion of the choice of base year, though slightly more information on the choice for the year 2010 is given in subsequent discussion. More detail describing this justification would be more helpful, as no justification is provided in the Final Report. For example, if there is a need for a future life cycle assessment of used oil, what criteria would be used to justify a future base year?

Appendix A details a well-developed methodology and well-justified data sources. More discussion on the quality of the data kept by DTSC would be helpful. Public records information reported to government agencies can contain numerous clerical errors. Does DTSC suggest that

there would be no such errors, or was anything done to assess the adequacy of the data kept by the agency? There are no comments on the quality of the DTSC data in Appendix A.

Table 17 and Table 26 of the Final Report present mass flow inventories that do not balance. It is possible that these tables do not present all the flows and parameters required for calculating the balances, but there are some peculiar figures. For examples:

- In Table 26, why does the quantity of used oil reprocessed between base year and extreme scenario change?
- In Table 26, the quantity of used oil reprocessed is likely provided in wet basis and secondary production quantities seem to be in dry basis. If this is the case, how can you produce 325 million kg of recycled fuel oil (or RFO) (dry basis) with 357 million kg of reprocessed used oil (16.5 percent moisture, wet basis)?

It is strongly recommended that these tables be reviewed. A more structured presentation of the flows with consistent use of the same basis (wet vs. dry) would be helpful to understand the reference flows of this study.

Electricity and Fuels Production and Distribution

The lack of non-fossil energy data in the electricity model seems problematic. There are several reliable estimates of the carbon intensity of electricity for California. Will average or marginal emissions factors be used? If marginal are used, would they be for power system expansion (combined cycle gas turbine) or intermittent peak (24-hour peak capacity) demand (single cycle gas turbine)?

Freight Transport

What was done: UCSB used transport modules in GaBi. Cargo capacity combined with emission data determine transport impacts.

Comment: The data in GaBi do not appear to correspond to transport of heavy goods such as oil. The cargo capacity for an 80,000 GVW truck is 25 metric tons. Truck fuel economy is 4 to 5 mi/gallon. The energy intensity of rail (GREET data) is 370 Btu (LHV)/ton-mile. These well know parameters should be consistent with the model inputs.

Emissions from CA EMFAC should be compared to the data in GaBi.

Analysis:

Transportation represents an important component of the used oil processing system as well as the system of substitute products from used oil recycling. Most transport is accomplished with medium duty trucks, heavy duty trucks, and rail car.

Emission factors for the transportation of any commodity via on-road vehicles (e.g., medium- and heavy-duty trucks) can be obtained from the ARB emission factor database, EMFAC (ARB 2013). These emission factors are generally expressed as grams per mile (g/mi) factors, and

need to be converted into grams per Megajoule (g/MJ) units using the fuel economy of each class of vehicle (mpg) and the heat content of the fuel (MJ/gal). A further conversion to mass emissions per mass of transported product (for this study Used Oil (UO), UO products, and corresponding petroleum-based products: recycled fuel oil (RFO), heavy fuel oil (HFO), marine distillate oil (MDO), and diesel fuel) is needed for incorporation into the total life cycle emissions associated with the management of used oil. This requires the energy intensity of the transport mode (e.g., MJ/kg-km, or Btu/ton-mi) and the transport distance (km or mi). Table 2 gives the parameters for expressing EMFAC emission factors in g/mi as mg/tonne-km (tonne is the metric ton, equivalent to 1.1 ton). Having emission factors in terms of mg/tonne-km only requires a specified transport distance to give an emission factor expressed as mg emissions/tonne UO or UO product.

Table 2. Input parameters for calculating emission factors

Parameter	Transport mode		
	HD truck	MD truck	Rail
Fuel economy, mpg	5.0	7.3	-
Cargo capacity, ton	25.0	10.5	-
Energy intensity (haul and back haul),			
Btu/ton-mi	1,028	1,676	370
MJ/tonne-km	0.741	1.209	0.267

Transport modes

What was done: UCSB used material flow analysis for transport modes and distances and reported quantities transported (metric tonne) and total distance transported (metric tonne-km). Quantities transported and origin/destination from manifests.

Comment: Detail difficult to wade through. UCSB attempts to reach mass balance closure; needs to present interpretable results. Data from different sources needs reconciliation

Reprocessing

Reprocessing Data Sources

Much of the data for reprocessing used oil in the UCSB study is confidential, and was not available to the reviewers. Therefore, the reviewers were unable to consider the detailed data on which the model inputs are based. However, it is possible look at the model results in comparison with other studies. These studies include those of Boughton and Horvath (2004), who used a Life Cycle Inventory approach to compare three types of used oil reprocessing in California: re-refining, distillation, and production of RFO; and Kalnes, et al. (2006) who conducted an LCA of a specific used oil re-refining process. Studies providing data on the production of virgin base oils include Cuevas (2010), Girotti, et al. (2011) and Worrell and Galitsky (2005). These studies inform the comparisons made in the following sections.

Products

The UCSB Final Report identifies several products resulting from the reprocessing of used oil. Depending on the process used, the resulting products are:

- Re-refined Base Oil
- Marine Distillate Oil
- Recycled Fuel Oil
- Other fuels (light ends)
- Asphalt flux
- Ethylene glycol

These products are listed in Table 15 of the UCSB report, along with the quantities of each produced in the 2010 Base Year and each of the three scenarios analyzed. The nature of the materials and their yields for each scenario appear to be generally consistent with the published literature.

Displaced Products

The reprocessing and use of collected used oil results in the displacement of other products. Depending on how the used oil is reprocessed, one or more of the following products may be displaced:

- Virgin Base Oil
- Diesel fuel (No. 2)
- Heavy Fuel Oil (No. 6)
- Natural gas
- Bitumen and road oils
- Ethylene glycol

All of these products, except ethylene glycol, are produced by refining petroleum. The quantities of each displaced product for the base year and three scenarios are listed in Table 15 of the UCSB Final Report. The quantities of displaced products generally appear reasonable, as they are usually close to or identical to the secondary production figures for the reprocessing.

Displaced Emissions

The UCSB report is based on life cycle inventories for petroleum refining in the U.S. and California. These inventories are described in the report *Crude Oil Refining in U.S. and California* (PE International 2012, referred to hereafter as the PE report). This report references an Excel workbook of inventory data that was also reviewed.

The PE report describes the process for allocating energy and emissions to various refinery products, though the description is fairly general. A comment on the Draft Report noted that specific results for the various refinery products from California and U.S. refineries were not presented in the report. The Final Report addresses this comment by including a detailed

discussion of displacement and how displaced products were incorporated into the life cycle assessment model in Appendix D.

REFINERY EMISSIONS

The refining data used in the model comes from various public databases containing air emissions and water discharge data. These data are then normalized by dividing by the refinery throughput of crude oil to obtain emission factors in terms of mass emitted per kilogram of crude processed.

For both the U.S. and California refineries, the quantity of crude processed is based on refining capacity, that is, the maximum crude throughput under ideal conditions, rather than the actual crude throughput. Since the air emission and water discharge data are based on actual 2010 operations, the calculated emission factors should be based on actual 2010 crude throughput. Actual crude throughput is available for the U.S. from the Energy Information Administration. Corresponding data is published for California in the annual compilations of its Weekly Fuels Watch Reports. These data are summarized in Table 3. As this table shows, the actual crude processed in both the U.S. and California was just 85 percent of the refinery capacity, meaning the calculated emission factors based on crude throughput should be proportionately greater. This difference between actual throughput and refinery capacity is not considered in the UCSB Final Report.

Table 3. Crude oil distillation capacity and throughput for 2010

	U.S.	California
Atmospheric Crude Oil Distillation Capacity, Operable barrels/stream day	17,808,000	1,939,000
Actual Average barrels/day	15,177,000	1,644,200
Actual/Capacity	85%	85%

The PE report provides life cycle impact (LCI) data for a variety of energy products used in this study through the GaBi model. In addition, PE provided a study of refinery modeling for California and U.S. petroleum products. The study provides the basis for LCI data for displaced products including:

- Marine Distillate Oil
- Light hydrocarbons (gasoline)
- Heavy fuel oil
- Diesel fuel
- Lubricant base oil

GREENHOUSE GAS EMISSIONS

The calculated CO₂ emissions factor for oil refining in California is approximately two-thirds higher than the corresponding U.S. figure in the PE report: 0.362 kg/kg crude oil in California versus 0.218 kg/kg crude oil for the U.S. average. While refineries do vary in their energy consumption and emissions depending on the depth of refining, greenhouse gas accounting practices can also have a large effect on the results, and it is not clear whether that is the case with the data included in the report.

Oil refineries typically produce electricity as well as steam in their power plants. These plants may operate as co-generation facilities providing steam to the refinery and selling excess electricity to the grid. Alternatively, the refineries may have captive power plants for the exclusive use of the refinery. In the former case, the emissions from the co-generation facility are only partly attributable to the refinery operations. Such distinctions are often not considered for regulatory reporting, however.

The production of hydrogen releases large quantities of greenhouse gases, but these emissions may or may not be counted in the refinery totals. At the Chevron Richmond refinery, for example, the hydrogen plant emissions are counted in the refinery totals. At Chevron’s El Segundo refinery, in contrast, the Air Liquide El Segundo hydrogen plant reports independently, even though it is a captive facility of the refinery. If the El Segundo refinery included the hydrogen plant’s emission in its total, the refinery emissions would be almost 20 percent greater.

Even if it is not possible to address these kinds of discrepancies within the scope of the life cycle assessment (LCA), they should be noted as a source of uncertainty, and assumptions as to whether displaced products come from U.S. average or California refineries should be clearly stated and documented where possible.

Refining emissions are just one part of the emissions associated with the displaced products. There are also emissions associated with producing, treating, storing, and transporting crude oil to the refinery. Instead of trying to obtain and compare data on each of the processes up to the point of use, a more aggregated look at emissions from displaced use and displaced production for each of the three scenarios is taken. The information in Table 4 is adapted from Table 32 of the UCSB report and is discussed in the context of the three reprocessing options.

Table 4. Global Warming Potential for 2010 base year and three scenarios from UCSB study

In million kg CO ₂ eq	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & hazardous waste disposal	35.9	33.2	33.2	33.2
Reprocessing	56.9	105	49.7	1.39
Use of secondary products	513	76.0	581	972
Displaced use	-508	-76.4	-581	-929
Displaced production	-185	-309	-144	-204
Net results	-87.5	-171	-61.0	-127

REFINERY LCI DATA

The displaced emissions from oil refineries are quite variable in LCA studies. The review team examined the PE data for oil refining and compared well-to-tank greenhouse gas (GHG) emissions as a proxy for emissions intensity since the primary sources of emissions from oil refining are combustion sources. A review of UCSB’s use of the PE data indicated that crude oil transport needed to be added to the model, which was accomplished in the final version of the model as discussed in the Final Report. Examining the data in Table 5 indicates a range in emissions from different studies, regions, and refined product types. The PE analysis shows lower emissions for diesel and gasoline refining than indicated in other studies. This distribution of emissions may be associated with the allocation method for emissions within refineries, although the method is comparable to the approach taken in a study by Jacobs Consultancy (Keesom

2009). PE examined the emission intensity of Group 2 lubricants rather than Group 1 lubricants. According to the study team, re-refining produces Group 2 quality lubricants. Interestingly, the PE approach assigns relatively high emissions to heavy fuel oil (HFO). This emission intensity is associated with HFO being the product of several refinery units.

Table 5. Well to tank GHG emissions from various LCA studies.

Model	US Diesel	US Gasoline	US HFO	US Lube	CA Diesel	CA Gasoline	CA HFO	CA Lube
PE	15.4	18.2	15.5	29.5	17.4	19.2	17.8	31.2
Jacobs	23.2	25.2			>25	>25		
CA GREET (CARBOB)	20.85	21.48	14.82	25.56	19.82	22.74	13.78	25.12
GREET_1	18.89	18.96	12.14			17.16		

Sources: PE International (2012); Keesom, et al. (2009); CA GREET (2009); GREET (2012)

Re-refining

The “Extreme Re-re” scenario corresponds to all of the reprocessed use oil being re-refined to base oil. According to the UCSB study, of the total of 306 million kg of secondary production, 231 million kg, or 75 percent, was for re-refined base oil. This fraction is essentially equivalent to the 72 volume percent cited in Boughton and Horvath (2004).

The UCSB Final Report states that 309 million kg of CO₂e are avoided due to displaced production. This is equivalent to 1.34 kg CO₂e/kg base oil. This figure is in the range of that given by Cuevas for life cycle emissions from the production of virgin base oil: 1.07 kg CO₂e/kg base oil. It is in the range of the figure given by Girotti et al. for the life cycle emissions from the production of mineral base oil: 1.02 kg CO₂e/kg base oil. (Though it should be noted the same study gives a much higher figure for synthetic—polyalphaolefin (PAO)—base oil: 1.92 kg CO₂e/kg base oil.) Thus, we consider the UCSB calculations for global warming potential (GWP) displacement from base oil production to be reasonable.

The emissions resulting from the use of fuels produced along with the re-refined oil is essentially the same as the emission reductions from the fuel displaced (No. 2 oil). Thus, these emissions and reductions have little effect on the net results. An independent check of the magnitude of the GHG emissions from the displaced No. 2 oil agreed within 2 percent of the reported figure.

Distillation to Marine Distillate Oil (MDO)

The “Extreme MDO” scenario corresponds to all of the reprocessed use oil being distilled to produce marine diesel oil, with a large amount of asphalt flux produced as a co-product. According to the UCSB study, of the total of 288 million kg of secondary production, MDO would account for 179 million kg, and asphalt flux would account for 109 million kg.

The UCSB Final Report indicates that use of the produced MDO would result in a GWP of 581 million kg of CO₂eq from the combustion of secondary fuels. This is identical to the avoided GWP from the avoided combustion of displaced primary fuel, No. 2 diesel fuel. Our own calculation of the emissions and reductions was slightly larger — 606 million kg of CO₂eq — but still within 5 percent. And because the emissions and displacement cancel each other out, the difference has no net effect.

Additional emission reductions result from displaced production. This figure accounts for the emissions that occur upstream of the use of the displaced No. 2 oil. (For motor fuels, this would be referred to as the “well-to-tank” emissions). A preliminary review of the UCSB data on refinery emissions related to the production of the displaced oil appeared to indicate that the UCSB emissions were much smaller than indicated by other studies. Emissions from the well to the refinery, however, appeared to be somewhat larger. For this study, the more important figure is the accuracy of the total upstream emissions to the point of use, rather than the individual processes that make up that total.

Dividing the displaced production global warming potential (GWP) emissions (62 percent of 144 million kg CO₂e) by the displaced use emissions (581 million kg CO₂e) shows that the production emissions in the UCSB model amount to 15 percent of the emissions from combusting No 2 oil. This figure is somewhat less than the corresponding figure for the GREET model (California GREET1.8b), which indicates that, for conventional diesel fuel, the upstream emissions to the point of use are equivalent to 27 percent of the emissions from burning the fuel. The GREET figures suggest that in the Extreme Marine Distillate Oil (MDO) scenario, the displaced production emissions for No. 2 oil could be more than 90 percent greater than are reported (170 vs. 89 million kg CO₂e), with a corresponding emission reduction in the net results.

Recycled Fuel Oil (RFO)

The “Extreme RFO” scenario corresponds to all of the reprocessed oil undergoing minimal treatment to be sold as recycled fuel oil. According to the UCSB figures, the 325 million kg of secondary production in this scenario would result in the displacement of 104 million kg of No. 2 oil, 111 million kg of No. 6 oil, and 92 million kg of natural gas. The mix of these fuels is driven in part by market forces that are outside the scope of this review.

Our analysis of the energy content of the displaced fuels and the secondary production of RFO indicated that the energy content of produced fuel and the sum of the displaced fuels matched within 1 percent, thereby indicating the overall reasonableness of the displacement quantities for this scenario.

The combustion of the recycled oil is reported to result in global warming potential (GWP) emissions of 972 million kg CO₂e. This figure appears to be slightly low. Our own calculation, assuming emission characteristics averaged between No. 2 and No. 6 oil results in emissions of 1,033 million kg CO₂e, slightly more than 6 percent greater than the UCSB figure. (Had the emission factor for No. 2 oil been used, our results would still be 6 percent greater than UCSB’s).

The displaced oil emissions reported by UCSB for the No. 6 and No. 2 oils and natural gas amount to 929 million kg CO₂e. Our own calculation agreed with this figure to within a fraction of 1 percent.

The accuracy of the displaced emissions from production of the displaced fuels is more difficult to assess as the reductions in emissions are not reported for each fuel separately. Overall, the upstream production emissions are equal to 19.6 percent of the combustion emissions for the respective fuels. As noted above for No. 2 oil, the GREET model indicates a corresponding figure of 27 percent, and upstream natural gas emissions are often reported to be a similar magnitude. While production emissions of No. 6 oil would be less than this figure, they would have to be far smaller to bring the average value down to that used by UCSB for this scenario. Thus, although we cannot provide a calculation of the extent to which the displaced production emissions in the UCSB analysis differ from those calculated from GREET, it appears that the difference is still significant but in percentage terms not quite as great as for the Extreme MDO scenario. It bears noting that the well-to-tank emission factors for the production of various refinery products used

in the UCSB analysis (taken from the PE refinery model) differ from those defined in GREET (see Table 134 of the UCSB Final Report).

Rejuvenation

Rejuvenation only applies to used dielectric oils. The advance draft report states: “displaced production and use is not modeled for dielectric oil rejuvenation, which is regarded as life time extension.” This leaves two options: dielectric oil is either not yet a used oil, or it is used oil. If it is, then the fraction of the market that is rejuvenating dielectric oil is a variable in the model with market volume and production impacts that need to be evaluated. This market impacts may still be negligible and, therefore, disregarded, but only if the evaluation proves this to be the case. More context is needed.

Dispose as Hazardous Waste

The data discussed in the UCSB report regarding this topic were for 2010. A brief note on why 2010 data were deemed to be representative of all years would be helpful. There is no reason to suspect that 2010 is not a representative year, but a short note to substantiate this assumption would suffice.

The biological degradation of the carbon in used oil disposed in an anaerobic municipal solid waste (MSW) landfill to methane and carbon dioxide is likely to be quite slow. Oil that reaches an MSW landfill in any year is likely to produce little or no methane in the year of its burial. Hence, there are two questions for the UCSB study:

- What is the methane generation potential for the carbon in used oil?
- How should that methane generation be modeled under the static annual environmental impacts modeling portrayed in the GaBi Envision models?

Morton Barlaz at North Carolina State University has done much work on modeling degradation versus long term storage of the biogenic carbon in biogenic carbon containing materials buried in an anaerobic MSW landfill. He may have some insights on the likely fate of the fossil carbon in used oil buried in an MSW landfill. He may also have some insights on the fate of used oil disposed in the typical hazardous waste landfill. This may be helpful in deciding how to estimate methane release from illegal disposal in an MSW landfill or legal disposal in a hazardous waste landfill. The methane benefits of decreasing disposal of used oil, whether legal or illegal, need to accurately reflect the short term methane generation rate for methane from used oil, rather than a long term release rate that will only occur over 100 years or more. At a minimum, the model should reflect the difference between short- and long-term methane reduction potentials from policies to decrease landfill disposal of used oil.

Improper Disposal

Section 4.10.3 of the UCSB report on used oil combustion with municipal solid waste (MSW) in MSW incinerators assumes there are no hydrocarbon emissions from burning used oil. This seems highly unlikely given start up and shut downs, upsets and the days when MSW arrives with very high moisture content. In all these situation complete carbon and hydrocarbon combustion seems likely to be inhibited. There are several data sources for MSW incineration emissions available—e.g., AP-42 (EPA 1995), the EPA/RTI MSW Decision Support Tool (DST) database; and emissions data reported by the three California incinerators (or surrogates such as Metro Vancouver MSW incinerator in Burnaby, British Columbia, the Marion County MSW incinerator in Oregon, and the several MSW incinerators in Massachusetts). Although these emissions may be small and not rise to the level of a regulatory limit, they should still be addressed in an LCA.

In many cases, life cycle assessments are comparing activities or management options that all meet regulatory standards and it is the low level pollutant emissions that can accumulate to favor one option over another in terms of environmental impact.

Assumptions used in the improper disposal model seem appropriate in general. The Appendix C illegal dumping model also seems well reasoned given the lack of information.

In Section 11.2.5 of the UCSB report there is some concern that the model, by the way it distinguishes coastal from inland counties, may underestimate impacts to freshwater, assuming the final disposition is the ocean. The 81 percent disposal in seawater seems far too high. Santa Cruz County, for example, has a large coastline. But it also has several long freshwater courses that improperly disposed oil pass through en route to the ocean. This is mentioned and could be modified with a few basic assumptions about how some oil might be retained in freshwater system. By default assuming 81 percent goes to the ocean seems to be an over-estimate. However, there does not seem to be an objective rationale for changing this approach. Given that most toxicological studies look at freshwater impacts, the impacts on oil disposed in ocean water may be over-estimated according to the UCSB team. This seems like an appropriate tradeoff.

Pathways for Improper Disposed Oil

The model for improperly disposed used oil is divided into three principal pathways: waterway (W), landfill (L), and soil (S). According to the UCSB report, no information was available to suggest how much oil is disposed of by each pathway, and thus each of the three is modeled with equal weight (33 percent). A brief review of the literature shows that there are reports that may give some indication of the amount oil entering these pathways, and thus provide a more meaningful split among the pathways than a simple assumption that the oil enters each equally. For example, the total amount of used motor oil improperly disposed (not including vehicle leaks) was described in a presentation to the March 2004 Used Oil Recycling/Household Hazardous Waste Conference (Browning 2004).

For the landfill (L) pathway, the California 2008 Statewide Waste Characterization Study report (CIWMB 2009) includes data on the tons of used motor oil disposed of as solid waste and the tons of steel in oil filters disposed of as solid waste. Depending on whether the data are for used oil and filters collected through municipal hazardous waste collection programs or represent sample data of municipal solid waste headed to disposal, the data in the report may be used to give a rough idea the quantity of improperly disposed of oil as oil or as residual oil in oil filters.

For the waterway (W) pathway, the California Environmental Protection Agency (Cal/EPA) report on the Characterization of Used Oil in Stormwater Runoff in California (Cal/EPA 2006) provides estimates of the total annual loading of oil and grease to state waters as well as information on the contribution of used oil to the total load borne by runoff. This report also gives an indication of the amount of used motor oil entering waterways from vehicle leaks as opposed to intentional, improper disposal.

The distinction between oil that is leaked into storm drains from vehicles and oil that is intentionally disposed of in these drains is important for two reasons. First, any policy changes related to the handling of oil drained from vehicles will not affect the quantities leaked into the environment from these vehicles. Second, leaks represent a widespread, but low level introduction of the oil into the environment, while intentional dumping to storm drains (or soil) represent a large localized release. The environmental effects of these two different types of releases will also differ. Thus, it is recommended that the two flows to storm drains be accounted for separately.

Improper disposal to soil (S) appears to have received the least amount of study, based on the available literature. Some projections of how much product enters this pathway may be able to be inferred from the difference between the total amount of oil improperly disposed and the estimated amounts entering the other pathways using other studies such as those noted above.

WATERWAY PATHWAY

The model contains a number of assumptions related to the waterway pathway that deserve further explanation:

- Of the oil entering storm drains, 20 percent is assumed to be diverted to wastewater treatment plants. This figure is based on the population of coastal counties with diverted drains, but appears to be applied to the whole state. Also, drain diversion remains a work in progress, and it is not clear that all of the oil in runoff from these communities is diverted. In short, the assumption of 20 percent diversion of oil entering storm drains needs greater explanation and justification. In particular, the estimate seems to be over-representing this flow because it is based on installed capacity, not actual throughput. If these systems only work during dry weather, some accounting of the frequency of operation (frequency of conditions that allow re-directing to wastewater treatment plants) must be incorporated into the probability assessment as well.
- Of the oil entering storm drains, 7 percent is assumed to enter filtered drains. The source for this figure should be cited and the methodology to apply the figure statewide should be explained. In addition, there is no accounting for the filtration system for functionality. There should be an assumption or at least sensitivity for fouled filters, filters not working properly, and the like. This feedback was not addressed in the Final Report, but may be inconsequential given the other assumptions made in the improper disposal model.
- Removal efficiency for the filtered storm drains comes from manufacturer data for one particular type of drain. Some discussion of the relevance of these data to the drains used in California should be given, particularly since the effectiveness of such drains depends highly on how well they are maintained and their age (if efficiency declines with time).
- Treatment efficiencies for wastewater treatment are reported to come from the U.S. EPA Risk Reduction Engineering Laboratory (RREL) Treatability Database (for oil diverted to wastewater treatment plants, <http://iaspub.epa.gov/tdb/pages/contaminant/findContaminant.do>), which is a database for drinking water treatment. It is not clear that the treatment efficiencies reported in this database are relevant to California wastewater treatment plants.

The ratio of used oil disposed to freshwater versus seawater seems too small, as mentioned above. The methodology used to justify the ratio assumes that San Francisco Bay Area counties are coastal counties when much of the region drains freshwater. The impacts to freshwater are therefore underestimated. There is mention of used oil passing briefly through freshwater in these coastal counties, but the time used oil spends in freshwater in coastal counties is probably much higher than the zero currently allotted to it. This could have significant impacts because the quantities of used oil would have more ecological impacts in freshwater bodies than in the ocean.

LANDFILL PATHWAY

The landfill (L) pathway represents used oil disposed of in municipal solid waste (MSW). The model seems to assume that all of the municipal waste is landfilled, with some residuals being incinerated. (The pathway to incineration is through landfilling). California has several waste-to-energy plants, however. Even though the actual and potential amount of waste oil that could be

directly combusted in these facilities is small, it would be more accurate to include the direct combustion of the oil in the model:

- The Columbia University Municipal Solid Waste Database: (<http://www.seas.columbia.edu/earth/recycle/>) indicates 1.2 percent of California’s MSW is combusted in waste to energy plants.
- The total capacity of the three MSW waste to energy plants in California amounts to approximately 3 percent of the amount of waste landfilled in 2011.

In addition, Section 4.10.3 of the UCSB report states that the landfill gas emission capture efficiency from the landfill is 30 percent in 2010, with the value increasing over the next 20 years. However, the GaBi model uses 25 percent for 2010, 75 percent for 2015 and 90 percent in 2020. In addition to the disagreement between 2010 values, one reviewer questions the wisdom of using the projected values in the GaBi model. The increase from 25 percent (or 30 percent) to 75 percent seems unlikely and should be justified.

Moreover, given the 20-year time horizon, the question arises concerning which IPCC global warming potential (GWP) is used to incorporate methane into the greenhouse gas impact calculation, the 20-year GWP or the 100-year GWP?

IMPROPER DISPOSAL SUMMARY

In summary, the improper disposal of used oil is an important pathway that in the model that deserves further explanation. Rather than simply assuming key values in the modeling of this pathway, the literature—particularly studies relevant to California—should be reviewed more thoroughly to make use of the information in them. In this way, the starting point for the sensitivity analysis will be past research rather than raw assumptions.

In addition, the terminology used for describing the informal management extreme management sensitivity analyses is somehow misleading. These are not four extreme scenarios; rather, it is a single extreme scenario with four different sensitivity analyses on its main parameters.

Oil Demand and Collection Categories

The quantities of used collected in California are important inputs into the model because the quantities of oil improperly disposed of are calculated as the difference between oil demand, and used oil collected and otherwise accounted for. The UCSB Final Report identifies three categories of oil demand: passenger car motor oil, heavy duty motor oil, and industrial oil. The report states that the first two categories correspond to “lubricating oils” as defined for California’s Used Oil Recycling Program (CCR Section 18601), while the third category corresponds to the regulatory definition of “industrial oil” plus dielectric oils.

Section 4.7 of the advanced Draft Report states that the demand for industrial oil in 2010 amounted to 82.7 million gallons. If the intent of this figure is to correspond to the regulatory definition of industrial oil plus dielectric fluid, then it appears to overstate the actual quantity. The reason for this overstatement is that the figure of 82.7 million gallons is based on the definition of industrial oil used in what has become known as the Kline Report (Kline 2012 Confidential and Proprietary), which differs from the CalRecycle definition. The Kline definition of industrial oil, for example, includes consumption in stationary and mobile industrial internal combustion engines. By California regulation, these are considered “lubricating” oils rather than industrial oils (CCR 1860.1).

The Kline report recognizes the differing definitions of industrial oil, and provides an adjusted figure to correspond with CalRecycle's definition. That figure is 63.4 million gallons for 2010, or almost 20 million gallons less than used in the UCSB report. However, the Final Report provides sufficient explanation justifying the quantity employed.

Improper Disposal Model

The UCSB report presumably (needs to be clarified) assumes that 15 percent (0.3kg/2kg) of the improperly disposed used oil goes directly to a municipal solid waste (MSW) landfill. Of the remaining, the report assumes half (50 percent) goes into the soil and half is spilled onto road surfaces (asphalt), which ultimately becomes found in storm water runoff. As noted above, 81 percent of this runoff represents discharges to seawater, the remainder to fresh water, wastewater treatment, or landfill.

The UCSB report does not mention direct flows into water bodies as a potential fate. The report seems to assume that dumping passes through storm drains and sewers, which only exist in incorporated areas of California. It would be more appropriate to assume a portion directly enters waterways without passing through storm drains and sewers. This is important due to the filtration assumption in the current improper disposal model. There should be a water route that directly leads to deposits in fresh or ocean water.

Other comments on the direct discharge to water pathway are:

- Clarify why it matters if disposed oil is deposited on agricultural soil or industrial soil (are these limitations imposed by the impact category?). In section 11.2.8 of the Final Report it is noted that this is an unimportant distinction, so does not warrant more clarification. .
- Is there a better way to develop a weighting between the proportion splits between soil and water? This will be an important sensitivity to analyze and should involve scenarios where all (or maybe 90 percent) or emissions go down each pathway. Based on the comments in section 11.2.8 it appears that this is not an important sensitivity.
- The fate of the unfiltered improperly disposed oil sent down the storm drain was unclear in the Draft Report. Because fates are determined by the TRACI model, this did not warrant being addressed in the Final Report.

Valence state of metals

The TRACI 2.0 model that is employed for environmental impact characterization requires that metal valence be identified in its characterization factors for metals, particularly chromium and vanadium. There was some discussion of the hexavalent chromium (Cr^{+6}) being overestimated because Cr^{+3} is more commonly a product of combustion. Further research on the long-term fate of chromium should be done here. Some brief research by a review team member shows that with minimal effort (UV irradiation, increased temperature) Cr^{+3} can become Cr^{+6} , while the remediation research suggests going in the other direction (reduction of Cr^{+6} to Cr^{+3}) is quite challenging. This emphasizes the need for metals valence data for discharges and their ultimate fate should be investigated.

Feed and Product Transport

The UCSB report notes that GREET emissions factors were changed to reflect conditions. Discussion regarding how these emissions factors differ from the California-modified GREET emissions factors used in California's low carbon fuel standard should be provided.

In addition, in instances in which transport emissions factors will vary over time, will these be based on emissions from new vehicles produced? Or an average from the fleet at any given time? This characterization could use better clarification in the Final Report. In the Final Report it is noted that the emissions factor takes into account fleet turnover.

Emission Factors and Life Cycle Data

This section describes the reviewer's comments on emission factors and life cycle data. The emissions factors that received the greatest attention were for combustion emissions. In part to address these UCSB developed a combustion emissions model that focused on a comparison of the emissions of recycled fuel oil (RFO) to heavy fuel oil (HFO) derived from petroleum refining. Combustion emissions factors derived from this model, combined with data to support combustion model development, and data from other sources were documented in the advance draft report. Thus, the critical review effort focused on these two elements: the combustion model and the set of emission factors documented. These reviews are summarized in the following subsections.

Combustion Emissions Model

As noted in UCSB's documentation, the combustion of used oil is a significant contributor to the overall environmental impacts of the used oil management system studied, although existing life cycle inventory databases were found to be inadequate with respect to accurately representing these processes. The UCSB study team therefore developed a detailed, parametric combustion model for RFO and HFO for the life cycle assessment (LCA) based on a review and analysis of various data sources, primarily existing literature and public databases, as well as some proprietary databases and with stakeholder consultation. The majority of the data were from 2006 or more recent. The model considers both the composition of the used oil burned and the combustion technology based primarily on U.S. fuels and practices. Where applicable, air pollution control technologies are also considered. Combustion of used oil, RFO, and distillate co-products are modeled in comparison with the combustion of primary fuels assumed to be displaced by these co-products. These included No. 2 distillate, No. 6 residual oil, and natural gas. Except for differences due to fuel composition, MDO produced from used oil was assumed to combust identically to primary MDO. The results of the combustion model are emission factors and retention rates, by combustion technology and fuel type, for criteria and toxic air emissions resulting from the combustion of recycled (re-refined) fuel oil and heavy fuel oil.

The combustion model was developed around a set of fuel-specific emission factors for eight key combustion pollutants, and technology-specific retention rates for selected elements and compounds whose emission factors are dependent on fuel composition. No new primary data collection was performed for development of the combustion model. The modeling of fuel combustion is therefore limited by data availability and relevance.

Based on the significance of combustion emissions to the model results and the uncertainty in the data, sensitivity analyses were conducted for both emission factors and retention rates using upper and lower bounds for emission factors and retention rates based on analysis of primary data. Additionally, due to the uncertainty of the limited data for used oil combustion, ranges of emissions factors and retention rates, by fuel type and combustion technology, were also estimated and used in sensitivity analyses.

A detailed review of the report's RFO and HFO combustion model is provided below. The review considered the overall modeling methodology and data analysis used, as well as data sources with respect to completeness, representativeness, and applicability. While the overall output of the combustion model has not changed from the draft version (i.e., emission factors and retention rates by combustion technology and fuel type for criteria and toxic air emissions from the combustion of RFO and HFO), the development of the model has been revised with respect to

documentation of data sources, model implementation and data analysis. The draft combustion model and documentation were distributed for review to the critical review team and interested stakeholders and where appropriate, input and comments received from the stakeholder review of the draft were incorporated into the final version of the recycled fuel oil (RFO)/heavy fuel oil (HFO) combustion model. The revised combustion model documentation is a marked improvement over the draft version and provides a more focused and detailed description of the modeling methodology, data sources and analyses, and results including comprehensive graphical summaries of combustion emissions data by fuel type, fuel composition, and combustion technology. Estimated emission factors and metal retention rates from the model, including expected upper and lower bound estimates, are well summarized in tabulated and graphical formats. Additionally, limitations associated with the methodology, data sources, and results of the combustion model are summarized in the Final Report.

Modeling Methodology

IMPLEMENTATION

The methodology implemented in the final version of the combustion model was not significantly altered from the draft version and was developed to meet the following objectives:

- Empirical basis—develop credible and scientifically-sound estimates of emission from used oil combustion based on data and measurement from primary data sources;
- Incorporation of fuel composition—develop fuel-specific estimates due to expected differences in emissions associated with differences in used oil composition;
- Parametric model implementation—large uncertainty in the limited data and wide disparity among data sources require evaluation with sensitivity analysis facilitated by a parameterized model structure
- Consistent use of lower heating value (LHV) equivalency—emission factors based on consistent use of the LHV for fuels, considered indicate of the functional utility of the fuel for modeling displacement (This reviewer notes an inconsistent reference to the higher heating value in the combustion model documentation (Section 10.2.4), which is assumed to be a typographical error)

The modeling approach separated combustion emissions into three categories: emission calculations based on retention rates, calculations based on average emissions factors by fuel type only, and emission calculations based only on technology. These categories are intended to describe the modeling approach taken for a given emission, not the flow's inherent properties. The division is made for modeling simplification purposes.

In the UCSB model, combustion emissions are calculated per mass of fuel burned with emission factors expressed as mass of pollutant emitted per mass of fuel burned. While certain emissions, such as heavy metals, can be estimated based on fuel composition and retention rates for different combustion technologies, given the lack of extensive data many of the emission estimates are an average of all the representative emission data available for a given fuel. In a few cases, the type of combustion source and any associated control technologies are the critical factors in determining emission rates and were therefore estimated based on combustion technology alone. The emissions estimation methodology used for the combustion model based on composition, and/or technology-dependence, represents a trade-off between technical accuracy and data collection efforts and is a reasonable modeling approach for the study.

COMBUSTION TECHNOLOGIES

As discussed in AP-42 (EPA 1995), the primary types of fuel oil burned by combustion sources include distillate oils and residual oils. These are further distinguished by grade numbers, with Nos. 1 and 2 being distillate oils while Nos. 5 and 6 are residual oils. Fuel oil No. 4 is typically either distillate oil or a mixture of distillate and residual oils. Distillate oils are more volatile and less viscous than residual oils. They have negligible nitrogen and ash contents and usually have low sulfur content (by weight). Distillate oils are used mainly in domestic and small commercial applications, while residual oils are used mainly in utility, industrial, and large commercial applications. The recycled fuel oil (RFO) combustion model developed for the project considered primarily those combustion technologies associated with the heavier residual fuel oils for the development of emission factors and retention rates.

UCSB reviewed emissions and emission factor data from a number of sources (discussed below) for combustion devices/technologies which support the use of liquid petroleum fuel oils. These include industrial boilers, commercial/institutional boilers, space heaters, asphalt plant kilns, cement and lime kilns, and steel production blast furnaces. Where applicable, combustion devices which incorporate the use of various air pollution control (APC) technologies are also included in the analysis. The heavy fuel oil (HFO)/RFO combustion model estimates technology-specific average emission factors and retention rates for criteria pollutants, particulate matter, and trace metals based on an analysis of all relevant data for each combustion technology. It was noted that most of the data available for model development were for fuel oils combusted in boilers and this represents a general limitation in the technology-specific emission factors and retention rates. Emission factors are estimated for RFO and its displaced product, HFO (fuel oil No.6), and compared with emission factors for other distillate fuel oils extracted from existing data sources (primarily AP 42 as discussed below).

When considering comments about the relative combustion emissions factors, the UCSB staff should keep in mind that emissions from combustion and the ultimate fate of emissions may yield different values. Concern for example from NORA suggested the sulfur emissions may be too high. Where appropriate, it may be helpful to incorporate more justifications where there are comments from stakeholders.

AIR POLLUTION CONTROL TECHNOLOGIES

The oil combustion model developed for the study considers a number of particulate matter (PM) control technologies based on the available data. These include fabric filters or bag houses; cyclones, in which dust-laden gas is spun in a cylindrical collector that causes large particles to transit to the edges for removal; venturi scrubbers, in which the gas stream is passed through a liquid that absorbs pollutants; and electrostatic precipitators (ESPs), which use static electricity to remove particulates as they pass through an electrical field.

UCSB's analysis of the data showed that, in general, batch asphalt plant kilns utilize bag houses (fabric filter) while cement kiln typically use ESPs for PM emission control. Particulate matter control technologies for large boilers generally include ESPs, venturi scrubbers or cyclones. Although the inclusion of PM emission control technologies in the combustion model is likely more relevant and lead to larger impacts on the estimated results, control technologies for other pollutants (i.e., NO_x, SO₂) should also be considered, or evaluated for use in the combustion model.

In the development and implementation of the combustion model, emissions are calculated as a mix of the combustion and emission control technologies discussed above. The current model implementation requires assumptions regarding the use of RFO combustor PM controls in

California. Table 6 shows the fraction of recycled fuel oil (RFO) combustors in the state by combustor category and presence of PM controls. UCSB indicated the distribution given in Table 6 is based on expert knowledge. While the RFO combustion technology split data shown in Table 6 were provided in the draft combustion model documentation, no reference was made to what data were used in the final version of the model. The authors note the model was developed with variable parameters to allow sensitivity analyses including this combustion technology split for RFO. The default values used in the life cycle assessment modeling scenarios should be noted in the Final Report. The study authors appropriately note the large uncertainty regarding these assumptions requires further review and evaluation with sensitivity analyses.

Table 6. Assumptions applied in LCA for end use of RFO in California.

Combustion Technology	% of RFO Combustors
Atomizing space heater with no control	2.5%
Vaporizing space heater with no control	2.5%
Boiler with control	10%
Boiler with no control	25%
Asphalt Plant with bag house filter	50%
Cement Kiln	10%

DATA SOURCES

The RFO/heavy fuel oil (HFO) combustion model is based on a variety of data sources, primarily existing literature and public databases, as well as some proprietary databases and with stakeholder consultation. Data were collected and reviewed for pollutant emissions and emission factors by fuel type (distillate and residual fuel oil, waste oil, used oil) and combustion technology. Additionally, data for retention rates of trace heavy metals by fuel type/composition, and combustion device were collected and included in the analysis. The data sources used in the model development include:

- MACT—Boiler MACT Draft Emissions and Survey Results Databases. <http://www.epa.gov/ttn/atw/boiler/boilerpg.html>.
- Entropy—Entropy, Inc. for National Oil Recyclers Association. Quantification of Metals Emissions from Burning Used Oil Fuel. Research Triangle Park, NC. 1996.
- Dyke/Lubrizol—Dyke, P. Emissions from Small Waste Oil Burner Burning Drained Lubricating Oil. 2012.
- Shaaban & Salvani—Shaaban, A. H., & Salvani, R. (1996, August). Heat recovery of used petroleum, oil, and lubricants (POL). In Energy Conversion Engineering Conference, 1996. IECEC 96, Proceedings of the 31st Intersociety (Vol. 3, pp. 1950-1955). IEEE
- AP-42 (EPA 1995)—Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources, AP-42, Fifth Edition, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, January, 1995.

- Vermont Agency of Natural Resources—Vermont Agency of Natural Resources, Vermont Department of Environmental Conservation. *Vermont Used Oil Analysis and Waste Oil Furnace Emissions Study*. Waterbury, Vermont. 1996
- GHG Protocol—“Emission Factors from Cross-Sector Tools”, version 1.3 (2012)

The data set used for the draft version of the model included 6,724 distinct measurements of fuel composition or heating value and 3,602 emission measurements, representing a total of 1,003 tests at 302 facilities. Overall, 67 percent of the tests were conducted 2006 or later. Seventy-eight percent of the composition measurements and 71 percent of the emission measurements were from the tests conducted in 2006 or later. These data were updated for use in the final version of the model as documented.

An updated Excel workbook, exported from the Matlab[®] data analysis software used for the model development, was provided with the model documentation for review. A master table of all composition measurements from all sources, reported in uniform units of kg pollutant per kg of fuel, was included, and accompanied by various supporting data sheets and summaries. All relevant data extracted from the sources referenced were included and tabulated by facility, date, data source, combustion device, and fuel type, as appropriate. A summary of the data available and used in the analysis, by fuel type and control technology and sample populations was provided in the model documentation.

As noted above, the combustion model groups emission and emission factors into a limited number of bins by combustion technology, including any applicable air pollution control (APC), as well as fuel type. The data collected and reviewed for the development of the combustion model are summarized below. Data sample counts and data sources are further documented in the UCSB Final Report. Similar summary data tables by air pollution control technology (NO_x or PM control) were also available with the model documentation for review.

A brief review of the various data sources referenced in the development of the recycled fuel oil (RFO)/heavy fuel oil (HFO) combustion model was conducted and is summarized below. A complete summary of the data sources used for the development of the RFO/HFO combustion model, including combustion technology and applicable control equipment, is provided in Table 128 of the UCSB Final Report.

MACT

Area source industrial, commercial, and institutional boilers are subject to rules based on emission limits and maximum achievable control technology standards (MACT) as required under Section 112(d) of the Clean Air Act (CAA) and the national emission standards for hazardous air pollutants (NESHAPs) for major and area combustion sources. Relevant data for the study were obtained through the EPA’s Air Toxics Website (ATW) as two linked databases including data regarding composition of the various fuels used in industrial, commercial, and institutional boilers; stack testing data; and information regarding the boiler devices and any control technologies installed. Each MACT composition and emission data point represents a single facility, parameter, and date of measurement and, for combustion emissions, a specific combustion device. All fuel composition and combustion emissions are converted to consistent set of units (i.e., kg emission per kg fuel combusted) using the lower heating value (LHV) for the fuel as appropriate. The MACT databases provided recent measurement-based fuel composition and emissions data for the development of the combustion model.

Entropy

Entropy completed a report titled “Quantification of Metals Emissions from Burning Used Oil Fuel” for the National Oil Recyclers Association in 1996. This study evaluated the release of metals from used oil combustion. The metal content of the used oil combusted was also considered and results reported in terms of the metal removal efficiency of the combustion technology. Data from this source are directly applicable to the recycled fuel oil(RFO)/heavy fuel oil (HFO) combustion model although it is nearly 20 years old.

Dyke/Lubrizol

This study tested the combustion of used oil in a small vaporizing space heater. Fuel samples are analyzed and emissions of criteria pollutants, metals, dioxin/furans, and organic compounds are reported. Results include fuel composition, and emissions, and metal retention rates for the combustion of two different test samples from 2007.

Shaaban & Salvani

This study conducted for the U.S. Air Force/Department of Defense was published in 1996 and documents composition and emissions from combustion of various type of used oil mixed with diesel in an atomizing boiler.

AP-42, 5th Edition (EPA 1995)

The EPA maintains numerous documents and resources for the development and estimation of emission and emission factors, including various combustion processes in *Compilation of Air Pollutant Emission Factors, Volume 1: Stationary Point and Area Sources*, AP-42, Fifth Edition (EPA 1995). Specifically, Chapter 1.3, Fuel oil combustion, and Chapter 1.11, Waste oil combustion, provide fuel composition information and emission factors for used lubricating oils, distillate oils, and residual oils. Although the fifth edition dates to 1995, EPA periodically supplements and updates the publications. The latest versions of the relevant AP-42 documentation are from 1996 for waste oil combustion and 2010 for fuel oil combustion. These data were considered by UCSB in the development of the combustion model and used when appropriate, specifically for waste oils and heavy residual fuel (for HFO combustion). It is noted that AP-42 air pollutant emission factors, specifically for fuel oil and waste oil combustion, are routinely adopted in various studies and regulations.^{1,2}

Vermont Agency of Natural Resources

Although conducted in 1996, this study provided information and data regarding the combustion of used oil in space heaters including emissions of metals and fuel composition.

GHG Protocol

The Greenhouse Gas Protocol provides estimates of methane and nitrous oxide emissions by fuel type, including used oil, No. 2 distillate oil and Nos. 4 and 6 residual fuel oils. Greenhouse gas emissions were considered independent of combustion technology although both methane (CH₄) and nitrous oxide (N₂O) are known to decrease with increasingly complete combustion.

¹ <http://www.iiasa.ac.at/~rains/PM/docs/documentation.html>

² <http://www.ec.gc.ca/inrp-npri/default.asp?lang=En&n=B66DA62F-1>

DATA PROCESSING AND ANALYSIS

UCSB provided a brief description of each of the data sheets included in the Excel workbook as well as a discussion of the various calculations and data analysis steps used in estimating emission factors and retention rates. Documentation was provided for how the data were grouped, application of any corrections, and handling of non-detects and detection limits. Additional data processing details relevant to understanding the modeling results were further documented for the final version of the model version. The data, processing steps, and model implementation descriptions were reviewed and found to support the combustion model development as documented.

The UCSB combustion model supports four approaches for dealing with non-detects: omit from data entirely, interpret as zero, assume a quantity equal to half the detection limit, and assume a quantity equal to the detection limit. The model currently assumes half the detection limit for all non-detects in which the detection limit is known to the model, both for composition and emission measurements, independent of the data source. Only non-detects in the MACT, Entropy, and Vermont data sources are treated in the current model version.

While the model includes non-detects (when a measurement was performed with no result) in the data, non-measurements (when no measurement was performed) are excluded. The model developers indicated only modest effects on the results due to the approach used and noted possible sensitivity analyses may be include in later versions. A summary of the results for alternative non-detect approaches was provided for evaluation.

In Appendix F, one reviewer suggests that a sensitivity analysis should be employed to the use of the USLCI data, since they are old, and tend to not be very complete. This reviewer suggests using U.S.-Ecoinvent data (Ecoinvent with U.S. background data, or GaBi data for these U.S. energy inputs), to assess the impact of the use of different data sources. That discussion can be added to the section on sensitivities.

This reviewer also suggests that data sources be cited for the primary recycling data. This reviewer also recommends citing suggestions for future research to prevent having to use data with quality 4 and 5 in future research? Data of quality 4 and 5 seem to be inappropriate for use in any life cycle assessment (LCA).

COMBUSTION MODEL SUMMARY

Based on a review of the combustion model and documentation, the methodology used by UCSB in the development of the model—to capture any significant variation among fuel type, combustion devices and control technologies relevant to the study while minimizing total number of groupings—provides a reasonably robust modeling approach to estimating emission factors for recycled fuel oil (RFO)/heavy fuel oil (HFO) combustion given the available data. In general, the objectives of the combustion model for use in the used oil LCA study as documented are satisfied given the limited available data and provide reasonable estimates for the study, as well as a tool for further development and sensitivity analyses.

Overall, the combustion modeling methodology and data were found to be appropriate for the study goals with respect to data quality, including consistency, completeness and representativeness. Although some data used in the model development were older, the RFO/HFO Combustion Model is generally considered representative as fuel compositions and emission controls are taken into account. Additionally, improvements in model documentation and presentation of results and sensitivity analyses have increased the understanding and

transparency of these significant life cycle inventory emission estimates resulting in a more robust and technically defensible life cycle assessment (LCA) study.

Combustion Emissions

The emission factors for combustion are a significant driver for the LCA study. The primary emission factors that affect the study are shown in Table 7. The table shows the source of emissions from some of the components of the used oil processing system and the complementary emission source in the displaced system. These two emission sources exhibit significant variability in the study. In some cases the emission factors in the displaced system are estimated by the UCSB team and in other cases they are from the GaBi model based on the PE study of oil refining (PE International 2012).

Table 7. Sources of combustion emissions in the LCA study

Emission Source	Used Oil System	Data Source	Reference System	Data Source
RFO combustion	RFO burned in cement kiln or asphalt plant	UCSB review of emission studies, metals retention analysis	HFO burned in cement kiln or asphalt plant	UCSB review of emission studies, metals retention analysis
Base Oil Production	Used oil re-refining Natural gas combustion, electric power, fugitives	Data from re-refiners, comparison with used oil studies	Virgin oil refinery. Combustion and fugitive emissions	Data in GaBi based on PE report (PE International 2012)

The four sources of emissions present interesting challenges. Figure 1 shows a comparison of the emission factors for recycled fuel oil (RFO) and heavy fuel oil (HFO) that was presented at the Used Oil LCA Study December 2012 stakeholder meeting. The comparison of emission factors in the figure illustrates several important issues including:

1. Should the NO_x emissions for RFO combustion be twice those for HFO combustion considering that RFO does not contain significant fuel bound nitrogen?
2. PM emissions from RFO combustion are eight times greater than those for HFO combustion. Is this reasonable for these types of fuel oil? RFO contains sludge that accumulates in the crankcase of automobiles. However, HFO also contains heavy components.
3. CO₂ emission factors in some instances appear to be 5 percent off. For example, the CO₂ emission factor for RFO is the same as that for a light hydrocarbon. The CO₂ emission factor for RFO may be correct as some lube oils are composed of saturated hydrocarbons. Nonetheless, data with suspicious CO₂ factors should be more closely reviewed.

The UCSB team has revised the emission factors during the course of the project. The issues identified in Figure 1 should be examined in the final data set used for this study.

Based on these initial observations, UCSB should present the ranges of data that best represent the choice of assumed emission factors. UCSB should also interpret the reasonableness of the data. Why are particulate matter (PM) emissions higher for RFO? Would the solids content of the oil affect PM emissions? Were any fuel characterizations available as part of the emission studies that were examined?

Pollutant	Emission factor, mg/MJ LHV			
	RFO	HFO	MDO	Diesel fuel
SO ₂	1.4	896	16.7	65.4
NO _x	106	58	80.6	38.4
CO	4.94	14	16.8	15.4
PM10	174	20		3.0
PM (2.5-10)	120	4.3	3.3	2.1
TOC	3.2	1.6	0.7	17.8
CO ₂	71,010	78,085	76,167	14,482

2x for same application? →

Missing Category →

Same as light paraffinic HC

These are just upstream emissions. What about combustion?

Figure 1. Combustion emission factors for criteria pollutants and CO₂ (from preliminary presentation)

As noted previously, fuel oil combustion emissions depend on the grade and composition of the fuel as well as the combustion technology, including the type and size of the combustion device, the firing and loading practices used, and the level of equipment maintenance. In general, the baseline emissions of criteria and non-criteria pollutants are measured or estimated as those from uncontrolled combustion sources, i.e., sources without add-on air pollution control (APC) equipment or other combustion modifications designed for emission control. Controlled emissions can be estimated based on baseline emissions and control efficiencies, or by direct measurement and/or stack testing. Typically, control technologies are designed for emission reductions of particulate matter (PM), sulfur oxides (SO_x), nitrogen oxides (NO_x), mercury, or carbon monoxide, or a combination of these pollutants.

Relevant pollutants considered for the used oil combustion model include criteria pollutants, particulate matter (separately), polycyclic aromatic hydrocarbons (PAH), halogenated compounds, greenhouse gases (carbon dioxide, methane, nitrous oxide), and heavy metals.

The following subsections discuss criteria pollutants and toxic air contaminants (TACs) respectively.

Criteria Pollutant Emissions

The criteria pollutants addressed in the Clean Air Act, as amended, are oxides of nitrogen (NO_x), carbon monoxide (CO), sulfur oxides (SO_x), ozone (O₃), particulate matter (PM), and lead (Pb). Ozone is not emitted in any significant quantity from combustion sources, but is indirectly regulated by emission limits on volatile organic compounds (VOC) in many areas of the U.S.

CRITERIA POLLUTANTS OVERALL

Observations on the criteria pollutant emissions factor data discussed in the UCSB report, and as summarized in Figure 1 include the following:

- Tabulated emission factors are not reported in common units; the unit of fuel in denominator is either MJ fuel (higher heating value (HHV) basis), MJ fuel (lower heating value (LHV) basis), L fuel, or kg fuel. Simple, direct emission comparisons frustrated.
- CO₂ emissions should reflect carbon content of fuel and lower heating value.
- Consider an “engineered data set” for some combustion scenarios versus use of “unvarnished” data.
 - Make NO_x emissions same for heavy fuel oil (HFO) and recycled fuel oil (RFO) combustion
 - Assume same CH₄ emissions for RFO as HFO where no data are available
 - Assume same N₂O emissions for Renewable Fuel Standard as HFO where no data are available
 - Do not refer to diesel particulate as dust
 - Address relative PM emissions from RFO compared to HFO combustion
- The combustion model is driving the result.
- Collect raw data, make if viable for purposes intended.
- Emission factors for the criteria pollutants in common units for each used oil (UO) recycling process product are given in Figure 1. These emission factors need to be compared to other routinely used emission factor sets such as AP-42 (EPA 1995) and EMFAC and differences explained. Combustion emissions for criteria pollutants and greenhouse gases are based on existing data sources and generally implemented within the combustion model in a manner similar to particulate matter (discussed below) emissions with respect to combustion technology and applicable control devices. A review of the treatment of these combustion emissions is not included within this report.

What was done: UCSB took emission factor data from different databases. Not only were reported units inconsistent, but the emissions species differed among the different data sources. For example, some had PM10, PM2.5, and PAH emissions, others had speciated organic toxic air contaminants (TACs).

Comment: UCSB should either align the life cycle criteria or perform a sensitivity analysis on the impact of leaving LCI data untouched.

PARTICULATE MATTER (PM)

According to a 2004 DOE study (DOE 2004), “There are few existing data regarding emissions and characteristics of fine aerosols from oil, gas and power generation industry combustion sources, and the information that is available is generally outdated and/or incomplete.”

Additionally, the study notes “Traditional stationary source air emission sampling methods tend to underestimate or overestimate the contribution of the source to ambient aerosols because they do not properly account for primary aerosol formation, which occurs after the gases leave the

stack.” Nevertheless, a limited amount of emission and emission factor data were available from sources cited and used in the combustion model development.

Particulate emissions may be categorized as either filterable or condensable. Filterable emissions are generally considered to be the particulates that are trapped by the glass fiber filter in a particulate sampler. Vapors and particles less than 0.3 microns pass through the filter. Condensable particulate matter is material that is emitted in the vapor state which later condenses to form homogeneous and/or heterogeneous aerosol particles. The condensable particulate emitted from boilers fueled with coal or oil is primarily inorganic in nature. Filterable particulate matter emissions depend predominantly on the grade of fuel fired. Combustion of lighter distillate oils results in significantly lower particulate matter (PM) formation than does combustion of heavier residual oils.

Additionally, particulate matter is generally further categorized by particle size, i.e., particulates with diameters of 2.5 μm and smaller (PM_{2.5} or “fine particles”), and particulates with diameters 2.5 μm to 10 μm (PM_{2.5-10}, or “inhalable coarse particles”). Often particulate emissions are also reported as total PM and/or PM₁₀ (particulates with diameters of 10 μm and smaller, including PM_{2.5}). A clear and transparent distinction among particulate matter measurement data was included in the model documentation.

In general, filterable PM emissions depend on the completeness of combustion as well as on the oil ash content. The particulate matter emitted by distillate oil-fired boilers is primarily composed of carbonaceous particles resulting from incomplete combustion of oil and is not correlated to the ash or sulfur content of the oil. However, PM emissions from residual oil burning are related to the sulfur content since low-sulfur No. 6 oil exhibits substantially lower viscosity and reduced asphaltene, ash, and sulfur, which results in better atomization and more complete combustion.

A number of particulate matter control technologies are used for oil-fired combustion sources. According to AP-42 (EPA 1995), large industrial and utility boilers are generally well-designed and well-maintained so that soot and condensable organic compound emissions are minimized. Particulate matter emissions are therefore more a result of emitted fly ash in such units. Post-combustion controls (mechanical collectors, electrostatic precipitators, fabric filters, etc.) or fuel substitution/alteration are typically used to reduce PM emissions from these sources. Large oil-fired power plants commonly utilize electrostatic precipitators (ESPs) to control PM emissions. In fabric filtration, a number of filtering elements (bags) along with a bag cleaning system are contained in a main shell structure incorporating dust hoppers (a bag house). The particulate removal efficiency of the bag house system depends on a variety of operational characteristics including particle size distribution, adhesion characteristics, and electrical resistivity. Relevant operational parameters affecting collection efficiency include air-to-cloth ratio, operating pressure loss, and maintenance and cleaning practices.

Toxic Air Contaminant Emissions

The toxic air contaminants (TACs) are those constituents regulated as such by EPA (EPA 1990), as well as by ARB (ARB 1999). These include the organic constituents listed in Table 8, and the toxic metals listed in Table 9.

In Appendix B, which details the combustion model, the data sources for the metals retention model seem to be appropriate and its sensitivities to categories of emissions factors for best and worst performing combustion sources (low, default, high) appear appropriate.

Table 8. Organic toxic air contaminant (TAC) constituents (EPA 1990)

Acetaldehyde	Diethyl sulfate	Methylene chloride
Acetamide	3,3-Dimethoxybenzidine	Methylene diphenyl diisocyanate
Acetonitrile	Dimethyl aminoazobenzene	4,4-Methylenedianiline
Acetophenone	3,3-Dimethyl benzidine	Naphthalene
2-Acetylaminofluorene	Dimethyl carbamoyl chloride	Nitrobenzene
Acrolein	Dimethyl formamide	4-Nitrobiphenyl
Acrylamide	1,1-Dimethyl hydrazine	4-Nitrophenol
Acrylic acid	Dimethyl phthalate	2-Nitropropane
Acrylonitrile	Dimethyl sulfate	N-Nitroso-N-methylurea
Allyl chloride	4,6-Dinitro-o-cresol, and salts	N-Nitrosodimethylamine
4-Aminobiphenyl	2,4-Dinitrophenol	N-Nitrosomorpholine
Aniline	2,4-Dinitrotoluene	Parathion
o-Anisidine	1,4-Dioxane	Pentachloronitrobenzene
Asbestos	1,2-Diphenylhydrazine	Pentachlorophenol
Benzene	Epichlorohydrin	Phenol
Benzidine	1,2-Epoxybutane	p-Phenylenediamine
Benzotrichloride	Ethyl acrylate	Phosgene
Benzyl chloride	Ethyl benzene	Phosphine
Biphenyl	Ethyl carbamate	Phosphorus
Bis (2-ethylhexyl) phthalate	Ethyl chloride	Phthalic anhydride
Bis (chloromethyl) ether	Ethylene dibromide	Polychlorinated biphenyls
Bromoform	Ethylene dichloride	Polycyclic Organic Matter
1,3-Butadiene	Ethylene glycol	1,3-Propane sultone
Calcium cyanamide	Ethylene imine	beta-Propiolactone
Captan	Ethylene oxide	Propionaldehyde
Carbaryl	Ethylene thiourea	Propoxur (Baygon)
Carbon disulfide	Ethylidene dichloride	Propylene dichloride
Carbon tetrachloride	Formaldehyde	Propylene oxide
Carbonyl sulfide	Glycol ethers	1,2-Propylenimine
Catechol	Heptachlor	Quinoline
Chloramben	Hexachlorobenzene	Quinone
Chlordane	Hexachlorobutadiene	Styrene
Chloroacetic acid	Hexachlorocyclopentadiene	Styrene oxide
2-Chloroacetophenone	Hexachloroethane	2,3,7,8-Tetrachlorodibenzo-p-dioxin
Chlorobenzene	Hexamethylene-1,6-diisocyanate	1,1,2,2-Tetrachloroethane
Chlorobenzilate	Hexamethylphosphoramide	Tetrachloroethylene
Chloroform	Hexane	Titanium tetrachloride
Chloromethyl methyl ether	Hydrazine	Toluene
Chloroprene	Hydrochloric acid	2,4-Toluene diamine
Coke oven emissions	Hydrogen fluoride	2,4-Toluene diisocyanate

Table 8. Concluded

Cresols/Cresylic acid	Hydroquinone	o-Toluidine
o-Cresol	Isophorone	Toxaphene
m-Cresol	Lindane	1,2,4-Trichlorobenzene
p-Cresol	Maleic anhydride	1,1,2-Trichloroethane
Cumene	Methanol	Trichloroethylene
Cyanide Compounds	Methoxychlor	2,4,5-Trichlorophenol
2,4-D, salts and esters	Methyl bromide	2,4,6-Trichlorophenol
DDE	Methyl chloride	Triethylamine
Diazomethane	Methyl chloroform	Trifluralin
Dibenzofurans	Methyl ethyl ketone	2,2,4-Trimethylpentane
1,2-Dibromo-3-chloropropane	Methyl hydrazine	Vinyl acetate
Dibutylphthalate	Methyl iodide	Vinyl bromide
1,4-Dichlorobenzene	Methyl isobutyl ketone	Vinyl chloride
3,3-Dichlorobenzidene	Methyl isocyanate	Vinylidene chloride
Dichloroethyl ether	Methyl methacrylate	Xylenes
1,3-Dichloropropene	Methyl tert butyl ether	o-Xylenes
Dichlorvos	4,4-Methylene bis(2-chloroaniline)	m-Xylenes
Diethanolamine		p-Xylenes
N.N-Diethyl aniline		

Table 9. Trace metal toxic air contaminants (EPA 1990)

Antimony (Sb)	Lead (Pb)
Arsenic (As)	Manganese (Mn)
Beryllium (Be)	Mercury (Hg)
Cadmium (Cd)	Nickel (Ni)
Chromium (Cr)	Selenium (Se)
Cobalt (Co)	

In Section 10.4.3.4.3, the 80/20 split between trivalent and hexavalent chromium oxidation states may be appropriate for combustion, but for heavy metals and the impact categories it influences most, like toxicity-related ones, the interest is in the fate of metals not the immediate products of combustion. Using ARB's combustion emissions information is not an appropriate justification for the fate of Cr⁺³ in the environment because they refer to the direct output of combustion, not the fate. The Cr emissions valence state split could be used as a proxy, but the question is: How do Cr species change over time in the environment? Cr is an important emission species and its emissions could impact all toxicity-related scenarios (ecotoxicity, health metrics, etc.)

ORGANIC TACS

Most of the organic TAC constituents in waste oil are volatile organic compounds (VOCs) that are destroyed in the used oil combustion process. The rest are in a category termed semivolatile organic constituents that are similarly destroyed in the waste oil combustion process. There is no reason why recycled fuel oil (RFO) combustion emissions would differ substantially from those

emissions from conventional petroleum residual fuel oil combustion. Similarly, there is no reason why marine distillate oil (MDO) combustion emissions would differ substantially from those from traditional petroleum-derived distillate fuel combustion.

The exception to this expectation regards the combustion emissions of chlorinated organic constituents. Of particular concern are the emissions of chlorinated dibenzo-p-dioxin compounds, commonly referred to as just dioxins. The most toxic and carcinogenic of the chlorinated dioxins species is 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). All of the chlorinated dioxin compounds have human health hazard indices (atmospheric concentrations associated with hazardous human health impacts), the lowest being that of TCDD. Thus, chlorinated dioxin emissions from combustion sources are often expressed in terms of a TCDD toxicity equivalent (TEQ). An air emission source TEQ emissions are the weighted sum of the emissions concentrations of all the chlorinated dioxin compounds measured in the emissions stream, weighted by each chlorinated dioxin compound's human health hazard index relative to that of 2,3,7,8-tetrachlorodibenzo-p-dioxin.

Dioxin emissions from chlorine containing fuel/waste combustion are low, usually in the pg/MJ range (EPA 1997), but because of their toxicity, these emissions in terms of TEQ can be of concern from a human health effects perspective. It has been found that dioxin and other chlorinated organic compound emissions vary with the chlorine content of the fuel/waste stream being burned; both emissions increase as the fuel/waste chlorine content increases (EPA 1997). Used oil waste streams usually contain more chlorine than corresponding fuel streams (residual and distillate fuel oils) (EPA 1995). However, waste oil chlorine content of typical used oil is on the order of 0.02 percent, significantly less than the percent or higher levels in chlorinated hazardous wastes, which might result in TEQ emissions from incineration (combustion) of concern. So, used oil combustion would be expected to yield TEQ emissions below any level having any significant human health effects. Even waste used oil with higher than typical chlorine contents should not result in TEQ emissions of significant concern, because waste used oils essentially never have the percent-level chlorine content of hazardous waste streams, which have combustion (incineration) TEQ emissions reaching levels of human health concern. Thus, the combustion of fuel oils will result in relatively low TEQ emissions compared to the combustion of other (chlorinated) hazardous wastes (EPA 1997).

TRACE METAL TACS

In the development of the recycled fuel oil (RFO)/heavy fuel oil (HFO) combustion model, heavy metal emissions were an important consideration due to the relatively high concentration of wear metals from motor engines that may be present in used motor oil, in addition to any elements added to the original lubricant products. It was noted that metal components in the oil are most likely to be released as particulates, subject to combustion conditions and control technologies that affect the release of particulate matter.

UCSB has compiled emission factors for all of the trace metal toxic air contaminants (TACs) listed in Table 9, in addition to several other trace metals not regulated by EPA (UCSB 2012a). These emission factors represent the fractions of the used oil fed to the combustion system that are released from the combustion source as air emissions to the atmosphere. UCSB defines several emission scenarios for each metal constituent. The default scenario has metal emission factors that the UCSB researchers considered to be the most like likely. Then USCBA defined three additional scenarios, termed high, medium, and low air emissions. The definition of each of these scenarios is more complicated than deserves discussion here. Suffice it to note that any discussion of trace metal emissions factors in this report assumes that the UCSB default emission factor

Air emissions of the trace metal toxic air contaminants (TACs) listed in Table 9 arising from the combustion of a used oil stream are determined by the concentration of each metal in the used oil stream and the fraction of each metal emitted in the air emissions from the combustion process as compared to the concentration of the metal in the used oil feed stream. These data are given in Table 10. The fraction of each metal emitted is less than 1 because the combustion system retains some of each metal, usually in the condensed into the particulate retained in the combustor a bottom ash collected or on interior surfaces of the combustor (e.g., on boiler tubes if the combustion system recovers the energy content of the waste oil in the form of steam for use in various applications).

Table 10. UCSB default trace metal emission rates and emissions fractions for used oil combustion

	UCSB Default		
	Emission rate, mg/kg feed	Used Oil Composition	Fraction of feed emitted, %
TAC trace metals			
Antimony (Sb)	0.178	0.438	41.79%
Arsenic (As)	0.702	0.75	96.23%
Beryllium (Be)	0.213	0.22	97.57%
Cadmium (Cd)	0.523	0.537	98.61%
Chromium (Cr)	1.79	1.79	98.08%
Cobalt (Co)	0.234	0.551	42.47%
Lead (Pb)	11.5	18.5	97.86%
Manganese (Mn)	5.61	4.62	39.99%
Mercury (Hg)	0.252	0.252	97.08%
Nickel (Ni)	2.20	4.00	98.06%
Selenium (Se)	0.542	0.542	97.96%
Other trace metals compiled			
Aluminum (Al)	25.4	26.2	96.95%
Barium (Ba)	16.6	17.2	96.53%
Boron (B)	3.96	4.00	50.00%
Copper (Cu)	34.4	35.7	74.43%
Iron (Fe)	72.4	84.1	86.09%
Vanadium (V)	0.898	1.80	49.89%
Zinc (Zn)	861	871	99.97%

Metal emission rate/metal feedrate (kg/kg) expressed as a percentage

As the table shows, most (almost all) of the trace metal content in the feed waste oil fuel fed to a combustor is emitted in the combustion gas emissions from the combustor. These waste oil combustion systems rarely have emission controls that would capture particulate phase trace metals (or vapor phase for that matter) so combustor emissions are the stack emissions to the atmosphere. Notable exceptions to this observation are antimony (Sb), boron (B), cobalt (Co), manganese (Mn), and vanadium (V). For these metals, emissions rates are 40 percent to 50 percent of the corresponding metal present in the waste oil feed. Presumably, a larger fraction of these metals is emitted in the vapor phase, or retained by the combustion system (e.g., deposited on boiler tubes or other combustor surfaces).

Table 11 summarizes the trace metal emission rates (mg/kg of metal in feed oil) for combustion emissions of the UCSB default waste oil feed. Also shown in the table are the corresponding emission rates for different fuel oil types taken from the EPA standard air emission factor document, AP-42 (EPA 1995). As indicated in the table, for the toxic air contaminants (TAC) trace metals, emission rates for the UCSB-defined default waste oil are comparable to those emissions rates for waste oil taken from AP-42, though there are a few exceptions. TAC trace metals emission rates for the UCSB-defined default waste oil are also greater (with a few exceptions) than the AP-42 defined residual oil, which could be considered the proxy for heavy fuel oil (HFO). This is likely due to the higher trace metal content of the used oil-based recycled fuel oil (RFO). All the waste oil (UCSB study or AP-42) emission rates for toxic air contaminants (TAC) trace metals are greater (sometimes significantly greater) than those from the AP-42 distillate fuel oil, as would be expected.

Comparisons between the TAC trace metal combustion emissions from the UCSB-defined, as well as the AP-42, waste oil and those from the combustion of the AP-42 petroleum refining residual fuel oil are mixed, though the emissions for the "other trace metals" (not TACs in Table 11) from combustion of the UCSB waste oil are uniformly much greater. In general, within the range of variations in trace metal emission rates from combustion of fuel oils (waste or other), the conclusion is that the default combustion model emission rates established for use by the UCSB team in proceeding with a life cycle assessment (LCA) of waste oil management processes incorporating waste oil combustion is as appropriate as any other defensible waste oil combustion emissions characterization.

EMITTED TRACE METAL VALENCE STATE

What was done: UCSB reported the emissions from different combustion sources of many trace metals (toxic air contaminants and others) with no valence state noted. For others a valence state was reported, presumably for the most stable oxide of the respective metal (combustion usually results in metal oxide emissions) The results are in several Excel spreadsheet provided by UCSB.

Comment: The estimates of some valence states does not match the likely combustion for some metals. This is the case for Cr and V.

Table 11. Comparison of UCSB default trace metal emission rates to AP-42 emission rates for liquid fuels

	Emission rate, mg/kg feed*			
	UCSB Default waste oil	AP-42		
		Waste oil	Residual fuel oil	Distillate fuel oil
TAC trace metals				
Antimony (Sb)	0.178	0.544	0.635	
Arsenic (As)	0.702	13.3	0.160	0.075
Beryllium (Be)	0.213	0.218	0.003	0.056
Cadmium (Cd)	0.523	1.12	0.048	0.056
Chromium (Cr)	1.79	2.42	0.102	0.056
Cobalt (Co)	0.234	0.025	0.728	
Lead (Pb)	11.5		0.183	0.169
Manganese (Mn)	5.61	8.22	0.363	0.113
Mercury (Hg)	0.252		0.014	0.113
Nickel (Ni)	2.20	1.33	10.21	0.056
Selenium (Se)	0.542		0.083	0.281
Other trace metals compiled				
Aluminum (Al)	25.4		0.311	
Barium (Ba)	16.6		0.213	0.113
Boron (B)	3.96		0.095	
Copper (Cu)	34.4		3.84	
Iron (Fe)	72.4		3.52	0.075
Vanadium (V)	0.898			
Zinc (Zn)	861			

*Metal emission rate/metal feedrate (kg/kg) expressed as a percentage

Analysis

Trace metal emissions from combustion sources, both for toxic air contaminants (TACs) and the other metals noted in Table 10 and Table 11, are generally in the form of a stable oxide compound of the metal (e.g., Sb_2O_3 , As_2O_3 , and so forth). Thus, the emitted valence state of the metal is that corresponding to its stable oxide (Sb^{+3} , As^{+3} , and so forth). For most TAC trace metals, the human health toxicity of the metal is presumed to be not significantly different among its various valence states, thus a single metal composition is cited. However, for a few TAC trace metals, the element's toxicity does depend on its valence state. The most notable example is chromium (Cr).

Of the two most common naturally occurring chromium oxidation states, hexavalent chromium (Cr^{+6}) is much more toxic (and carcinogenic) than trivalent chromium (Cr^{+3}). Chromium in the air

emissions from combustion sources are most likely as its most stable chromium oxide (Cr_2O_3) in airborne particulate (trivalent Cr^{+3}), or as chromate (CrO_4^{2-}) or dichromate ($\text{Cr}_2\text{O}_7^{2-}$) in aqueous solution or associated with a cation such as sodium or magnesium (hexavalent Cr^{+6}). Chromate or dichromate can be water pollutants produced in electrochemical processes, and can also be found in combustion products, though usually at smaller fractions than Cr^{+3} . The hexavalent form is much more toxic than the trivalent form. Thus, assuming air emissions of chromium to be Cr^{+6} can lead to highly misleading conclusions.

In the Final Report, UCSB states that “The California Air Resources Board assumes that chromium emitted from combustion of used oil and other wastes to be ‘principally in the trivalent state.’ ” UCSB adopts this assumption in the combustion model developed and employed to estimate emissions in the life cycle assessment (LCA), and assumes that 80 percent of chromium emissions are as trivalent and 20 percent hexavalent.

Table 12 shows some select trace metal emission data taken from the UCSB spreadsheets. The data in the table illustrate a few disturbing items. Most noticeable is the wide difference between the concentrations of the metals noted in the two oil products. These differences have a significant effect on the LCA results reported (and to be reported) by UCSB. Heavy fuel oil (HFO) is the petroleum product to be replaced by waste oil-based recycled fuel oil (RFO), and its replacement gives rise to the recycled fuel oil (RFO) environmental benefits (credits) in the LCA. In particular, both Cr^{+3} and Cr^{+6} concentrations are reported in the table for RFO, but only noted as Cr^{+6} for HFO. The Cr^{+6} fraction of total Cr (sum of +3 and +6) is 20 percent, in keeping with the ARB recommendation. However, only Cr^{+6} emissions are shown for HFO combustion, which is suspicious and likely misleading. The Cr measurement data comprising the Cr concentration noted in Table 12 for HFO were most likely total Cr measurements. Thus, showing all Cr as Cr^{+6} is not in keeping with UCSB’s stated presumption, and overly conservative.

Table 12. Select reported emission factors from the December 2012 UCSB spreadsheets

Pollutant	Emissions per Fuel Energy Content, $\mu\text{g}/\text{MJ}$ LHV	
	RFO	HFO
Cr^{+3}	0.75	0
Cr^{+6}	0.19	1,115
Cu^{+2}	234	0
V^{+3}	3,562	7

Similarly for vanadium (V), air emissions from the combustion of UO recycling products are included in the UCSB composition sheets as trivalent V^{+3} . This presumes that the V emissions from the combustion of used oil (UO) and its recycling products is V_2O_3 . However, the most common vanadium oxide is V_2O_5 , in which the oxidation state of the V is V^{+5} . Only V_2O_5 has a human health effects exposure limit. The Occupational Safety and Health Administration (OSHA) has set an exposure limit in the workplace for worker exposure to V_2O_5 dust averaged over an 8-hr workday for 40-hr/week of 0.05 mg/m^3 (OSHA 2009). Thus, the UCSB assumption that vanadium is emitted in the gaseous emissions from UO and its recycling products (RFO, HFO, and MDO) as V^{+3} is misleading.

Displacement factors

Displacement factors are the fractions of the petroleum product that is displaced by the used oil processing product. For example recycled fuel oil (RFO) does not displace heavy fuel oil (HFO) on a kg/kg basis because the RFO heat content (MJ/kg) is less than that of HFO.

The life cycle assessment (LCA) model is set up to calculate the impacts of the used oil system and those of the displaced products. The treatment of re-refined products from the used oil system and substitute products is shown in Figure 2 and Figure 3. For the used oil system, products such as re-refined base oil are treated as co-products with a displacement credit. The displacement credit may be adjusted for economic factors. So, for example, 1 kg of base oil from re-refining might displace 0.99 kg of base oil from virgin production based on supply/demand considerations from the economic study.

UCSB should acknowledge the different treatment of products from the used oil system and compared products from the displaced system. In the used oil system, co-products are potentially adjusted with supply/demand displacement factors. However, no supply/demand effects for the virgin oil production can be taken into account.

An alternative approach would have been to examine the virgin oil system with the same detail as the used oil system since the value of displaced products is the key driver to the LCA study. Also the source of emission factors for the PE analysis of oil refineries is different than the primary data and other sources used in the used oil system. We recognize that the model configuration cannot be change. UCSB should identify the limitations of using life cycle impact (LCI) data for virgin base oil, MDO, and HFO production because the emission impacts are as large as those from the used oil system.

It bears noting that no direct primary data from refineries were collected to validate U.S. EPA statistics that have been used from literature, for example to validate that California refineries do indeed use more energy. The UCSB report does not give a justification and it seems to be a relevant difference that could be explained in terms of crude input and/or mix of technology. That justification is missing.

In Appendix D where displacement modeling is described, was the completeness of the PE models versus the LCI collected in the study for the combustion and other used oil management practices reviewed to warrant that displacement factors are not missing emissions that are in the used oil management model and vice versa. Perhaps a good way to review this is to look for the main contributors per impact category and make sure the LCI data are covered in both parts of the model. Has this check been performed, and if so, where is it reported?

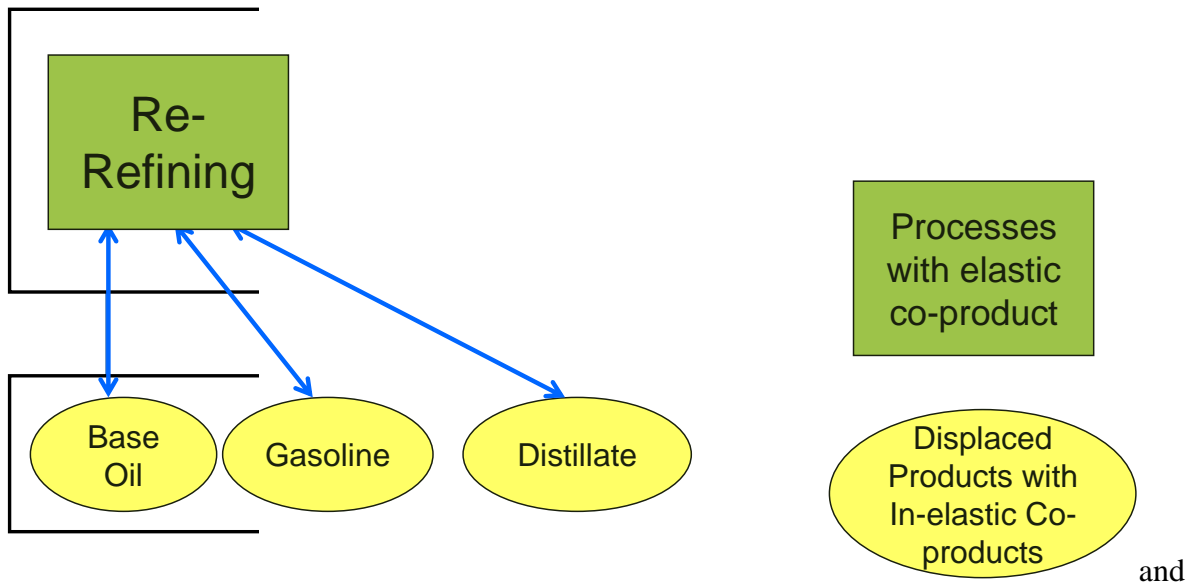


Figure 2. Displaced products from re-refining may be treated with elasticity factors.

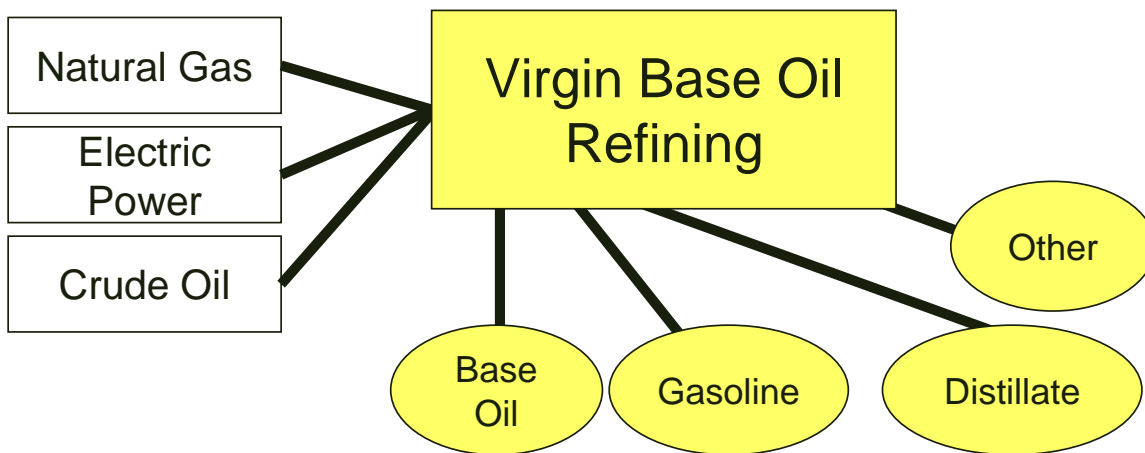


Figure 3. Inputs and displaced products from virgin oil production are not treated with displacement factors.

The UCSB approach to displacement to date can be summarized as follows:

What was done: Information reported by UCSB to date has focused on used oil (UO) and its management processes quantities needed to be managed (e.g., generation rates and quantities transferred in/out of state). Detailed displacement factors regarding the quantities of petroleum products that may be displaced by UO and its management process products have not been presented to date, though summary information has been reported.

Comment: Details regarding displacement factors are needed for proper review of the life cycle assessment (LCA). Such details are expected to discuss: rebound due to marketplace price drops, the use technical energy equivalent displacement factors, and the methods by which displacement factors are calculated.

In the UCSB Final Report, a detailed list of displacement relationships is provided at Table 9. The last column indicates that displacement rates are based on MJ/MJ or kg/kg basis. Furthermore, for some fuel products such as recycled fuel oil (RFO) or onsite combustion of used oil, a mix of No. 2 distillate, No. 6 residual and natural gas is used with identical proportion.

The UCSB report indicates (Section 4.3.6) that these assumptions are based on a consequential approach (by referring to consequential LCA). Furthermore, the appendix D, which describes the displacement model, includes several references to consequential procedure and LCA. However, none of these procedures have really been used for determining the displaced products or the displacement rates. In fact, the report indicates that a (appendix D, p. 289): “1:1 technical displacement rate is assumed in the Used Oil LCA model” and “where a product has the potential to displace several primary products, an equal split between the primary products is assumed.”

These assumptions are essentially attributional approaches because they do not consider relationships such as price elasticity, joint production constraints or impact on marginal processes between used oil management system co-products and displaced products. In other words, the study assumes that additional production of this used oil co-products can always be absorbed by the market and they will lead to direct substitution of equivalent products without any consequences.

Furthermore, the refinery model presented in the PE’s document (November 2012) is a purely attributional life cycle impact (LCI) model. This means that refinery co-products are essentially independent from each other and their production output can vary independently (no joint production constraints).

Take note that system expansion should not be considered a de facto consequential approach. As mentioned in the ILCD Handbook (General guide for LCA, March 2010, section 6.5.2, p. 77), “Substitution is also applicable for attributional modeling that is interested to include existing interactions with other systems.”

Therefore, the only real consequential approach in this study is the Direct Impacts Model developed by ICF International which is used for determining the reference flow for the 10 scenarios.

The actual description of the life cycle impact (LCI) model creates an ambiguity about the modelling approach. The authors should avoid this ambiguity and be clear about what is really consequential modelling and what is not. This is especially important because this study is for macro-level decision support with a long term perspective and direct and indirect consequences on the petrochemical sector could be significant. These consequences are not necessarily captured by this model and this should be presented as a limit of this study.

Impact Analysis

What was done: UCSB defined suite of impact indicators (greenhouse gas (GHG) emissions, smog formation, etc.), calculated impact indicators using TRACI 2.0 (EPA). Combustion of UO recycling products (RFO, MDO+rerefined) beneficial (net negative impact) when weighed against avoided burden of petroleum products replaced for all but two indicators (eutrophication, human health air criteria).

Comment: Air emissions end point impacts seem appropriate: GHG emissions, air acidification captures SO₂, NO_x emissions, smog captures NO_x, VOC emissions, cancer cases captures diesel PM emissions, air criteria captures PM10 emissions) Eutrophication captures aquatic impacts.

More needs to be said about the interpretation of eutrophication example. Because eutrophication is place specific, and the disposition route is key in determining net environmental burden/benefit, can it be determined in any way where the eutrophication takes place? Is it an impaired body or water? Is it a protected one? One can envision a scenario where the study's interpretation of a net benefit can actually increase the burden on a particular body of water? Likewise, something seen as a net burden might largely impact an area where eutrophication is already present as a problem. It is recognized that TRACI 2.0 is not site specific, but because eutrophication has impaired more than 50 percent of rivers, it would be good to at least have some better context to interpret reported results.

Phosphorous has bigger impacts to freshwater lakes, while nitrogen has bigger impacts to coastal environments. Can any conclusions be drawn from the constituents of the kg N eq metric and its actual impact on the particular water systems where the impacts occur? Any differentiation between nitrogen and phosphorous induced eutrophication is not described in the Final Report.

A better explanation for ecotoxicity is warranted. Unlike the other impact metrics, this one is not intuitive and it is not clear what the metric conveys, aside from its relative significance compared to other scenarios and sensitivities. The implications of the toxicity findings remain difficult to interpret in the Final Report.

Nevertheless the impact categories developed for the used oil life cycle assessment (LCA) seem comprehensive, with the exception of the aquatic impacts. While eutrophication does capture some aquatic impacts (it should be noted that eutrophication also applies to terrestrial systems), it does not capture all or the most relevant aquatic impacts from used motor oil processing or improper disposal. Eutrophication as an impact category is largely driven by nitrogen, phosphorous, and biological oxygen demand from organic materials. However, there are more relevant impact categories for impacts to aquatic ecosystems. Both freshwater aquatic ecotoxicity and marine aquatic ecotoxicity should also be used to assess aquatic impacts as they may have very different results than eutrophication. This is particularly near the San Francisco Bay where the proposed re-refining facility will most likely release effluents. However, it appears that the TRACI 2.0 model does not make this differentiation. Perhaps a summary of how the aggregated

metric could be distilled into various sub-impacts could be provided in the interpretation. It is noted in the Final Report that this requires further study to evaluate.

Also abiotic depletion and terrestrial ecotoxicity would better represent impacts not captured by the proposed impact categories currently under evaluation. Are data on these also not available? These issues are described as a limitation in the advance draft report, but could use further elaboration when interpreting results that are currently aggregated across several media.

Section 5.1.2 of the UCSB report presents the Global Warming Potential results. These results are presented in a table, in a waterfall graphs and they are described in the text. There are some discrepancies between the numerical value presented by these three representations. For example, Collection and Hazardous Waste Disposal numbers are different between the table and the graphs. The net results also are not the same in the text and the table. This observation seems to apply on all other impact category result sections.

The choice of lumping all the environmental mediums (air, soil, and water) into ecotoxicity seems unjustified. Why human health cancer and non-cancer might be lumped is understandable, because humans are not likely to be directed exposed to emissions to air, soil, and water. However, ecotoxicity seems more appropriately evaluated at least by each medium because there are species/ecosystems directly impacted by these emissions. If the analysis is not possible, a justification describing the rationale for this is warranted and this should be added to a section on limitations. In the Final Report these ecotoxicity factors are broken out into medium in Table 36, which helps with the interpretation of the results.

Environmental Impacts of Air, Water, and Land Emissions

One way to analyze whether there are any data gaps and/or biases in comparing used oil recycling impacts and displacement offsets is to examine impact results and determine which pollutants in available emissions profiles are the drivers for each environmental impact. Pollutants that drive a recycling impact or a displacement product's impacts should be included in emissions profiles for both recycling and displacement products. If not, then the impact assessment may have a bias in one direction or another. As indicated in the following three subsections, there are not any important pollutant drivers for any environmental impact for used oil (UO) recycling or the displacements from recycling that are not included in emissions profiles for both recycling and displacements impacts.

The following discussion does reveal that there are a number of instances where results reported in the UCSB Final Report could not be replicated through calculations using emissions profiles exhibited in the UCSB developed GaBi Envision model provided to the peer review panel and also provided to stakeholder reviewers. Evaluating the transparency and replicability of a life cycle assessment (LCA) are important aspects of a peer reviewer's responsibilities. In the case of the UCSB study, transparency for emissions profiles was compromised due to confidentiality requirements on some data provided by industry participants in the study, as well as certain data sets in the GaBi model used by UCSB that GaBi model developers require be kept confidential. Hence, UCSB had to manipulate the GaBi Envision model provided for reviewers' use. This was done so that reviewers could not see or reverse engineer the model to reveal confidential emissions data. The problem is that if this model, as disguised or manipulated to conceal confidential emissions data, is to be provided to CalRecycle for follow-on use, it would behoove UCSB to be sure that the model gives results for scenarios that are consistent with the Final Report. This assumes that the Final Report is correct and can be used as a standard against which to verify outputs of the GaBi model that CalRecycle will receive.

UO Recycled to RFO

Table 13 provides such a comparison for recycled fuel oil (RFO). The pollutant drivers for impacts from used oil (UO) processing into RFO and combustion of RFO are shown in the columns labeled RFO. Drivers for avoided life cycle impacts from displacement of diesel, heavy fuel oil (HFO), and natural gas are shown in columns labeled Displacements. Percentages in each column indicate the proportion of a specific environmental impact that is caused by a specific pollutant. As can be seen from the percentages shown in each column, surprisingly few pollutants, less than ten and sometimes only one, actually cause most of any given impact. In addition, the few pollutants driving each particular impact tend to be different for different impacts. Furthermore, fewer than 20 pollutants cause almost all of every environmental impact tabulated in Table 13, as well as Table 14 and Table 15 discussed below.

The displacement life cycle profiles include production of diesel, HFO and natural gas in addition to combustion emissions. The percentages in each column indicate the proportion of each environmental impact that are caused by a particular pollutant based on emissions profiles provided in the GaBi Envision Used Oil Management 1_59 Review Revised Final 2013_07_13 model provided by UCSB to the reviewers. Ignoring exports from California, one kilogram (kg) of UO available for recycling can be processed into 0.91 kg RFO. The UCSB developed Envision model estimates that each 0.91 kg of RFO combustion displaces production and combustion of approximately 0.24 kg No. 2 distillate oil (diesel), 0.25 kg No. 6 residual oil (HFO), and 0.21 kg natural gas.

The RFO combustion emissions profile contains under 35 pollutants, with most having environmental impact characterization factors that are included in TRACI 2.0. By contrast the RFO processing emissions profile and the diesel, HFO, and natural gas combined production and combustion emissions profiles cover over 325 pollutants, of which about half are characterized in TRACI 2.0. Total RFO combustion impacts tend to be two or more orders of magnitude larger than processing impacts, except for human health—cancer for which combustion impacts are many more than two times higher than reprocessing, and ecotoxicity for which RFO processing impacts are many times larger than from combustion.

Comparisons in Table 13 do not reveal any cases where a pollutant that causes a substantial portion of an environmental impact for RFO processing and combustion is not covered by the emissions profile for diesel, HFO, and natural gas production and combustion, or vice versa. However, the table does indicate that there are pollutants for which the RFO impact proportion differs substantially from the displaced diesel, HFO and natural gas impact proportion. Pollutants causing environmental impacts for which these RFO versus Displacement proportion differences are large are highlighted in Table 13.

The sulfur content of diesel or HFO versus RFO may be the cause of the disparities for sulfur dioxide and PM2.5 shown for human health respiratory impacts from criteria air pollutants. That is, sulfur dioxide accounts for 74 percent of human respiratory impacts for displaced fuels, but only 31 percent for RFO. PM2.5 accounts for 48 percent of RFO impacts, and just 13 percent of displacements impacts

For human non-cancers and ecotoxicity, zinc emissions drive more than 95 percent of the environmental impact for RFO. However, zinc does not dominate the emissions avoided by RFO displacements because arsenic, barium, copper, and silver also drive virgin fuel production and combustion human non-cancer and ecotoxicity impacts. For human cancers, hexavalent chromium, mercury, lead, and arsenic, in that order, cause most of RFO's impact. Impacts avoided by RFO displacements flow from arsenic, nickel, mercury, and hexavalent chromium.

Table 13. Impact assessment for RFO

Pollutants	Percent of Environmental Impact Caused by Indicated Pollutant for RFO Processing and Combustion Versus Virgin Oil Production and Combustion Displacements in California																	
	Climate Change		HH - Criteria Air		HH - Cancers		HH - Non-cancers		Acidification		Eutrophication - Air		Eutrophication - Water		Smog		Ecotoxicity	
	RFO	Displacements	RFO	Displacements	RFO	Displacements	RFO	Displacements	RFO	Displacements	RFO	Displacements	RFO	Displacements	RFO	Displacements	RFO	Displacements
Carbon Dioxide	99.6%	93.5%																
Methane	0.1%	6.3%													0.0%	0.1%		
Nitrous Oxide	0.3%	0.2%																
Sulfur Dioxide			31.1%	73.8%					65.0%	69.3%								
Nitrogen Oxides			3.2%	6.4%					32.7%	30.0%	22.0%	91.0%			99.3%	99.4%		
Hydrogen Chloride									2.3%	0.3%								
Hydrogen Sulfide									0.0%	0.2%								
PM10			17.4%	6.9%														
PM2.5			48.3%	12.8%														
Nitrogen											0.0%	6.5%						
COD													8.0%	62.6%				
Phosphate													0.0%	14.3%				
Phosphorus											78.0%	2.3%	59.9%	0.4%				
BOD													4.2%	8.5%				
Ammonia											0.0%	0.3%	1.6%	5.1%				
Ammonium													10.1%	0.4%				
Nitrate													16.2%	8.7%				
Hydrogen Fluoride									0.0%	0.2%								
Isoprene															0.0%	0.1%		
n-Butane															0.0%	0.1%		
Propane															0.0%	0.2%		
VOCs															0.6%	0.0%		
Phenol																	0.0%	0.4%
Anthracene																	0.0%	0.1%
Barium(II)								0.0%	6.4%								0.0%	19.8%
Beryllium(II)								0.0%	0.4%									
Silver(I)								0.1%	0.2%								0.3%	15.9%
Copper(II)																	1.3%	37.0%
Arsenic(V)					7.1%	40.7%	0.1%	23.5%									0.1%	6.4%
Nickel(II)					2.2%	21.8%											0.0%	6.3%
Zinc(II)							97.5%	42.3%									95.6%	12.4%
Mercury(II)					27.4%	18.0%	0.5%	16.7%									0.0%	0.1%
Chromium(III)																	0.0%	0.4%
Chromium(VI)					48.1%	14.8%											0.1%	0.4%
2,3,7,8 - TCDD					0.0%	0.1%											0.1%	0.4%
Lead(II)					10.0%	2.9%	0.5%	7.9%									0.0%	0.1%
Antimony (III)							0.0%	0.0%										
Cobalt (II)																	0.1%	0.0%
Cadmium(II)					5.2%	1.3%	0.2%	2.6%									0.0%	0.6%
Molybdenum							1.0%	0.0%										
Thallium																	2.5%	0.0%
Benzene					0.0%	0.3%											0.0%	0.0%
Totals	100.0%	100.0%	100.0%	100.0%	99.9%	99.8%	99.9%	100.0%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	99.9%
Impacts/kg used oil recycled to RFO	2.75E+00	-3.21E+00	2.32E-03	-1.65E-03	2.08E-10	-3.01E-10	1.46E-06	-3.84E-08	3.39E-01	-5.36E-01	5.57E-04	-1.95E-04	8.44E-07	-1.85E-05	6.90E-02	-1.00E-01	1.58E+00	-1.94E-01
Net Impact	-4.55E-01		6.74E-04		-9.29E-11		1.42E-06		-1.97E-01		3.62E-04		-1.77E-05		-3.10E-02		1.38E+00	
		kg CO2 eq		kg PM10 eq		cases		cases		kg H+ moles eq		kg N eq		kg N eq		kg O3 eq		PAF.m ³ .day.kg ⁻¹
											5.58E-04	-2.14E-04	} Air + water eutrophication					
											3.44E-04		} in above table					
Final Report Extreme RFO Scenario Results																		
Impacts/kg used oil recycled to RFO	2.75E+00	-3.20E+00	2.10E-03	-1.54E-03	3.17E-10	-4.11E-10	1.01E-06	-3.35E-08	3.10E-01	-4.97E-01	5.58E-04	-2.07E-04			6.91E-02	-1.00E-01	1.10E+00	-2.67E-01
Net Impact	-4.51E-01		5.62E-04		-9.39E-11		9.72E-07		-1.87E-01		3.51E-04				-3.11E-02		8.37E-01	

There also are substantial differences in the proportions of RFO versus displacements impacts for particular pollutants for eutrophication. RFO eutrophication of air is 78 percent from phosphorous and 22 percent from NOx emissions. In contrast, NOx constitutes 91 percent and phosphorous just 2 percent of eutrophication of air avoided by RFO displacements. For eutrophication of water, phosphorous accounts for 60 percent of RFO impacts, but chemical oxygen demand causes 63 percent of avoided impacts.

For climate change, acidification, and smog there are no substantial differences between drivers of RFO and RFO displacements impacts.

Rows in the bottom section of Table 12 under the heading “Impacts/kg used oil recycling to RFO” and rows below the table under the heading “Final Report Extreme RFO Scenario Results” show net impacts of recycling one kilogram used oil into RFO in California as computed from the GaBi Envision model provided to reviewers by UCSB and as reported in UCSB’s Final Report. For climate change, human health—cancers, acidification, eutrophication (air plus water), and smog, the two sets of net impacts estimates are quite close. Given that UCSB had to populate the GaBi Envision model in a way that concealed confidential information provided to UCSB for their LCA, and given the aggregated and rounded numbers for impacts and used oil quantities shown in the Final Report, such differences are not problematic.

However, the differences between GaBi Envision model results and report results for human health—criteria air and cancer and for ecotoxicity are not so easy to overlook. The approximately 15% difference for human health—criteria air impacts may be caused by some disparities in classifying particulate emissions as PM2.5 or PM10, as has been discussed by UCSB with the peer review panel. The differences between reviewer’s Envision model calculations and UCSB’s Final Report for human health— non-cancers and for ecotoxicity are greater than 30 percent. Since these two impacts are driven by metals emissions, as shown in Table 13, there may be a problem with the metals emissions populating the extremes Envision model scenarios. Whatever the cause, if this model, as disguised or manipulated to conceal confidential emissions data, is to be provided to CalRecycle for follow-on use, it would behoove UCSB to be sure that the model gives results for scenarios that are consistent with the Final Report, assuming that the Final Report is correct and can be used to verify outputs of the GaBi model that CalRecycle will receive.

UO Recycled to Re-refined Lubricating Oil

Table 14 provides a similar set of comparisons for recycled lubricating oil that is re-refined for use again as lubricating oil. In this case, the displaced products are virgin lubricating oils, bitumen (an asphalt component), ethylene glycol (an antifreeze component), and several minor co-product fuels. Processing one kilogram of used oil into re-refined lubricating/base oil (RRBO) yields 0.64 kg RRBO, 0.14 kg bitumen replacement, 0.08 kg fuels, and .001 kg ethylene glycol.

Pollutant emissions from processing used oil to make a portion of it usable again as base lubricating oil, yielding the two co-products bitumen and ethylene glycol and the light fuel co-products along the way, are shown in columns labeled RRBO. That column also accounts for combustion of the light fuel co-products. Emissions reductions from avoided production of virgin lube oil, bitumen, and ethylene glycol, as well as from avoided production and combustion of displaced fuels are tabulated in columns labeled Displacements.

Table 14. Impact assessment for re-refined lubricating oil

Pollutants	Percent of Environmental Impact Caused by Indicated Pollutant for Processing and Production of Re-refined Base Oil (RRBO) and Co-Products Versus Virgin Oil and Co-Product Displacements in California																	
	Climate Change		HH - Criteria Air		HH - Cancers		HH - Non-cancers		Acidification		Eutrophication - Air		Eutrophication - Water		Smog		Ecotoxicity	
	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements	RRBO	Displacements
Carbon Dioxide	93.0%	88.4%																
Methane	6.9%	11.3%														0.2%	0.2%	
Nitrous Oxide	0.2%	0.3%																
Sulfur Dioxide			94.7%	63.8%					86.8%	75.3%								
Nitrogen Oxides			2.6%	4.0%					11.8%	23.1%	78.2%	88.9%			93.9%	97.4%		
Hydrogen Chloride									0.4%	0.3%								
Hydrogen Fluoride									0.1%	0.1%								
Hydrogen Sulfide									0.8%	0.8%								
PM10			1.1%	16.7%														
PM2.5			1.6%	15.5%														
Nitrogen											20.6%	9.3%	4.4%	43.0%				
COD													19.2%	24.0%				
Phosphate													3.6%	18.3%				
Phosphorus											0.4%	0.3%	33.9%	0.3%				
BOD													11.0%	6.0%				
Ammonia									0.1%	0.3%	0.7%	1.5%	10.5%	5.8%				
Ammonium													6.5%	0.2%				
Nitrate													10.9%	2.4%				
Carbon Monoxide															0.0%	0.1%		
n-Butane															0.0%	0.2%		
Isoprene															2.6%	0.8%		
Pentane															0.0%	0.1%		
Ethane															0.0%	0.1%		
VOCs															2.9%	0.6%		
Propane															0.0%	0.5%		
Barium(II)							59.8%	23.0%									49.0%	37.4%
Silver(I)							1.5%	0.9%									44.2%	32.4%
Copper(II)																	1.2%	16.7%
Arsenic(V)					19.3%	67.1%	14.0%	30.3%									1.1%	4.4%
Nickel(II)					2.4%	8.6%											0.4%	1.7%
Zinc(II)							10.5%	29.0%									3.5%	6.1%
Mercury(II)					9.9%	15.6%	11.6%	11.2%										
Chromium(III)																		0.1%
Chromium(VI)					65.4%	4.3%											0.3%	0.0%
2,3,7,8- TCDD					0.1%	0.1%												
Lead(II)					0.4%	2.2%	1.2%	4.8%										
Cadmium(II)					0.4%	0.4%	1.1%	0.7%										0.0%
Phenol																	0.0%	0.3%
Benzene					2.0%	1.4%									0.2%	0.0%		
Formaldehyde					0.0%	0.1%												
Totals	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.8%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	100.0%	99.9%	99.7%
Impacts/kg used oil recycled to ReRe	5.77E-01	-1.13E+00	4.15E-04	-1.03E-03	1.77E-10	-2.57E-10	1.79E-08	-4.22E-08	1.38E-01	-2.66E-01	2.31E-05	-7.64E-05	3.42E-05	-6.02E-05	1.08E-02	-3.91E-02	3.40E-01	-4.04E-01
Net Impact	-5.52E-01		-6.14E-04		-8.04E-11		-2.42E-08		-1.28E-01		-5.33E-05		-2.60E-05		-2.83E-02		-6.38E-02	
		kg CO2 eq		kg PM10 eq		cases		cases		kg H+ moles eq		kg N eq		kg N eq		kg O3 eq		PAF.m ³ .day.kg ⁻¹
												5.73E-05	-1.37E-04) Air + water eutrophication				
												-7.94E-05) in above table				
Review Report Extreme ReRe Scenario Results																		
Impacts/kg used oil recycled to RFO	5.07E-01	-1.08E+00	3.66E-04	-1.13E-03	3.39E-10	-2.80E-10	1.65E-08	-4.17E-08	1.19E-01	-2.60E-01	5.18E-05	-1.28E-04			8.99E-03	-3.26E-02	3.04E-01	-4.16E-01
Net Impact	-5.73E-01		-7.66E-04		5.99E-11		-2.52E-08		-1.41E-01		-7.66E-05				-2.36E-02		-1.12E-01	

Comparisons in Table 14 do not reveal any cases where a pollutant that causes a substantial portion of an environmental impact for used oil (UO) recycling into re-refined base oil (RRBO) and co-products is not covered by the emissions profile for displaced products and fuels. In addition, the table indicates that there are only five pollutant-impact combinations for which the RRBO impact proportion differs substantially from that for displaced products and fuels. Pollutants causing environmental impacts for which these RRBO versus Displacement proportion differences are large are highlighted in Table 14.

For sulfur dioxide, Table 14 for criteria air pollutants indicates that sulfur dioxide accounts for 95 percent of this human health impact from processing and production of RRBO and co-products. At the same time this pollutant explains 64 percent of displacement impacts. The RRBO compared with Displacements proportions for arsenic and hexavalent chromium are substantially different for human cancers. Lastly, the nitrogen and phosphorous proportions are substantially different between RRBO and Displacements for eutrophication of water impacts.

The comparison between GaBI Envision model extremes scenario and the UCSB Final Report estimates of impacts per kilogram of used oil re-refined into new lube oil is more troubling for RRBO than for recycled fuel oil (RFO). As indicated in Table 14, the two sets of estimates are within 10 percent of each other only for climate change, human non-cancers and acidification. Smog estimates differ by more than 15 percent, criteria air estimates differ by about 25 percent, and eutrophication estimates differ by more than 40 percent. The ecotoxicity impact estimates differ by 75 percent. Lastly, the impact estimates for human cancers have different signs—i.e., the Envision model for the extreme re-refining scenario shows re-refining having a net positive impact by reducing the potential for human cancers, while the UCSB Final Report estimates that re-refining increases the potential for human cancers.

UO Recycled to Marine Distillate Oil

Table 15 provides comparisons for recycled lubricating oil that is distilled into a marine distillate oil (MDO) and co-products. Processing one kilogram of used oil into this marine fuel yields 0.52 kg MDO, 0.31kg bitumen, and less than 0.01 kg light ends used as fuels.

As was the case for RFO in Table 13 and RRBO in Table 14, comparisons in Table 15 do not reveal any cases where a pollutant that causes a substantial portion of an environmental impact for UO recycling into MDO and co-products is not covered by the emissions profile for displaced products and fuels and vice versa. Moreover, the table indicates that there are eight pollutant-impact combinations for which the MDO impact proportion differs substantially from the displaced products and fuels impact proportion. Pollutants causing environmental impacts for which these MDO versus Displacement proportion differences are large are highlighted in Table 15.

At 61 percent, chemical oxygen demand (COD) dominates water eutrophication from MDO displacements, whereas phosphorous provides 45 percent of MDO processing and combustion impacts compared with just 17 percent for COD. Barium and silver are important for MDO processing and combustion ecotoxicity impacts, but are less than half as significant for ecotoxicity avoided by MDO displacements. Silver is a driver of cancer and non-cancer impact potential for product and fuel production and combustion displacements. Mercury is dominant for cancer and non-cancer impacts from MDO processing and combustion.

The comparison between UCSB Final Report and reviewer calculations using the UCSB developed GaBI Envision extreme MDO model estimates of environmental impacts per kilogram of used oil recycled to MDO shows that the two sets of estimates are within 5 percent for climate, acidification, eutrophication, and smog. Human cancer, criteria air pollutant, and eutrophication impacts differ by less than 15 percent. Non-cancer and ecotoxicity have opposite signs in the two sets of estimates, with Envision showing a negative net impact in both cases and the UCSB Final Report estimating a positive net environmental benefit.

Table 15. Impact assessment for MDO

Pollutants	Percent of Environmental Impact Caused by Indicated Pollutant for Processing Used Oil into MDO and Co-Products and MDO Combustion Versus Virgin Oil Production of Marine Fuel and Co-Products and Marine Fuel Combustion Displacements in California																	
	Climate Change		HH - Criteria Air		HH - Cancers		HH - Non-cancers		Acidification		Eutrophication - Air		Eutrophication - Water		Smog		Ecotoxicity	
	MDO	Displacements	MDO	Displacements	MDO	Displacements	MDO	Displacements	MDO	Displacements	MDO	Displacements	MDO	Displacements	MDO	Displacements	MDO	Displacements
Carbon Dioxide	97.1%	93.7%																
Methane	1.0%	4.6%																
Nitrous Oxide	1.9%	1.7%																
Sulfur Dioxide			23.3%	26.1%					15.6%	18.2%								
Nitrogen Oxides			25.4%	23.6%					84.3%	81.5%	99.3%	98.9%			99.3%	99.3%		
Hydrogen Chloride									0.1%	0.1%								
Hydrogen Sulfide									0.0%	0.1%								
PM10			6.7%	8.8%														
PM2.5			44.6%	41.5%														
Nitrogen											0.4%	0.7%						
COD													16.8%	61.2%				
Phosphate													0.0%	14.9%				
Phosphorus											0.3%	0.3%	44.8%	0.4%				
BOD													9.6%	8.2%				
Ammonia											0.0%	0.0%	8.4%	5.5%				
Ammonium													7.8%	0.5%				
Nitrate													12.6%	9.3%				
VOCs															0.6%	0.6%		
Phenol																	0.0%	0.5%
Anthracene																	0.0%	0.1%
Barium(II)							6.9%	3.3%									40.4%	18.6%
Beryllium(II)					0.0%	0.2%	0.2%	1.3%									0.0%	0.1%
Silver(I)							2.3%	0.1%									39.1%	14.0%
Copper(II)																	3.2%	32.5%
Arsenic(V)					11.1%	31.4%	6.2%	23.7%									2.7%	11.0%
Nickel(II)					1.2%	4.2%											0.7%	3.9%
Zinc(II)							23.6%	31.4%									11.8%	14.9%
Mercury(II)					54.8%	20.9%	52.4%	26.0%									0.3%	0.2%
Chromium(III)																	0.1%	0.5%
Chromium(VI)					29.1%	38.7%											0.9%	1.5%
2,3,7,8 - TCDD																		
Lead(II)					1.5%	2.5%	4.2%	9.1%									0.0%	0.1%
Antimony (III)							0.2%	0.1%									0.2%	0.1%
Cobalt (II)																	0.2%	0.1%
Cadmium(II)					1.9%	1.9%	3.9%	5.1%									0.2%	0.9%
Selenium(IV)																	0.3%	0.8%
Benzene					0.3%	0.1%												
Totals	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	100.0%	100.0%	100.0%	99.9%	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	99.9%	99.9%
Impacts/kg used oil recycled to RFO	1.83E+00	-2.10E+00	2.16E-03	-2.44E-03	6.07E-10	-7.56E-10	7.52E-08	-7.19E-08	9.83E-01	-1.07E+00	9.23E-04	-9.71E-04	2.08E-05	-1.51E-05	5.16E-01	-5.41E-01	2.00E-01	-1.95E-01
Net Impact	-2.74E-01		-2.78E-04		-1.49E-10		3.23E-09		-8.24E-02		-4.77E-05		5.74E-06		-2.50E-02		4.68E-03	
	kg CO2 eq		kg PM10 eq		cases		cases		kg H+ moles eq		kg N eq		kg N eq		kg O3 eq		PAF.m ³ .day.kg ⁻¹	
											9.44E-04	-9.86E-04	} Air + water eutrophication					
											-4.20E-05		} in above table					
Review Report Extreme MDO Scenario Results																		
Impacts/kg used oil recycled to RFO	1.77E+00	-2.03E+00	2.87E-03	-3.19E-03	1.54E-09	-1.71E-09	7.18E-08	-7.27E-08	9.50E-01	-1.03E+00	9.08E-04	-9.49E-04			4.98E-01	-5.23E-01	2.07E-01	-2.21E-01
Net Impact	-2.64E-01		-3.17E-04		-1.70E-10		-8.68E-10		-7.87E-02		-4.10E-05				-2.45E-02		-1.37E-02	

Uncertainties

Also, as important as concerns regarding the life cycle assessment (LCA) comparisons of products made from recycled used oil (UO) and the virgin products displaced by those recycled-content products, is the general issue of data uncertainties. These may include:

- Use of “canned” GaBi emissions profiles that may or may not be representative of actual practices in California.
- Exclusion of impact contributions from more than 50 specific pollutants included in emissions profiles that are not covered by TRACI 2.0 impact characterizations.
- Exclusions of impacts from pollutants included in broad categories used in the inventories of emissions profiles, such as, among others, aldehydes, alkanes, alkenes, polycyclic hydrocarbons, non-methane hydrocarbons, and non-specific dioxins.
- Exclusions of radioactive emissions activity levels from human and ecosystem health impact characterizations provided by TRACI 2.0.

Sensitivity Analysis

Reviewer comments on the sensitivity analysis presented in the Final Report include the following:

- Tested and default parameters for the displacement assumptions regarding recycled fuel oil (RFO) sensitivity analysis are not presented.
- In Section 6.2.2 of the Final Report, the IMPACT 2002+ ecotoxicity categories have not been considered in this sensitivity analysis. Is there any reason for this?
- In section 6.2.3 of the Final Report, the text incorrectly indicates that “Using TRACI 2.0, marine distillate oil (MDO) and ReRe are shown to have lower or negative environmental impacts versus RFO.” In fact, this is only true for air ecotoxicity. Water and soil ecotoxicity results show the exact opposite.
- The text describing Figures 52 and 53 indicates: “Used oil composition can be seen to have very little effect on CML marine toxicity and, strangely, ReCiPe freshwater toxicity.” In general, it would be expected that a LCA practitioner can provide a precise explanation for this type of observation, at least for the inventory flows and characterization factors that are behind this result.

The thorough assessment of the toxicity sensitivity is definitely a welcomed addition to this the final version of the UCSB report. The testing of different LCIA methods and the most sensitive parameters clearly shows all the possible range of variability for results and conclusions. However, the complexity and number of analyses presented in the sensitivity analysis section of the report make it difficult for the reader to draw strong and useful conclusions. There is really a need for a wrap up of the main conclusions that goes beyond the general statement provided in Section 6.2.5 of the Final Report. In other words, are there strong conclusions that arise from all the variability observed for the toxicity categories? Alternatively, should we assume that results are too uncertain to consider the results from this environmental issue in final decision-making?

An option for summarizing all this information would be to provide a ranking table with a color code to easily highlight consistent trends for each scenario.

Regional Analysis

The lack of any regional analysis within the state of California makes interpreting these results very difficult. It will be difficult for policy-makers to draw conclusions about the distribution of impacts within the state. This is generally the case with life cycle assessments (LCAs), but someone with some familiarity of where impacts would occur in the extreme scenarios should be able to assess generally where impacts will occur and if they will occur near impaired waterways, out-of-compliance air sheds, etc. The research team and stakeholders should come up with some generalizations for how impacts would be distributed across the state. These limitations are not described in the limitations section of the report.

Interpretation of Results

In general, the results, conclusions, and recommendations for future work are not clearly indicated and that makes the UCSB report of a lesser value than it can have. The researchers should spend more time on the conclusions section and interpretation of results for a non-technical audience. There is not much to go on for policy makers with so few words that are used in the current report, and that is one of the goals of the LCA.

In section 6.1, it is stated that many results are driven by one or more impacts. More discussion is needed on the certainty of the impacts, are they measured, estimated, calculated, from primary sources, or literature? The quality of the values of the impact is relevant information for the interpretation and can guide as to which impacts can be best used now for recommendations, and which should be researched more to be more certain about the aggregated impact and hence differences between the different scenarios. These qualifications will improve the ability for readers to interpret the results.

Section 6.2.6 should have a short (one-sentence) explanation for why there are no significant changes in any scenario.

Section 6.5 on conclusions seems far too short. There are many conclusions that can be drawn. For example, the results in 6.1 can be tied to the sensitivities in the following sections. More conclusions should be added as they pertain to the LCA and not the policy recommendations.

A section on recommendations for future research should be added: what should be developed in the coming years to be able to address some of the difficult parts where you had to make the biggest assumptions?

A section on limitations should be added to the conclusions section. These limitations can be directly related to recommendation for future research. The LCA team's expertise will be very helpful in determining future research directions, data needs, etc.

The LCA results in the advanced draft LCA report provide interesting insight to the used oil recycling system. The presentation of separate cases (ReRe, Extreme Marine Distillate Oil (MDO), and Extreme Recycled Fuel Oil (RFO)) is essential for the reviewers and readers of the study. These cases should also appear in the Final Report. Reviewing study results reveals some interesting observations.

- Greenhouse gas (GHG) emissions from RFO combustion are about the same as those from HFO combustion
- GHG emissions from virgin heavy fuel oil (HFO) production are much higher than those from RFO production

- Emissions from marine distillate oil (MDO) processing (1.0×10^8 kg) are considerably lower than those from virgin MDO production (1.77×10^8 kg). This result is not completely surprising because virgin production includes the upstream energy to produce crude oil and additional oil refining steps.
- Comparing the MDO case to the recycled fuel oil (RFO) case raises questions about the disposition of all of the mass. The MDO case appears to involve less processing of finished products because the emission from virgin MDO processing are lower than those from heavy fuel oil (HFO) production. Also, the combustion emissions from MDO are far lower than those from HFO. Is this difference due to the used oil ending up in a waste stream? How many MJ of useful product are produced from RFO vs. MDO vs. ReRe options? A chart on total energy produced (with base oil shown on a MJ basis) would be helpful in explaining the fate of the oil.

The life cycle interpretation in this study does not fully comply with the elements described in ISO 14044. According to ISO, interpretation should identify significant issues from the life cycle impact (LCI) and life cycle impact assessment (LCIA) phases, evaluate the completeness, sensitivity, and consistency of the systems and provide conclusions, limitations, and recommendations.

Considering the objectives of this study, it would have been expected that the report provide CalRecycle a complete assessment of the quality of these results and the limitation regarding their use for statutory changes. The interpretation could be improved in other to ensure that the report minimally fulfills these objectives

The results section, covering the base year model and the extreme scenarios over the different impact categories, provides only a superficial description of the quantitative results. Unfortunately, this description provides little insight into the identification of the key parameters or the most significant issues. For example, in the Global Warming results section (5.1.2) for the extreme re-refining scenario, the explanation for the 174 million kg CO₂ eq reduction is quite simple: the production of secondary products such as re-refined oil, asphalt and ethylene glycol generates 174 million kg CO₂ eq less than equivalent primary products. Unfortunately, this key information is not sufficiently highlighted in the results description paragraph. In addition, this paragraph should provide additional information that explains this result. In this specific case, it should be explained how secondary products generate approximately one third of the impact of primary products. Two possible explanations are that 1) secondary products do not bear the impact of the virgin raw material (in this case oil) and 2) re-refining is a far less greenhouse gas intensive process than traditional virgin oil refining. It would be interesting to mention which point is the most relevant for explaining the observed results.

This comment for the extreme re-refining global warming result could be applied on virtually all sub-life cycle stage and impact category result sections.

Section 6, which aims at identifying key parameters common to several impact categories, provides a very limited number of observations, which in some cases generates more questions than answers. For example, zinc is identified as a key parameter for ecotoxicity potential (ETP) and human health non cancer potential (HHNCP) impact categories. However, this study uses a characterization model for metals that is no longer recommended in more recent version of the same method. How does this affect these conclusions? What is the level of confidence in the zinc emission at the inventory and LCIA level?

In other cases, the description is rather vague. For example, the report notes conclusions based on volatile organic compounds (VOC) and polycyclic aromatic hydrocarbons (PAH) assumptions

without mentioning or recalling what these assumptions are, or a making direct link between these and the sensitivity analysis. In addition, the interpretation should incorporate limitations and sensitivity analyses better, while these are unfortunately presented in a separate section without any links.

A consistency check should also be provided that would address some issues identified by the reviewers in the advanced draft report such as differences between emission models between used oil system and the displaced products. The consistency check could also discuss the limit arising from using different LCI databases in the same study.

A completeness check is also important to highlight the fact that the different sources of data may not provide the same completeness between the compared options (or displaced products). Another important issue regarding LCIA completeness is the fact that the impact characterization of the Improper Disposal model excludes a significant part of the inventory. Unspecified hydrocarbons, which represent 94.3 percent of the oil composition, are not characterized in TRACI 2.0. This means that thousands of tons of hydrocarbons directly released in the environment are overlooked. Considering only *used oil, improperly disposed, to fresh water via unfiltered drain storm*, this represents 3,720 tons of hydrocarbons. This issue could explain why impacts to human health non cancer are almost three orders of magnitude higher than impacts to human health cancer.

Comparative assertions intended to be disclosed to the public should contain an evaluation of the significance of the differences found, and this evaluation should be based in part on an uncertainty analysis. The standard does not request any specific methodology, but at least a qualitative discussion (also called Tier 1 approach) should be provided in the interpretation section. Without any discussion on uncertainty, doubts remain that differences found for the different impact categories are indeed significant.

Finally, the results for the scenarios section does not provide any interpretation of the results. Because these results are one of the main objectives of this study, the lack of any interpretation creates a serious doubt that this report provides the capacity and the knowledge to CalRecycle to adequately use and interpret these results. Furthermore, the absence of interpretation renders virtually impossible the review of results, the detection of potential errors, and the opportunity to provide meaningful comments on this section.

The lack of discussion about whether or not the different results or conclusions (especially for the Direct Impacts Model (DIM) scenarios) are significant or meaningful is probably the greatest weakness of the Final Report. For example, the Final Report states: “Table 24 indicates that the Human health criteria—Air Potential (HHCAP) score for the informal management in the base year is between -16 and 150 tons of PM10-eq depending on the ratio of dumping and on site combustion which are two factors that are generally unknown. Hence, the actual impact is probably somewhere between these two values. One consequence of using 150 instead of -16 tons of PM10-eq is that the used oil system as a whole would not present a net benefit for the environment anymore with respect to the HHCAP category.” Such statements leave the reader unsure as to which impact value, if any, could affect the main conclusions of the report such as the trend of the DIM scenarios to decrease or increase impacts and the relative importance between them.

Environmental Justice

Environmental justice is an important impact consideration for this assessment. Environmental Justice is defined in statute as, “the fair treatment of people of all races, cultures, and incomes with respect to the development, adoption, implementation, and enforcement of environmental

laws, regulations and policies.” (U.S. Government Code Section 65040.12). Federal Executive Order 12898 says each “Federal agency must make achieving environmental justice part of its mission by identifying and addressing, as appropriate, disproportionately high and adverse human health, environmental, economic and social effects of its programs, policies, and activities on minority and low-income populations, particularly when such analysis is required by NEPA.”

Because the development of a used oil recycling facility would be connected to state policy, it is important that environmental justice considerations be assessed. The California Office of Environmental Health Hazard Assessment (OEHHA) is currently in the final stages of developing a Community Environmental Health Screening Tool (CalEnviroScreen), which uses existing environmental, health, and socio-economic data to understand the cumulative impacts of pollution in communities across the state. The tool could help estimate the relative increase in environmental burdens to communities that live near the used oil processing facilities, and can help identify whether the facility is located in an area vulnerable to environmental exposures such as increased ozone, PM, or air toxics emissions. At least some qualitative assessment of the environmental justice outcomes of the siting of potential used oil processing facilities that may arise from the life cycle assessment (LCA) should be identified. For example, will there be increases in environmental pollution in communities that have been defined as vulnerable by California public health officials? They could be seen as an environmental justice issue.

UCSB has not fully addressed comments about environmental justice and marginal emissions offered in past review efforts. It is recognized that a calculation of local exposure levels and an assessment of the marginal emission impacts are typically not included in LCA studies. However, the Final Report should address qualitatively the following questions:

- Where does UCSB believe that recycled fuel oil (RFO) would be burned? Will the RFO be burned outside California? Will the combustion of RFO compared to heavy fuel oil (HFO) be subjected to modifications of an emission permit? Does RFO combustion occur in urban areas?
- What are the constraints on expanding re-refining in California? Would facilities need to get a new air permit? Would they need to obtain offsets for increases on NO_x or particulate emissions? Would additional emission controls be required?

Developing the answers to these questions is beyond the scope of the LCA study. However, the environmental impacts depend on such factors. These uncertainties should be identified in the UCSB report as a limitation, but remain absent in the final version.

Conclusions

The critical review of the UCSB life cycle assessment (LCA) of used oil management in California, as documented in the final Contractor Report dated July 29, 2013, (UCSB 2013b) concludes that the LCA team did a thorough and well-documented LCA given the available data base of emission and discharge stream composition data and the available data on the quantities of used oil directed to the several management options employed in practice. Moreover, the final Contractor's Report represents a distinct improvement over the advance Draft Report issued in March 2013. The LCA performed adopted accepted protocol and procedures, and results were reported in accordance with ISO reporting standards. In light of the available input data for the LCA, many of input parameters were based on assumed values. In these cases, sensitivity analyses were performed with the parameter varied over a range of possibilities, and resulting impacts on LCA results were reported. Throughout the LCA, critical review panel comments on the progress of the LCA were readily considered and, for the most part, appropriately addressed by the LCA team. Resolution of many reviewer comments are reflected in the LCA Final Report (UCSB 2013b).

The critical review process has helped assure that the study met the ISO 14040 standards. The scope and activities of the study were consistent with LCA standards and the UCSB team was aware of the requirements for peer reviewed LCAs. UCSB took great effort to perform technically valid data collection activities to enhance the understanding of used oil management, emissions from combustion processes, and the disposition routes for used oil. The UCSB team reviewed all available public information as well as proprietary data. The study used standard assessment models to examine the impacts of used oil processing. The scenarios for the study were developed in conjunction with an economic study of used oil recycling, which among its many objectives, aimed to relate used oil policies with collection rates and processing options.

CalRecycle will be interpreting the results of the study in its Report to the Legislature, so interpretation of the results by the study team was not within the scope of the study.

Several few critical review comments and observations highlight potential areas for future research.

Regarding the sensitivity analyses, the thorough assessment of the toxicity sensitivity is definitely a welcomed addition to the final report. The testing of different LCA methods and the most sensitive parameters clearly shows all the possible range of variability for results and conclusions. However, the complexity and number of analyses presented in the report make it difficult for the reader to draw strong and useful conclusions. CalRecycle will need to discuss the variability of the emissions impacts of the oil management pathways in their interpretation of the study results.

Regarding the environmental impact assessment, it was suggested that UCSB ensure that the GaBi Envision model provided to CalRecycle be consistent with that employed in the final report. There are differences between the emissions data in the most GaBi Envision model provided to reviewers and the final LCA report that appear to be substantial. Consistency between the model version employed for the final LCA report and that provided to CalRecycle is important. A more easily accessible version of the study modeling tools should be made available to stakeholders.

The report states the following for the virgin lube producers: "The current modeling approach assumes that an increase in re-refined lubricating oil recovered leads to a corresponding displacement in virgin lube sales in California. The displacement is considered a net loss for virgin producers and ignores the possibility of increased exports to other states or increased

production of other petroleum products.” This can be seen as a net loss for the virgin producers, but it would represent a net profit for the system; the overall operations get cheaper. From a societal perspective, that is a good trend. The results seem to be skewed by the way they are handled now by only taking a direct economic ‘value’ perspective, and this choice seems to be an important driver when looking at the results. Would it be possible to do an interpretation from a consumer perspective?

Finally, the life cycle assessment (LCA) does not address the local impacts of used oil management, which is typical for an LCA. The study does not mention potential environmental justice concerns due to the potential distribution of emissions from used oil management, which should definitely be addressed in the interpretation of the results.

Overall, the critical review finds the scope of the assessment to be sufficient to achieve the study goals described in the final LCA report and provides detailed modeling results for informing recommendations and policy decisions based on the life cycle assessment of used oil management practices in California

There is a tremendous amount of knowledge the LCA team has gained on the impacts from used oil collection. The team should be well-positioned to make clear suggestions for other researchers.

Bibliography

- ARB (1999), Houghton, M., *Final Staff Report: Update to the Toxic Air Contaminant List*, California Air Resources Board, Stationary Source Division, December 1999.
<http://www.arb.ca.gov/toxics/Finalreport.pdf>.
- ARB (2013), EMFAC2011 Model Update, California Air Resources Board, Mobile Source Emission Inventory, January 2013 release. <http://www.arb.ca.gov/msei/msei.htm>.
- Boughton, B., & Horvath, A. (2004), "Environmental Assessment of Used Oil Management Methods," *Environmental Science & Technology*, Volume 38 Number 2, December 12, 2003, pp. 353–358. doi:10.1021/es034236p
- Browning (2004), Browning R., with J. Rogers and H. Shafer, "Improper Disposal of Used Oil & Filters: New Evidence & Possibilities", presented at the Used Oil Recycling/Household Hazardous Waste Conference, March 2004.
<http://www.calrecycle.ca.gov/homehazwaste/Events/AnnualConf/2004/Presentation/RBrowning.pdf>.
- CA GREET (2009), Updated California-GREET Model version 1.8b (modified by Life Cycle Associates LLC), California Air Resources Board, Sacramento, California. 2009.
http://www.arb.ca.gov/fuels/lcfs/ca_greet1.8b_dec09.xls.
- Cal/EPA (2006), Mazur, L. C. Milanec K. Randles, and C. Salocks, *Characterization of Used Oil in Stormwater Runoff in California*, California Environmental Protection Agency, Sacramento, California, September 2006. <http://oehha.ca.gov/water/reports/OilInRunoff0906.pdf>.
- CCR (1860.1) California Code of Regulations (CCR) § 1860.1: "Lubricating oil includes oil intended for use in an internal combustion engine crankcase, transmission, gearbox, or differential in an automobile, bus, truck, vessel, plane, train, heavy equipment, or other machinery powered by an internal combustion engine".
- CIWMB (2009), *California 2008 Statewide Waste Characterization Study*, report prepared by Cascadia Consulting Group to the California Integrated Waste Management Board (now CalRecycle), August 2009.
<http://www.calrecycle.ca.gov/publications/Documents/General%5C2009023.pdf>.
- Cuevas, P. (2010), Comparative Life Cycle Assessment of Biolubricants and Mineral Based Lubricants. Master of Science Thesis, Swanson School of Engineering., University of Pittsburgh, Pittsburgh, PA, March 2012. <http://d-scholarship.pitt.edu/6829/1/Cuevas-4-7-2010.pdf>.
- DOE (2004), England, G.C., *Development of Fine Particulate Emission Factors and Speciation Profiles for Oil and Gas-fired Combustion Systems, Final Report, 2004*, Report prepared for the U.S. Department of Energy, National Energy Technology Laboratory, October 2004.
<http://www.netl.doe.gov/kmd/cds/disk23/F-Air%20Projects/15327%5CBC15327-FinalRpt.pdf>.
- EPA (1990), The Clean Air Act Amendments of 1990 List of Hazardous Air Pollutants, U.S. Environmental Protection Agency, Technology Transfer Network (TTN), December 2010.
<http://www.epa.gov/ttn/atw/orig189.html>.
- EPA (1995), *Compilation of Air Pollutant Emission Factors, Fifth Edition*, U.S. Environmental Protection Agency, Office of Air Quality Planning and Standards, AP-42, January 1995.
<http://www.epa.gov/ttnchie1/ap42/>.

- EPA (1997), *Locating and Estimating Air Emissions from Sources of Dioxins and Furans*. U.S. Environmental Protection Agency, EPA-454/R-97-003, May 1997.
<http://www.epa.gov/ttnchie1/le/dioxin.pdf>.
- EPA (2010a), “EPA Finalizes Regulations for the National Renewable Fuel Standard Program for 2010 and Beyond,” EPA-420-F-10-007, February 2010.
<http://www.epa.gov/otaq/renewablefuels/420f10007.pdf>.
- EPA (2010b), *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*, U.S. Environmental Protection Agency EPA-420-R-10-006, February 2010.
<http://www.epa.gov/otaq/renewablefuels/420r10006.pdf>.
- Girotti, G., A. Raimondi, G. Blengini, and D. Fino (2011), “The Contribution of Lube Additives to the Life Cycle Impacts of Fully Formulated Petroleum-Based Lubricants,” *American Journal of Applied Sciences*, Volume 8, Issue 11, 2011, pp. 1232-1240, 2011. doi : 10.3844/ajassp.2011.1232.1240.
- GREET 1 2012 rev2 (2012), The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, Argonne National Laboratory, 2012. <http://greet.es.anl.gov/>.
- Kalnes, T. N., Shonnard, D. R., & Schuppel, A. (2006), “LCA of a Spent Lube Oil Re-refining Process,” *Computer Aided Chemical Engineering*, Volume 21, 2006, pp. 713–718. doi: 10.1016/S1570-7946(06)80129-X.
- Keesom, W. H., S. Unnasch, and J. Moretta (2009) “Life Cycle Assessment Comparison of North American and Imported Crudes,” Prepared by Jacobs Engineering and Life Cycle Associates for Alberta Energy Research Institute, AERI File 1747.
<http://eipa.alberta.ca/media/39640/life%20cycle%20analysis%20jacobs%20final%20report.pdf>.
- Kline (2012 Confidential and Proprietary) *Lubricant Consumption and Used Oil Generation in California: A Segmented Market Analysis, Part 1 Report, California’s Lubricant Consumption 2000-2020*, Proprietary report prepared by Kline & Company for CalRecycle, Agreement Number: DRR12004, September 2012.
- PE International (2012), *Crude Oil Refining in US and California*, Report prepared by PE International and Five Winds Strategic Consulting for the University of California, Santa Barbara, November 2012.
<http://www.cce.csus.edu/portal/admin/handouts/05.%20UCSB%20PE%20Draft%20Report.pdf>.
- UCSB (2012a), “Used Oil Combustion Modeling Methodology, Used Oil Life-Cycle Assessment (LCA),” project paper for the Stakeholder Meeting December 4, 2012. CalRecycle web page, December 2012. <http://www.cce.csus.edu/portal/fileShareView.cfm?forumID=369>.
- UCSB (2012b), Used Oil Composition - to stakeholders - 09/18/2012, Used Oil Life-Cycle Assessment (LCA) spreadsheet for discussion at the Stakeholder Meeting September 18, 2012. CalRecycle web page, September 2012.
<http://www.cce.csus.edu/portal/fileShareView.cfm?forumID=369>.
- UCSB (2012c), Emission factor spreadsheet to stakeholders
- UCSB (2013) Geyer, R., B. Kuczenski, A. Henderson, and T. Zink, *Advance Draft Life Cycle Assessment Report*, report prepared for CalRecycle, March 2013.
<http://www.cce.csus.edu/portal/admin/handouts/06.%20UCSB%20Advance%20Draft%20LCA%20Report.pdf>.

UCSB (2013b) Geyer, R., B. Kuczenski, A. Henderson, and T. Zink, *Life Cycle Assessment of Used Oil Management in California*, report prepared for CalRecycle, July 2013.
<http://www.cce.csus.edu/portal/admin/handouts/Contractor%20Report%20UCSB%20-%20Used%20Oil%20LCA%2029%20Jul%202013.docx>.

Worrell, E. and C. Galitsky (2005), *Energy Efficiency Improvement and Cost Saving Opportunities For Petroleum Refineries An ENERGY STAR® Guide for Energy and Plant Managers*, Lawrence Berkeley National Laboratory Report LBNL-56183, February 2005.
http://www.energystar.gov/ia/business/industry/ES_Petroleum_Energy_Guide.pdf.