Used Oil Recovery in Alberta and BC

Preliminary Life Cycle Assessment (v1 - Final)

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for AUOMA / BCUOMA

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Executive Summary

This report presents the results of a preliminary life cycle assessment (LCA) of the impacts of used oil management from a do-it-yourself oil change, in which the oil, containers, and spent filter are returned to AUOMA-registered processors for recycling. Figure 1 shows the numerical results, in terms of net environmental benefit, for two indicators.

The report makes comparative assertions about the relative ecological impacts of different routes. The study has not been critically reviewed, and results should be interpreted after consideration of the study's limitations. Environmental hazards of used oil are discussed in a separate document.

Study Design

- Impacts are reported for recycling one liter of used oil, along with 68 g of HDPE plastic and 66 g of recoverable steel.
- Three scenarios are considered:
  1. Re-refining into base oil, fuels, and asphalt additives;
  2. Combustion of recycled fuel oil (RFO), displacing distillate fuel;
  3. Combustion of recycled fuel oil, displacing natural gas.
- Recycled products are assumed to displace equivalent primary products ("avoided burden" methodology).
- Optimistic lost-in-use rate of 5% is assumed (95% recovery).

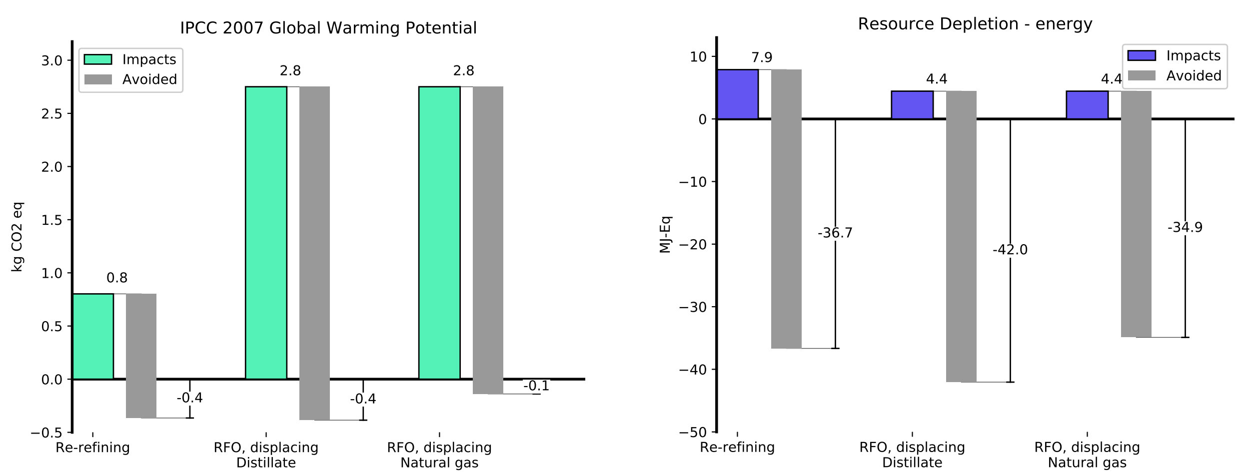

Figure 1: Net impacts / benefits of used oil recycling under three different scenarios, measured by global warming potential (left) and energy resource requirements (right). Positive (colored) bars indicate impacts and negative (gray) bars indicate avoided emissions.

Major Results

General findings:

- *Recycling conserves resources*. If recycled products are used in place of primary products, there are benefits in terms of reduced consumption of energy and minerals.
- Consumer drop-off is a (relatively) major source of GWP and smog emissions. Under the study's modest assumption of a 5 km trip distance, consumer drop-off is the second-largest contributor.
- Transport of recycled materials has a (relatively) small impact across the board, because of the relative efficiency of commercial freight (trucking and rail).

Used oil management options:

- All three routes produce modest net improvements for global warming potential (GWP) *in the best-case*. This result is strongly dependent on the used oil products (re-refined base oil; recycled fuel oil) displacing primary products.
- RFO: displacing natural gas instead of diesel results in smaller GWP benefits and results in a net increase in smog impacts.
- As modelled, RFO has higher particulate emissions than both diesel and natural gas, although this can be mitigated through air pollution control technologies.

Material systems:

- All three materials (oil, plastic, steel) produce net resource savings when recycled.
- Steel recycling conserves mineral resources by a similar amount to oil recycling;
- HDPE recycling conserves energy resources but not mineral resources.

Limitations

- *Study design excludes the biggest benefit of used oil management*, avoiding ecological and health hazards from dumping. Toxicity effects are not characterized because of the complexity of the measurement and the challenge of comparing the effects of used oil dumping with the effects of virgin oil refining.
- *Proxy study*: the reported results reflect average assumptions about material quantities and fates, including the re-refineries, combustion equipment, and the displaced primary products.
- *Limited scope*: DIY automotive oil change may not be representative of other cases. The results in this study should not be scaled up to a provincial or program level.
- *Losses in use* are optimistic, and their impacts are omitted.

- *Crude oil process chain*: benefits (avoided impacts) resulting from displaced primary petroleum production are based on inventory data of unknown quality.

Next Steps

The study could be extended by addressing limitations discussed above. Alternately, a new study could be developed using the same background system to consider a different scope or objective. Selecting the next course of action will depend strongly on the UOMAs' objectives.

- *Expanded scope*: Including other sources or types of oil, recycling of other materials, or more in-depth modelling of containers or filters would help make the study more representative.
- *First-mile / last-mile*: The sustainability performance of the used oil system is strongly affected by impacts during consumer drop-off, and by the fate of recycled materials in the market.
- *Toxicity*: Toxicity impacts were omitted from the preliminary study due to their complexity, but could be added later to better measure the ecological and health benefits of responsible used oil management.

1 Background

1.1 Lubricating Oils, Filters, and Containers

Lubricating oils are used throughout the industrial economy. The most common application is engine oil, which provides lubrication of internal combustion engine crankcases and transmissions. Most lubricants contain an additive package that makes up 5–20% of the product weight and gives the oil the characteristics necessary to function. Some common additives include anti-wear compounds, detergents, viscosity modifiers, corrosion inhibitors, and others. Both the base oil and the additives can present hazards to the environment and human health, particularly at the end of the oil's useful life.

Sources of environmental hazard from used oil are documented in Annex A.

During use, lubricating oils are continuously filtered to remove dust and particles from wear. As time goes on, the capacity of the oil to perform its purpose steadily declines because of the breakdown of oil molecules and additives, and the buildup of contaminants. Oil and filters are routinely replaced, generating a large potentially hazardous waste stream. Because of the potential hazard, conventional waste management systems like curbside collection and deposit in landfill are not suitable to deal with used oil. In addition, though the oil is contaminated it still retains significant value as a petroleum product, and disposal would waste this value.

Although the containers used to package new lubricating oils are typically made from the same materials used to package other products, the presence of the oil makes these containers unfit for recycling along with other containers.

1.2 Used Oil Management Routes

Used oil can be reused or recycled in a number of ways (Graziano & Daniels, 1995; Boughton & Horvath, 2004).

- Lubricants in some applications, such as thermal transfer and dielectric oils, can be rejuvenated simply through filtration to remove water and contaminants.
- Used oil can be treated with heat and chemicals to separate water, debris, and sediments, and subsequently burned for energy recovery. The product of this minimal treatment process is called Recycled Fuel Oil (RFO) and can be used to replace more costly fuels.
- Used oil can be recycled through distillation and hydrotreatment in a refinery to produce a recycled base oil that is comparable to primary base oil. This process is known as re-refining, and generally produces additional co-products including light fuels and distillation bottoms.

The distillation bottoms, which retain most of the contaminants in the used oil, are used as asphalt additives.

1.3 Used Oil Recovery in Alberta and British Columbia

Management of used oil, containers, and filters in Canada is based on an extended producer responsibility (EPR) framework, in which the producers and sellers of lubricants collaborate with used oil collectors and recyclers to ensure that their products are managed responsibly at end of life. Used oil, oil filters, and oil containers are assessed an environmental handling charge (EHC) at the point of purchase, which is paid back as a return incentive (RI) to processors when the products are recycled.

The used oil collection and recycling program is administered on a provincial basis by used oil management associations (UOMAs). The difference between EHC collected and RI paid provides operating funds for the UOMAs.

In British Columbia (as well as other jurisdictions), used antifreeze and antifreeze containers are also included in the scope of the program.

1.4 About Life Cycle Assessment

Life cycle assessment (LCA) is an analytic approach to estimate the potential environmental impacts of a product or service. LCA must take into account both the direct impacts of the product and the upstream / downstream impacts associated with producing, distributing, and disposing of it.

Performing an LCA requires developing a model of the different processes or stages the product goes through during its life cycle, and then estimating the environmental implications of each stage. This model includes a foreground, which describes the system that has been directly observed, and a background, which includes the industrial ecosystem that provides electricity, fuels, and other materials. Both the foreground and background may use proxy data to describe systems whose actual properties are not known.

The quantitative result of an LCA is a set of numerical impact scores that describe the total potential impacts in terms of an equivalency factor that helps interpret the significance of the impact. For instance, global warming potential of many different gases is expressed in terms of an equivalent amount of carbon dioxide.

2 Goal and Scope

- Study Commissioner: Alberta Used Oil Management Association (AUOMA) and British Columbia Used Oil Management Association (BCUOMA)
- Study Practitioner: Brandon Kuczenski, PhD, Associate Researcher in Industrial Ecology, University of California, Santa Barbara.

2.1 Goal of the Study

The goal of this study is to estimate the relative environmental impacts and benefits of various options for responsible management of used lubricating oil, containers, and filters. These study results are meant to provide information to AUOMA/BCUOMA boards of directors and program participants about the relative magnitudes of environmental impacts and benefits that may arise as a consequence of used oil management activities.

This is a *preliminary* study that uses existing inventory data as a proxy for the actual conditions in Alberta and BC. No new inventory data sets were prepared for this study.

- Target Audience

  AUOMA and BCUOMA Boards of Directors and program participants.

- Intended Application

  The intended application is to inform the target audience about the environmental significance of program activities, and to provide advice and support for policy decisions.

- Comparative Assertions

  The report includes comparative assertions:

  - about the relative significance of impacts from recycling activities compared with the potential benefits of avoided activities;
  - about the relative impacts of different material systems (oil, plastic, metal).

  ISO 14044 requires that LCA results be critically reviewed before they are used to support comparative assertions disclosed to the general public.

  Although the present report has not been critically reviewed, the study model is based on a critically-reviewed LCA study for the state of California (Geyer *et al.*, 2013) and uses many of the same methods and assumptions.

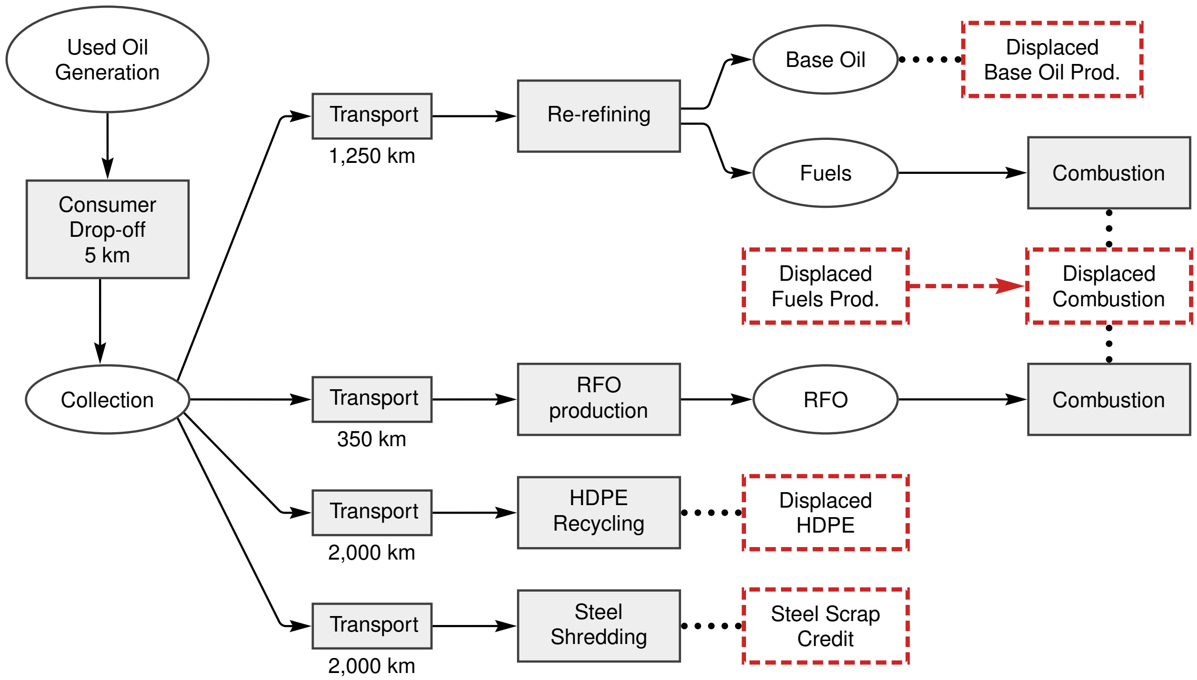

Figure 2: Diagram of the system modelled in the report.

2.2 Scope of the Study

2.2.1 Function of the system under consideration

The primary function of the system under consideration is to responsibly manage the used lubricating oil hazardous waste stream. Because used oil is required to be managed through the program, no alternative disposal route is considered to be "avoided" through responsible management.

The system modelled in this study includes the activities of the used oil recycling system and the downstream effects of used oil and other materials recycled in the program. The production of secondary products from used oil is considered to "displace" the production of alternative products:

- Production of re-refined base oil is assumed to displace an equal amount of primary base lubricant on a volume basis;
- Production of recycled fuel oil is assumed to displace an equal amount of primary fuel, either diesel or natural gas, on a lower heating value basis;
- Production of recycled high-density polyethylene (HDPE) is assumed to displace an equal amount of primary HDPE;
- Recycling of steel filters is assigned a credit associated with the "value of scrap" to displace primary steel.

2.2.2 Functional Unit

Output: 1 liter Used Lubricating Oil, for collection

Study functional unit, representing the collection and processing of 1 L ofused engine oil, and related supplies, from a DIY-style oil change.

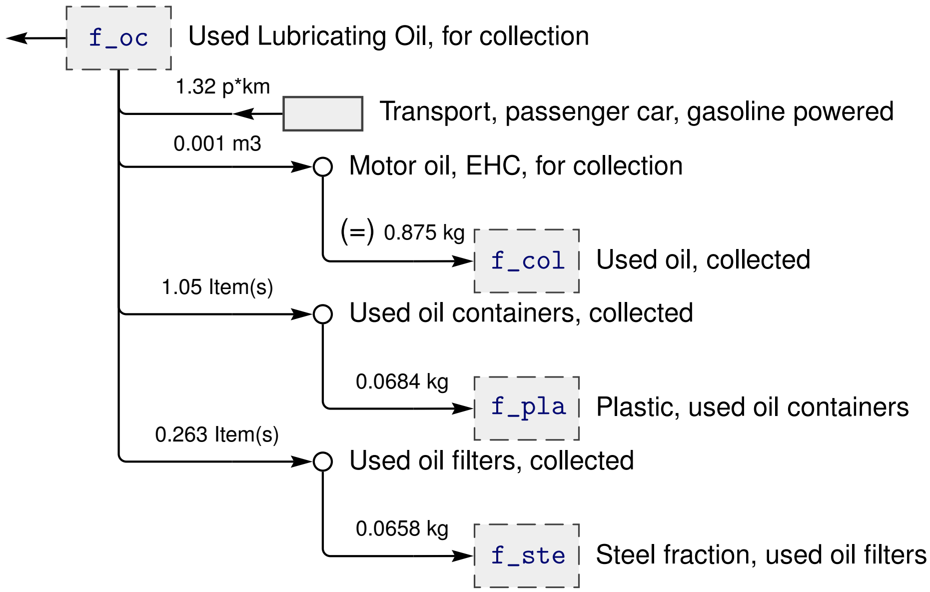

Figure 3: Diagram of the functional unit.

The functional unit is one liter of used motor oil, and a proportionate amount of plastic from containers and metal from filters, recycled within the program to various end-use fates:

(A) **1 L oil**, 875 g:

  (i) (ReRe) to re-refining, to displace primary base oil;

  (ii) (RFO - Distillate) to combustion as recycled fuel oil (RFO), to displace diesel fuel;

  (iii) (RFO - Natural Gas) to combustion as RFO, to displace natural gas;

(B) **1.05× 1-L container, HDPE plastic**, 68 g: recycled to secondary HDPE;

(C) **1.05× 25% of steel from a typical filter**, 66 g: recycled as scrap steel.

The dimensions of the functional unit are based on the assumption that an oil change recovers 95% of the oil supplied to the engine (5% lost in use). This is a much higher recovery rate than can be expected for the programs as a whole, but it reflects the findings of a prior study in British Columbia (Spence, 2005). Other estimates place the loss rate for light-duty vehicle oil at 10–14% (Kline & Company, Inc., 2013).

Assuming that a typical oil change requires 4 L of oil. As a result, each oil change generates in 3.8 L of used oil collected, 4 containers, and one filter. This corresponds to approximately 1.05 1-L containers and 26.3% of the steel contained in one filter per L of oil recovered.

The HDPE weight of 65 g / L of new oil is the estimated weight of a single 1-L HDPE container, based on marketing information obtained from an online search.[1]

The steel weight of 62.5 g / L of new oil is based on an estimate of 250 g of recoverable steel per average filter, according to a filter recycling feasibility study (Smailer *et al.*, 2002, Table 4).

The used oil trapped inside the filter is assumed to be recovered and recycled, and is included within the 1 L functional unit.

3 Inventory Modelling

The core of the model is the CalRecycle Used Oil LCA model (Geyer *et al.*, 2013). The CalRecycle model included custom data collection and modelling efforts to describe petroleum refinery products, used oil collection, and used oil re-processing and recycling. Products of used oil recycling were assumed to displace primary petroleum products, which were assigned negative impact scores when displaced.

In the current model, the CalRecycle model was extended to include recycling of used oil containers and filters. The containers were assumed to be made of HDPE plastic and recycled using mechanical and thermal processing to yield a secondary resin that could substitute for primary resin. The filters were assumed to be shredded and mixed with other steel scrap to be used as blast furnace charge. More details on the foreground models can be found in Section B.

3.1 Background Data Sources

The core of the CalRecycle model, and also the present model, was constructed using the US Life Cycle Inventory (US LCI) database, which is freely available (National Renewable Energy Laboratory, 2014). The US LCI database was used to model:

- Fossil fuel production and combustion for foreground processes;
- Electricity production, except renewables;
- Freight transport;
- Private vehicle transport;

[1] http://www.parker-plastics.com/shop/1-qt-hdpe-oblong describes a typical product. Other results ranged from 50–75 g.

- HDPE plastic recycling and virgin resin production.

For a number of processes for which the US LCI database lacked adequate coverage, datasets from Thinkstep were used to supplement. These include:

- Renewable electricity production from geothermal, solar photovoltaic, wind, and hydro power;
- Displaced production of primary petroleum products;
- Diesel fuel production for freight transport;
- Wastewater treatment.

Finally, the credit for steel scrap recycling was adopted from the World Steel Association's recommended life cycle assessment methodology (World Steel Association, 2011). In their approach, the steel is assigned a "value of scrap" which represents the reduction in impacts that result from the introduction of steel scrap into primary steel manufacturing. The Worldsteel model is also adapted from the Thinkstep database.

It is important to note that the avoided impacts of primary petroleum production are potentially the most significant aspects of the model. However, available life cycle inventory data representing crude extraction and refining is of unknown quality. Effects of unconventional extraction such as tar sands and deep-water extraction are likely not accurately represented. Further review of these processes is advised.

3.2 System Boundary

The oil first enters the system boundary when it is collected from an engine. The used oil is assumed to arrive at the point of collection burden-free: the burdens of producing the oil are assigned to the use phase of the lubricant. This is called the "zero-burden assumption" and is common in LCA studies of waste management (Ekvall *et al.*, 2007).

The system includes impacts from the following foreground activities:

- transportation of used oil, containers, and filters at local collection;
- transportation of used oil, containers, and filters from collection facility to recycling facility;
- energy use at the pre-treatment facility for de-watering;
- aggregated impacts of re-refining operations;
- direct combustion of re-refining fuel co-products;
- direct combustion of recycled fuel oil;
- energy and water use at plastic recycling;
- wastewater treatment at plastic recycling;

- avoided direct combustion of primary diesel fuel;
- avoided direct combustion of natural gas fuel.

The system includes incurred and avoided impacts from the following background activities:

- Electricity production from various technologies;
- Natural gas production, US;
- Diesel fuel production, North America;
- Primary base oil production, North America;
- Primary HDPE production, North America;
- Steel recycling credit, Global.

The following activities are excluded from the system:

- Non-recycling activities at all facilities, including employee activities;
- Production of chemicals for waste oil pre-treatment;
- Treatment and disposal of combustion ash;
- Disposal of solid wastes;
- Radioactive wastes;
- Impacts of capital production, facility construction and decommissioning;
- Impacts of infrastructure production and maintenance;
- Equipment manufacturing, maintenance and wear, and decommissioning;
- Facility start-up and shut-down operations, non-normal operations, accidents, and emergencies.

3.3 Cut-off Criteria

- Reference Flow

  The system considers the reference flow to be a material flow measurement at the point of collection. From that point the material is followed until it is put to use or lost through combustion. Impacts for the subsequent use phase are not included. Used oil, containers, and filters are all assumed to enter the system burden-free.

- Foreground System

  Foreground process cut-off flows are identified in the system boundary definition above.

- Background System

  The study inherits cut-off flows from reference data sources used in the model. The US LCI database, in particular, cuts off many significant flows including:

- Electricity generation from waste, biogas, petroleum coke, and other small-volume fuels;
- Solid waste disposal;
- Some types of pipeline transport.
- Electricity production from renewable energy (datasets published by Thinkstep were used to model electricity production from of geothermal, solar photovoltaic, wind, and hydro.)

The Thinkstep database cuts off some significant waste flows:

- Mine tailings and overburden;
- Radioactive wastes;

The process model used to assess the steel scrap credit includes a lengthy set of cut-off flows, which almost all fall into some category of waste for recovery. For further information please consult the WorldSteel LCA Methodology report.

3.4 Recycling Allocation and Avoided Burdens

This model uses consequential system expansion to apply the assumption that recycled materials produced within the system boundary will result in the displacement of primary production elsewhere. For instance, Re-refined base oil is assumed to displace primary base oil, with the result that for every liter of re-refined base oil produced, one fewer liter of primary base oil will be produced. As a result, the displaced production results in an "avoided burden," which manifests as a credit in the computation of the impact scores.

This assumption is counterfactual, because it requires considering a situation that did not occur – in other words, it requires the reader to imagine what would have happened if the used oil were not collected and recycled. In the case of lubricating base oil, the assumption of displacement is sound because the demand for base oil is approximately constant. In the case of plastic recycling, the displacement assumption is less sound because it is not clear whether the recycled materials will be selected by the market in place of primary materials.

Steel recycling is complex because scrap steel is intrinsically required by the steel-making process. The WorldSteel Value of Scrap model is designed to account for the benefits that result from increased supply of steel scrap.

Sensitivity to the displacement assumption is considered in Section 5, Life Cycle Interpretation.

3.5 Inventory Results

The three scenarios are:

Re-refining – re-refining of oil into base oil, with light fuel and asphalt co-products, assumed to displace primary petroleum products on a mass basis (except fuels on a net calorific value basis);

RFO, displacing distillate – production of recycled fuel oil, assumed to displace diesel fuel on a net calorific-value basis;

RFO, displacing natural gas – production of recycled fuel oil, assumed to displace natural gas on a net calorific-value basis.

The inventory results are reported in Table 1.

Table 1: Life Cycle Inventory Results

Flow	Unit	ReRe	RFO - Dist.	RFO - NG
Used Oil Collected	L	1.0	1.0	1.0
Used Oil to Formal Management	kg	0.875	0.875	0.875
Re-Refined Base Oil	kg	0.574	–	–
Light Fuel Co-product	kg	0.058	–	–
RFO Co-product	kg	–	0.806	0.806
Asphalt Product	kg	0.113	–	–
Avoided Base Oil	kg-Av	0.574	–	–
Avoided Distillate	kg-Av	0.058	0.776	–
Avoided Natural Gas	kg-Av	–	–	0.681
Avoided Bitumen	kg-Av	0.113	–	–

4 Life Cycle Impact Assessment

4.1 Impact Category Indicators

The Life Cycle Impact Categories reported for the study include climate change, respiratory inorganics, abiotic resource depletion, and photochemical ozone creation (smog creation). The category indicators were drawn from the International Reference Life Cycle Data System (ILCD), which represents a broad consensus of LCA scholarship. The following indicators are reported:

- Climate change; midpoint; GWP100; IPCC2007; **kg CO2-eq**. Climate change measures the contribution of the system to the accumulation of heat-trapping gases in the atmosphere, predominantly carbon dioxide from fossil fuel combustion.

- Respiratory inorganics; midpoint; Rabl and Spadaro 2004-Greco et al 2007; **kg PM2.5-eq**. This indicator reports the emissions into the air of substances that cause harm to human health when inhaled.
- Resource depletion; midpoint; abiotic resource depletion; Van Oers et al. 2002; **kg Sb-eq**. This indicator measures the extraction of non-renewable resources by making reference to their economic reserve base, i.e. the quantity of economically-extractable reserves known. This category is highly sensitive to modelling inconsistencies across data sources, and quantitative results should be interpreted with caution.
- Resource depletion; non-renewable energy; **MJ net calorific value**. This indicator measures the extraction of non-renewable energy resources in terms of their energy content.
- Photochemical ozone formation; midpoint - human health; Van Zelm et al. 2008; **kg C2H4-eq**. This indicator reports the contribution of the system to compounds that can generate smog through photochemical decay, particularly nitrogen oxides and volatile organics.

Although one major motivation for used oil management is to avoid ecological harm due to improper disposal, the toxicity impacts of used oil management are not modelled. Measuring toxicity is very complex because different substances can have vastly different effects, and because the ultimate fate of toxic materials is strongly dependent on the circumstances of disposal. Moreover, it is hard to compare the toxicity impacts of dumping with the toxicity impacts of primary petroleum extraction and refining because of insufficient data about petroleum production and because the activities happen in completely different locales. For more information about the potential environmental hazards posed by used oil, please refer to the Annex.

4.2 Scenario Results

Each impact indicator was computed for each of the three scenarios identified in Section 2.2. Each scenario is shown as a waterfall chart, in which the vertical axis indicates zero. The waterfall starts at the top of each chart with a zero value. Positive-valued impacts grow left-to-right, and negative-valued avoided burdens grow right-to-left. At the bottom of the waterfall, the net result is shown with a red triangle. Results to the left of the vertical axis indicate a net benefit. Blue bars are used for the plastic material system; black bars indicate steel; the remaining color indicates used oil-related impacts.

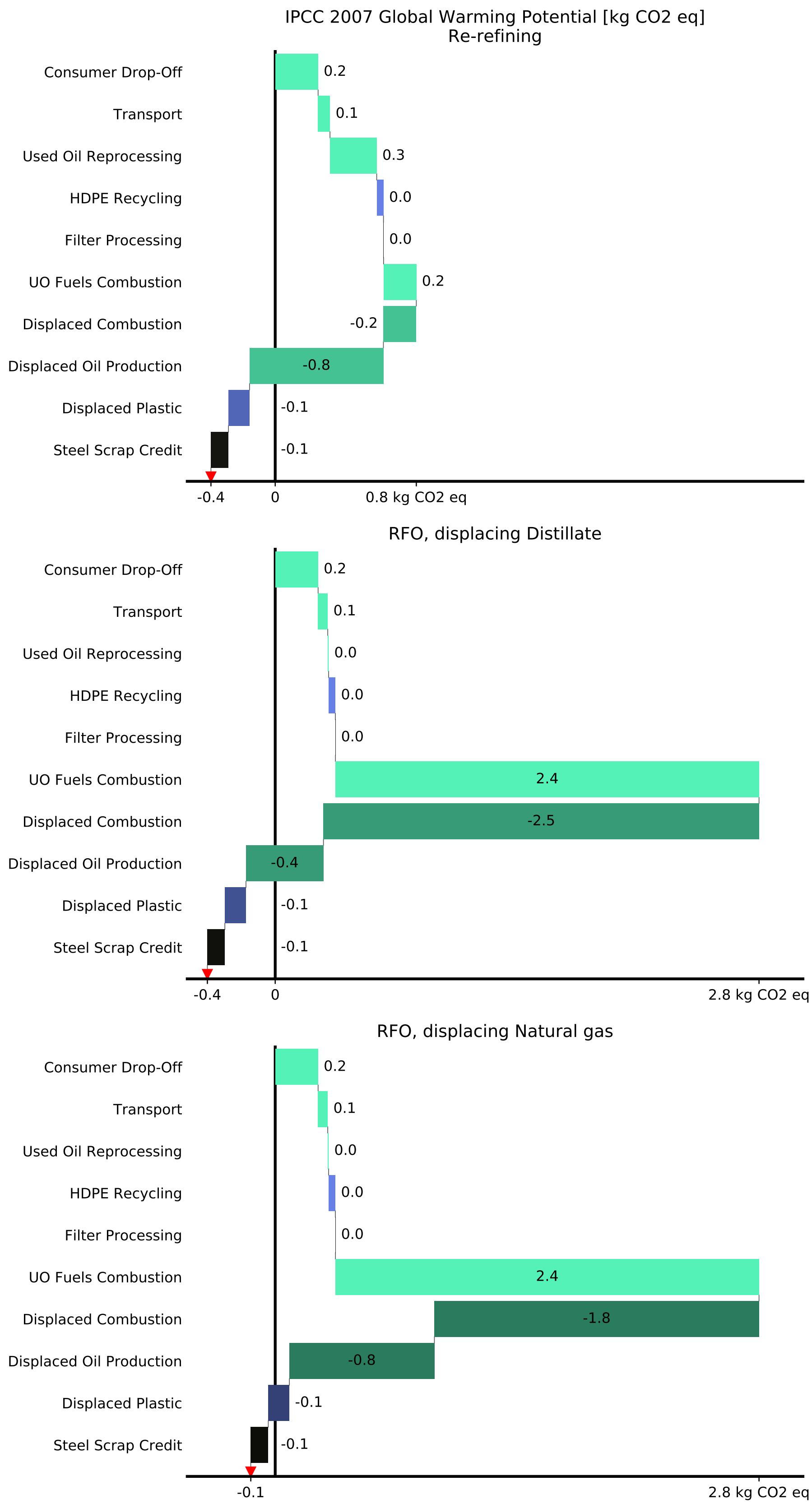

Figure 4: Waterfall chart showing global warming potential impacts for the three scenarios.

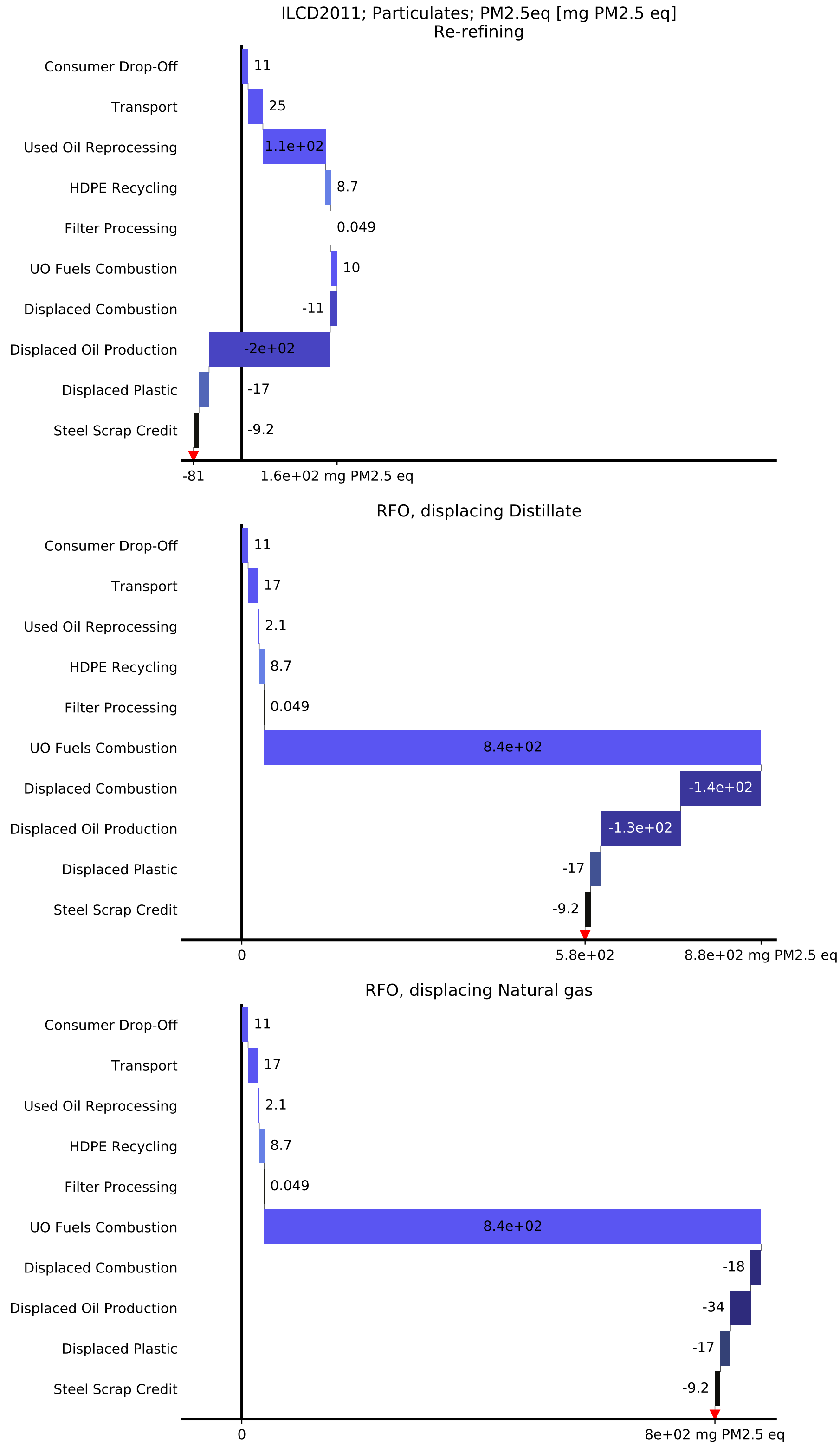

Figure 5: Waterfall chart showing particulate emission potential impacts for the three scenarios.

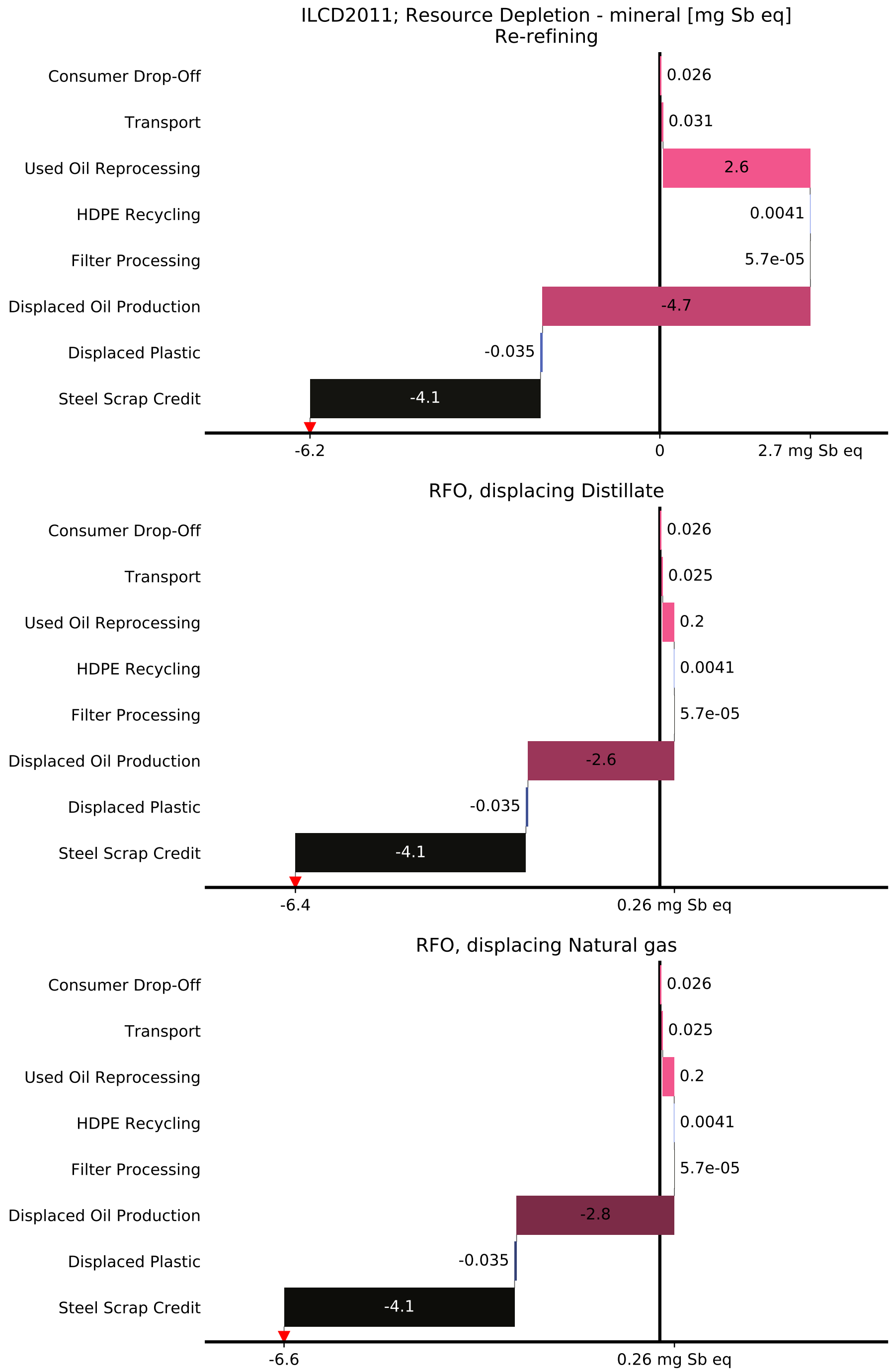

Figure 6: Waterfall chart showing mineral resource depletion potential impacts for the three scenarios.

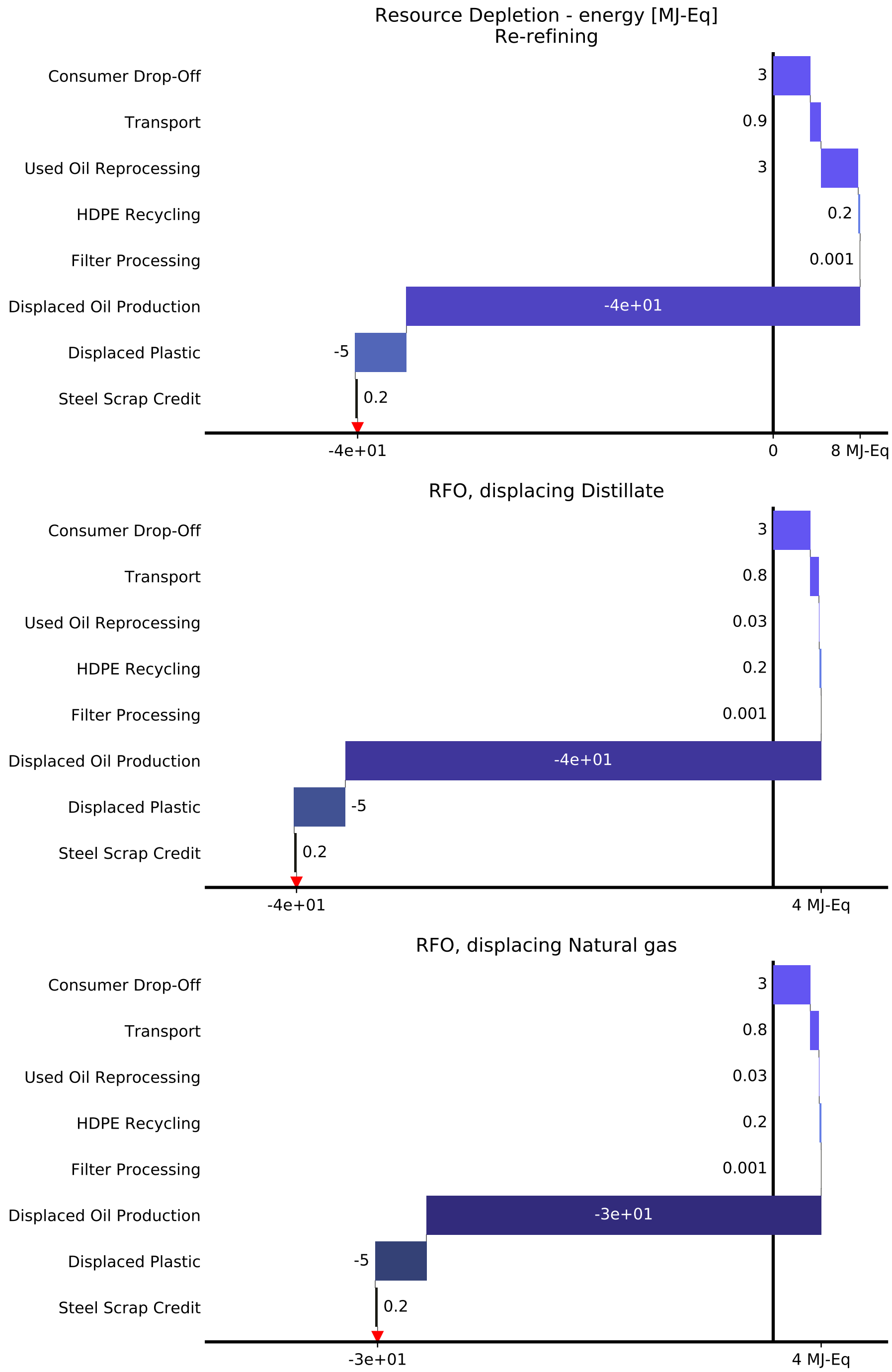

Figure 7: Waterfall chart showing energy resource depletion potential impacts for the three scenarios.

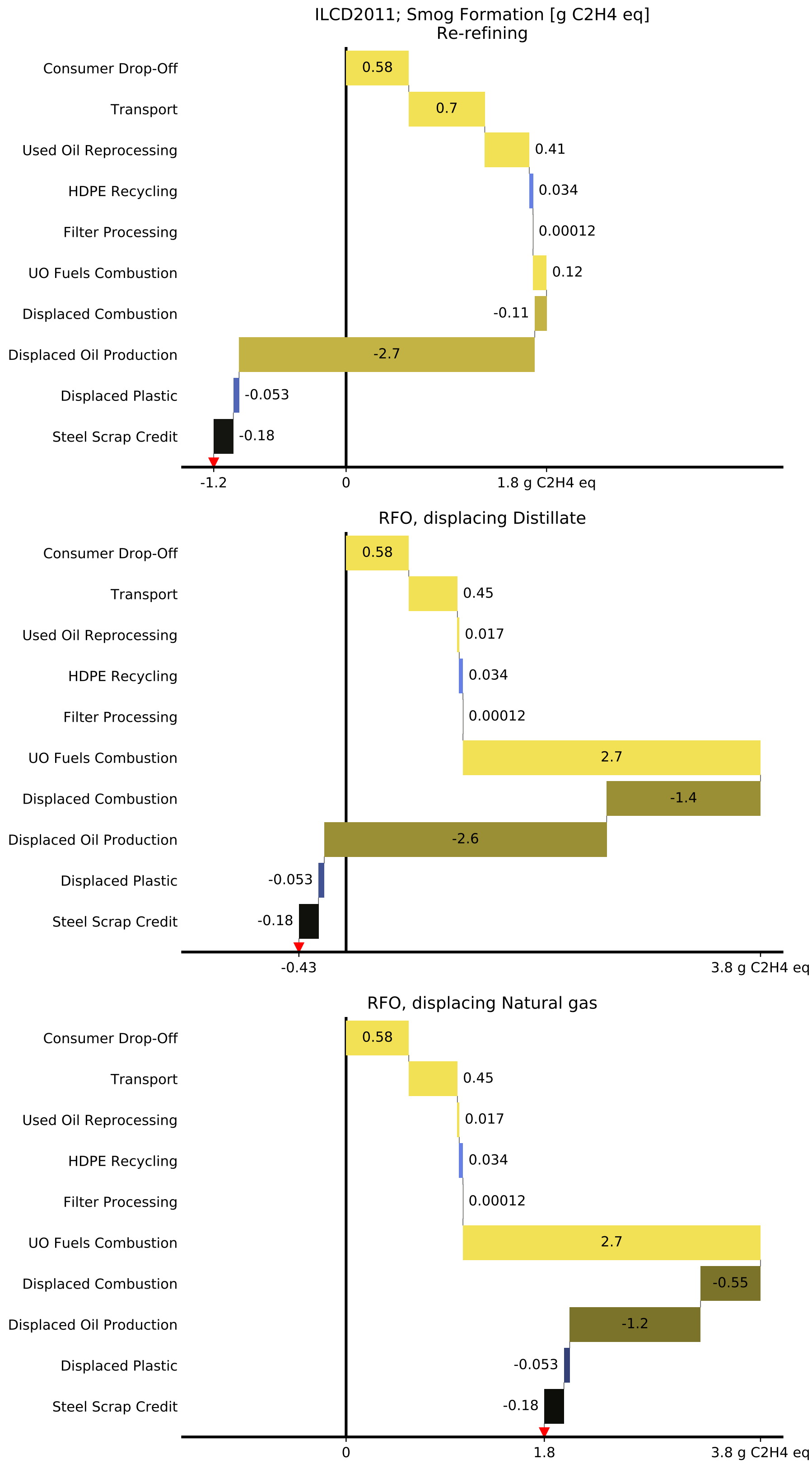

Figure 8: Waterfall chart showing smog formation potential impacts for the three scenarios.

4.2.1 Climate Change

All three scenarios show a small net reduction in global warming potential after considering both direct and avoided impacts. Both RFO routes result in significantly higher direct emissions than the ReRe route (factor of 3.4), and also in larger avoided emissions. Because natural gas is more carbon-efficient than used oil, the natural gas route has the smallest net reduction of the three routes. This is slightly offset by the high estimated production emissions of natural gas, due to methane leakage assumptions. The consumer drop-off stage is a large contributor in comparison to the net result.

4.2.2 Respiratory Inorganics

The primary contributor to respiratory inorganics impacts is particulates from combustion emissions. The ReRe route shows a modest net reduction in this category. However, RFO has a relatively high ash content, and RFO combustion has high particulate emissions when compared to other combustible fuels. As a consequence, the RFO combustion routes both show significant increases over the displaced combustion. Natural gas, being particularly clean burning, shows the smallest avoided burdens.

4.2.3 Abiotic Resource Depletion - Minerals

Mineral abiotic depletion measures the consumption of non-renewable resources in proportion to economically viable proved reserves. In all cases, reprocessing generates the largest depletion impacts, but avoided impacts due to displaced production are much greater and are evenly split between steel scrap value and displaced petroleum production. The net reduction in abiotic depletion potential is roughly constant across all 3 scenarios.

4.2.4 Abiotic Resource Depletion - Energy

Energy abiotic depletion measures the consumption of non-renewable resources in terms of their calorific value. It is also called cumulative non-renewable energy demand. In all cases, the avoided production of primary oil resources is the dominant feature of the system, with avoided plastic production providing a smaller benefit proportionate with its energy content.

4.2.5 Photochemical Ozone Formation

Smog formation is associated with both transportation emissions and other forms of fuel combustion. In the ReRe scenario, transport (including consumer drop-off) is the dominant driver of emissions, but avoided emissions from displaced production exceed the direct impacts. In the RFO routes, RFO combustion is a much greater contributor. In the case where RFO displaces distillate, the net effect is roughly zero; but when RFO displaces cleaner-burning natural gas, the RFO route generates a net increase in burdens.

5 Life Cycle Interpretation

5.1 General Observations

Three of the four impact categories (excluding abiotic resource depletion) are mainly driven by combustion impacts. Because the RFO routes involve combustion of used oil, these routes show significantly higher impacts in these categories. However, in the combustion cases, the large emissions from used oil combustion directly offset emissions from displaced fuel combustion. These combustion and avoided combustion processes are the largest contributors to life cycle impact.

In all categories, the impacts from consumer drop-off are comparable in magnitude to the other reverse logistics steps. The distance driven by the consumer can thus have a significant effect on the results. If the assumed distance of 5 km were doubled, then the net impact reductions in global warming and smog formation would be all but erased.

5.2 Significance of the Different Materials

The contribution analysis results presented in the modelling details (Section B) show that each of the three material systems on its own results in a net reduction in environmental burdens when recycled. In the combined system, the contributions from plastic and steel recycling, and avoided plastic and steel burdens, are modest but detectable. In particular, the steel recycling credit accounts for roughly half the net benefit for abiotic resource depletion. However, with regard to the emission-driven categories, the benefits from recycling are roughly proportionate with the masses recycled, and the mass of oil greatly exceeds the mass of plastic and steel.

5.3 Sensitivity to Displacement

The displacement assumption is more apt in some cases than in others. The demand for base oil is roughly constant and the quality of re-refined base oil is comparable to virgin oil. Therefore it is likely that re-refining generates a high degree of displacement. However, fuel combustion is much more elastic and there is the possibility that fuels displaced by RFO will still be produced and sold elsewhere, meaning that no burdens are avoided.

If no displacement is assumed, then the negative impact scores will not apply and only the positive impacts will accrue. The primary environmental benefit of the recycling system would be to responsibly manage a hazardous waste product, without bringing about any reduced burdens through recycling. In this case re-refining has significantly lower overall impacts than RFO for every category except abiotic resource depletion. Evaluating the validity of the displacement assumption in the particular cases of Alberta and British Columbia will require further study.

6 Future Work

The results have a number of limitations that have been discussed elsewhere in the report. Further LCA work for AUOMA / BCUOMA can address some of these limitations.

- *Expanded scope*:
    - *i*. The study's models for container and filter collection and recycling are limited because of a lack of up-to-date information. However, both filters and containers are experiencing major changes that will affect collection and processing activities as well as sustainability metrics. The study could be expanded to include these changes.
    - *ii*. The drop-off and collection models could be extended to include larger-volume automotive sources such as quick-lube shops or heavy-duty vehicles, or expanded to industrial or agricultural oils. Taking this route would enable the results to be more representative of the program's activities.
    - *iii*. The study could be paired with sales and/or collection information in order to indicate the breadth of coverage.
    - *iv*. Additional materials such as antifreeze could be added to the study. This could further emphasize how by bringing additional materials into a stewardship program can magnify the program's impact.
- *First-mile impacts*: Consumer delivery of used oil is an important area of concern, both from an LCA perspective and otherwise. Additional study could focus on transportation requirements and compliance burdens for the first link in the logistics chain, and may indicate possible beneficial uses of incentive payments.
- *Last-mile impacts*: The benefits of recycling depend strongly on the fate of recycled materials. More study on where the materials are going and how they are ultimately marketed could strengthen (but could also weaken) claims of environmental benefit and could conceivably influence incentive payments.
- *Toxicity modelling*: The ecological benefits of responsible management could be highlighted. Approaching this question is very complex and could take several paths.

i. The toxicity content of present-day oil could be evaluated with laboratory testing. This may make arguments against Alberta's road oiling policy more persuasive.

ii. Toxic emissions from re-refining are probably minimal but could be evaluated. Toxic emissions from combustion are more significant but still less than dumping (see Toxicity Annex). These indicators could be added to the study.

iii. The toxic emissions from primary oil extraction and refining could be studied, in order to compare with the (likely milder, but more local) emissions from re-refining and recycled fuel oil combustion.

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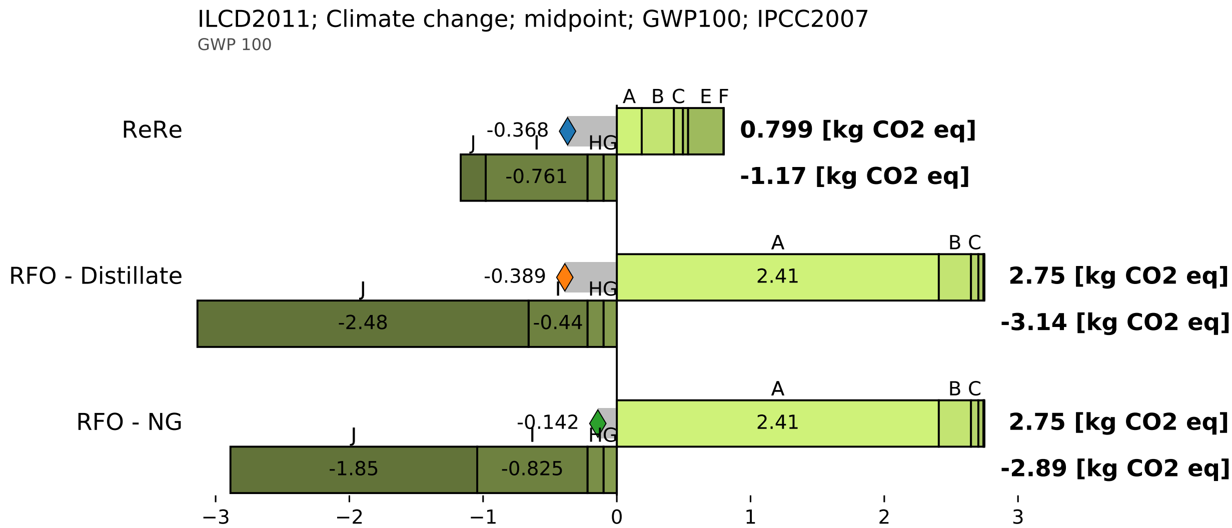
Appendices

Appendix A Tabular Results

These charts show positive and negative contributions of each stage across each scenario. The results are shown in bar chart form, and the vertical axis indicates zero. Positive-valued impacts appear on a higher bar and grow to the right, and negative-valued "avoided burden" credits appearing on a lower bar and growing to the left. The net of positive and negative impact scores is shown with a gray bar and marked with a diamond. In the tables, the most significant stages are highlighted in bold.

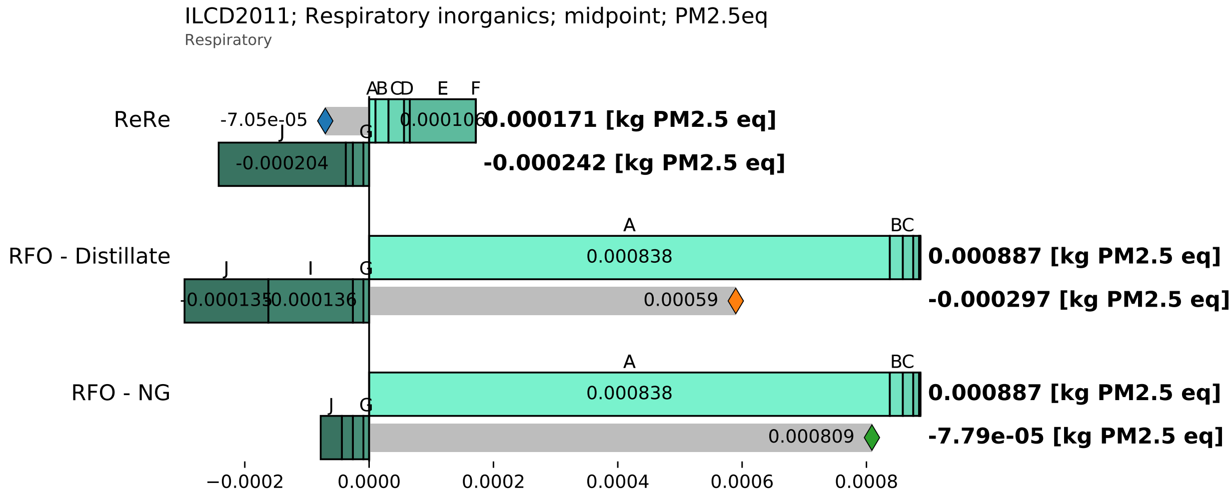
A.1 Climate Change



ILCD2011; Climate change; midpoint; GWP100; IPCC2007

Stage	ReRe	RFO - Distillat	RFO - NG
A – Use	1.86e-01	**2.41e+00**	**2.41e+00**
B – Consumer Drop-Off	**2.41e-01**	2.41e-01	2.41e-01
C – Transport	6.78e-02	5.50e-02	5.50e-02
D – HDPE Recycling	3.84e-02	3.84e-02	3.84e-02
E – Reprocessing	**2.65e-01**	4.90e-03	4.90e-03
F – Steel Shredding	5.01e-04	5.01e-04	5.01e-04
G – Steel Scrap Credit	-9.95e-02	-9.95e-02	-9.95e-02
H – Displaced Plastic Credit	-1.20e-01	-1.20e-01	-1.20e-01
I – Displaced Prod.	**-7.61e-01**	-4.40e-01	**-8.25e-01**
J – Displaced Use	-1.87e-01	**-2.48e+00**	**-1.85e+00**
TOTAL:	**-3.684e-01**	**-3.888e-01**	**-1.420e-01**

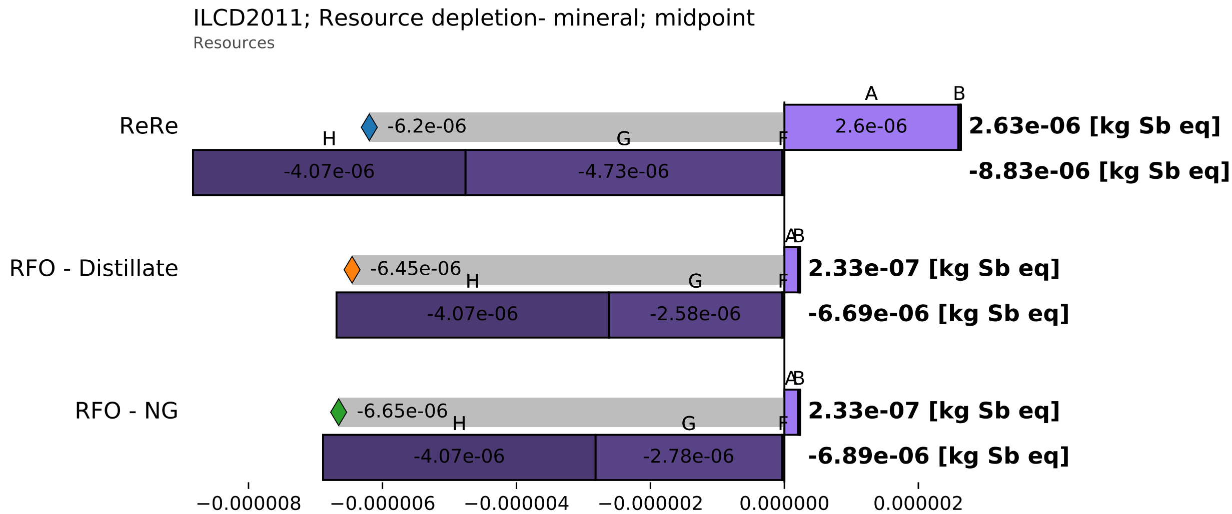
A.2 Respiratory Inorganics



ILCD2011; Respiratory inorganics; midpoint; PM2.5eq

Stage	**ReRe**	**RFO - Distillat**	**RFO - NG**
A – Use	1.03e-05	**8.38e-04**	**8.38e-04**
B – Consumer Drop-Off	2.09e-05	2.09e-05	2.09e-05
C – Transport	2.50e-05	1.68e-05	1.68e-05
D – HDPE Recycling	9.23e-06	9.23e-06	9.23e-06
E – Reprocessing	**1.06e-04**	2.13e-06	2.13e-06
F – Steel Shredding	5.20e-08	5.20e-08	5.20e-08
G – Steel Scrap Credit	-9.23e-06	-9.23e-06	-9.23e-06
H – Displaced Plastic Credit	-1.69e-05	-1.69e-05	-1.69e-05
I – Displaced Use	-1.14e-05	**-1.36e-04**	-1.77e-05
J – Displaced Prod.	**-2.04e-04**	**-1.35e-04**	-3.41e-05
TOTAL:	**-7.054e-05**	**5.898e-04**	**8.088e-04**

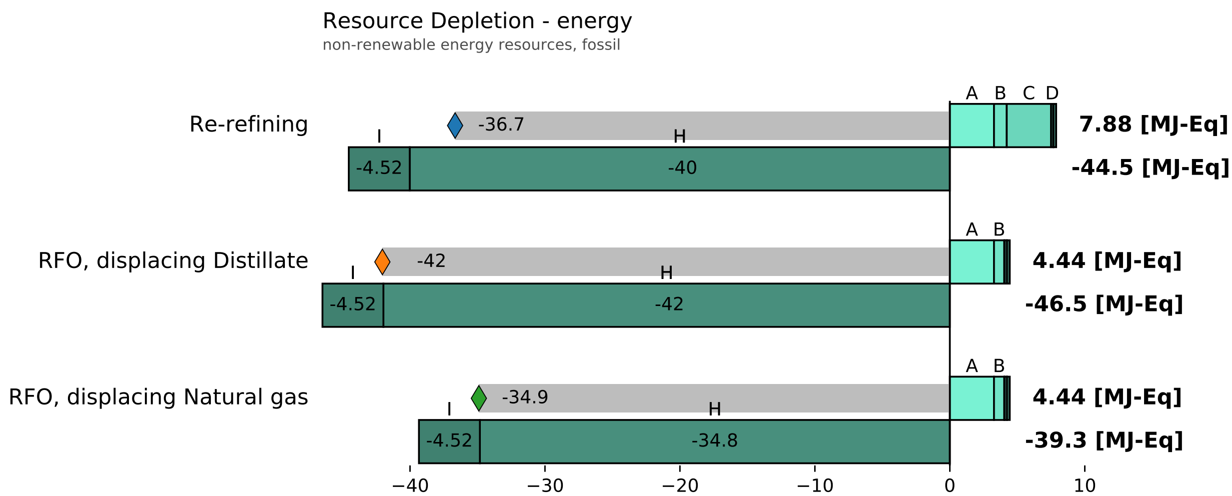
A.3 Abiotic Resource Depletion - Minerals



ILCD2011; Resource depletion- mineral; midpoint

Stage	ReRe	RFO - Distillat	RFO - NG
A – Reprocessing	**2.60e-06**	2.03e-07	2.03e-07
B – Transport	3.08e-08	2.48e-08	2.48e-08
C – HDPE Recycling	2.88e-09	2.88e-09	2.88e-09
D – Consumer Drop-Off	2.20e-09	2.20e-09	2.20e-09
E – Steel Shredding	4.97e-11	4.97e-11	4.97e-11
F – Displaced Plastic Credit	-3.55e-08	-3.55e-08	-3.55e-08
G – Displaced Prod.	**-4.73e-06**	**-2.58e-06**	**-2.78e-06**
H – Steel Scrap Credit	**-4.07e-06**	**-4.07e-06**	**-4.07e-06**
TOTAL:	**-6.197e-06**	**-6.454e-06**	**-6.654e-06**

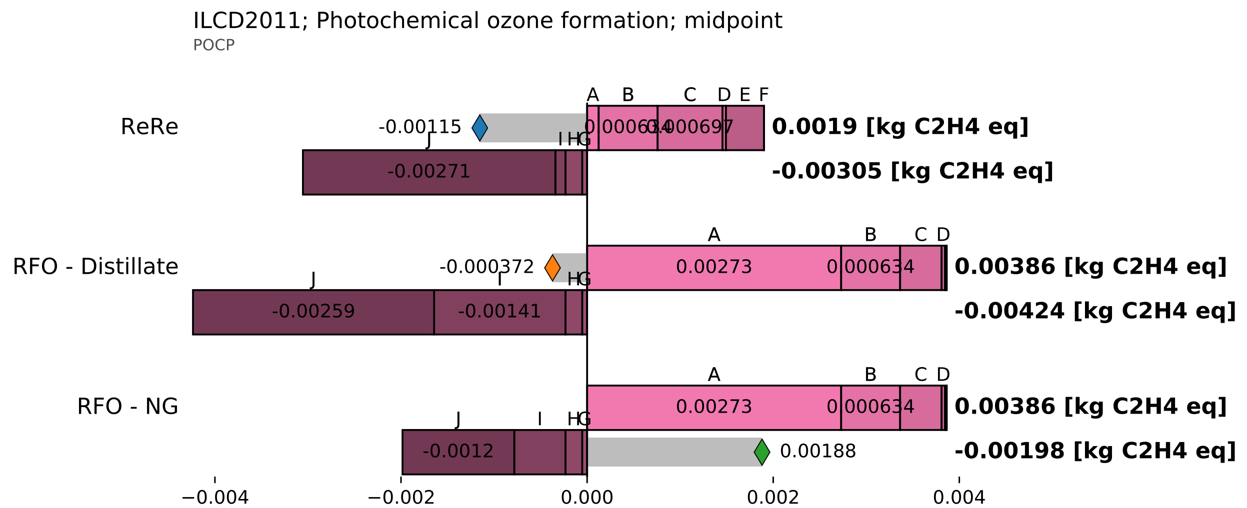
A.4 Abiotic Resource Depletion - Energy



Resource Depletion - energy

Stage	Re-refining	RFO – Distillat	RFO – NG
A – Consumer Drop-Off	3.27e+00	3.27e+00	3.27e+00
B – Transport	9.45e-01	7.62e-01	7.62e-01
C – Used Oil Reprocessing	3.28e+00	2.69e-02	2.69e-02
D – HDPE Recycling	1.70e-01	1.70e-01	1.70e-01
E – Filter Processing	9.80e-04	9.80e-04	9.80e-04
F – UO Fuels Combustion	–	–	–
G – Displaced Combustion	–	–	–
H – Displaced Oil Production	**-4.00e+01**	**-4.20e+01**	**-3.48e+01**
I – Displaced Plastic	-4.52e+00	-4.52e+00	**-4.52e+00**
J – Steel Scrap Credit	2.08e-01	2.08e-01	2.08e-01
TOTAL:	**-3.666e+01**	**-4.205e+01**	**-3.490e+01**

A.5 Photochemical Ozone Formation



ILCD2011; Photochemical ozone formation; midpoint

Stage	**ReRe**	**RFO - Distillat**	**RFO - NG**
A – Use	1.24e-04	**2.73e-03**	**2.73e-03**
B – Consumer Drop-Off	**6.34e-04**	6.34e-04	**6.34e-04**
C – Transport	**6.97e-04**	4.46e-04	4.46e-04
D – HDPE Recycling	3.72e-05	3.72e-05	3.72e-05
E – Reprocessing	4.08e-04	1.70e-05	1.70e-05
F – Steel Shredding	1.39e-07	1.39e-07	1.39e-07
G – Displaced Plastic Credit	-5.30e-05	-5.30e-05	-5.30e-05
H – Steel Scrap Credit	-1.80e-04	-1.80e-04	-1.80e-04
I – Displaced Use	-1.08e-04	**-1.41e-03**	-5.50e-04
J – Displaced Prod.	**-2.71e-03**	**-2.59e-03**	**-1.20e-03**
TOTAL:	**-1.154e-03**	**-3.719e-04**	**1.880e-03**

Appendix B Model Details

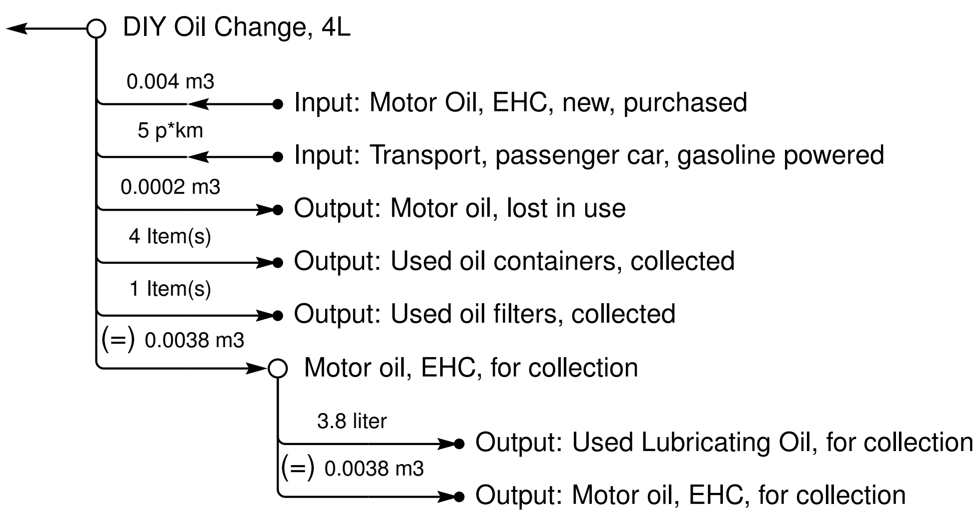
f_oc

B.1 DIY Oil Change, 4L

Output: 1 Item(s) DIY Oil Change, 4L

One typical 4-L oil change. The collected oil is assumed to be transported a short distance (5 km) by private vehicle to a collection location. 5% losses in use are assumed for used oil, leading to a collected volume of 3.8 L per oil change, along with 4 L of HDPE containers and one steel filter.

Input	5	p*km	Transport, passenger car, gasoline powered
Input	0.004	m3	Motor Oil, EHC, new, purchased
Output	4	Item(s)	Used oil containers, collected
Output	3.8	liter	Used Lubricating Oil, for collection
Output	1	Item(s)	Used oil filters, collected
Output	1	Item(s)	DIY Oil Change, 4L
Output	0.0038	m3	Motor oil, EHC, for collection
Output	0.0002	m3	Motor oil, lost in use



Contribution Analysis

No Impacts.

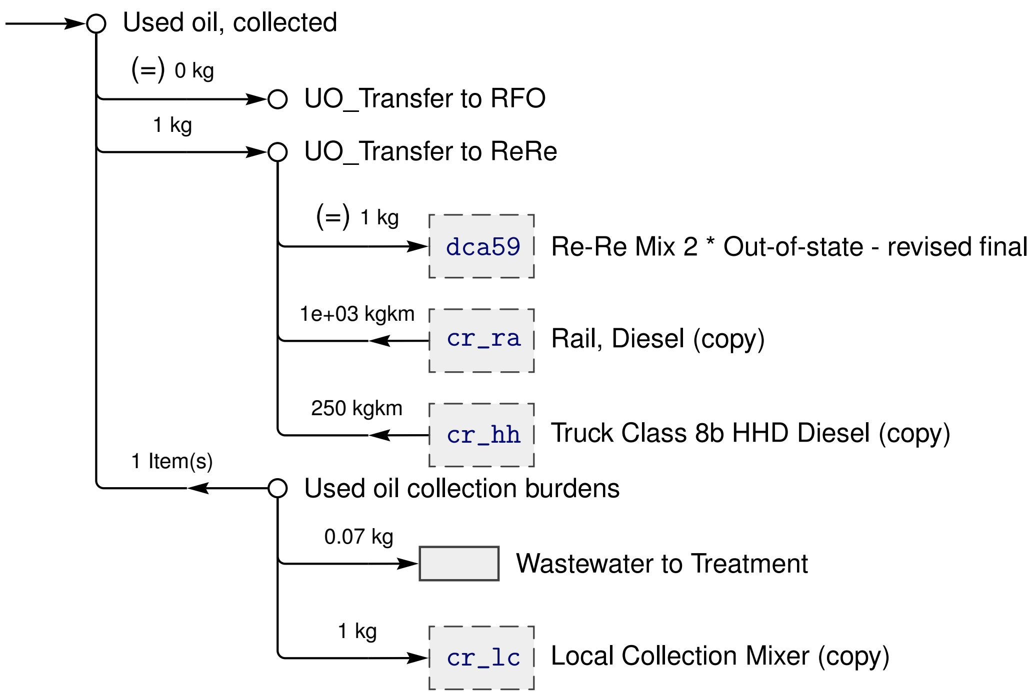
f_col

B.2 Used oil, collected

Input: 1 kg Used oil, collected

This model component follows the collected used oil through the selected disposition route, being either re-refining or RFO production and combustion. The Re-refining and RFO routes themselves are reproduced as-modeled in the CalRecycle study. Reverse logistics includes a local collection stage where oil from collection stations is bulked, followed by a reverse logistics stage in which the oil is shipped either by truck or by rail to the point of reprocessing or use. Shipment to re-refining was assumed 1,250 km, 80% by rail and 20% by truck. Shipment to RFO use was assumed 350 km, 70% by large truck and 30% by small truck. Treatment of waste water generated during pre-processing is included. Inventory data shown reflect the ReRe scenario.

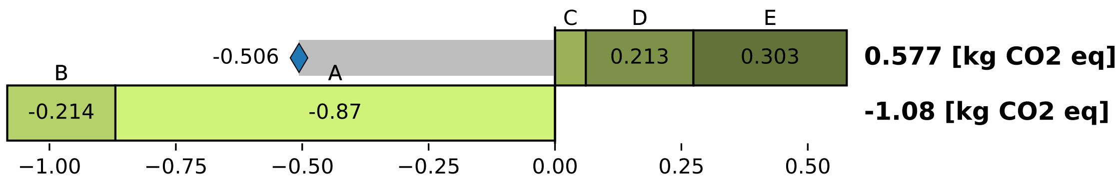
Input	1.03	kgkm	US: Dummy_Transport, pipeline, unspecified
Input	1	kg	Used oil, collected
Input	0.0323	MJ	US: Electricity, Transmission losses
Input	0.00191	kg	US: Dummy_Disposal, solid waste, unspecified, to unspecified treatment
Input	0.000641	MJ	US: Dummy_Electricity, fossil, unspecified, at power plant
Input	0.000102	MJ	Secondary fuel
Input	3.19e-05	kg	US: Dummy_Disposal, lignite coal combustion byproducts, to unspecified reuse
Input	1.94e-05	kg	US: Dummy_Disposal, solid waste, unspecified, to sanitary landfill
Input	9.73e-06	MJ	Secondary fuel renewable
Output	1	kgP	Used Oil Collected
Output	1	kg	Used Oil to Formal Management
Output	0.656	kgP	Re-refined Base Oil
Output	0.656	kg-Av	Avoided Base Oil
Output	0.656	kg	UO_re-refined base oil
Output	0.373	MJ	Thermal energy (MJ)
Output	0.13	kgP	Asphalt Product
Output	0.13	kg-Av	Avoided Bitumen
Output	0.13	kg	UO_Asphalt Flux
Output	0.067	kg-Av	Avoided No 2 Distillate
Output	0.0667	kgP	Light Fuel
Output	0.0152	kg	UO_EG LERT Bottoms
Output	0.0152	kgP	Ethylene Glycol
Output	0.00639	kgkm	US: Dummy_Transport, pipeline, coal slurry
Output	0.000299	kg	US: Dummy_Disposal, solid waste, unspecified, to underground deposit
Output	4.07e-05	kg	US: Dummy_Disposal, ash and flue gas desulfurization sludge, to unspecified reuse
Output	1.14e-09	kg	US: Dummy_Disposal, anthracite coal combustion byproducts, to unspecified reuse


Used oil, collected
(=) 0 kg
UO_Transfer to RFO
1 kg
UO_Transfer to ReRe
(=) 1 kg
dca59
Re-Re Mix 2 * Out-of-state - revised final
1e+03 kgkm
cr_ra
Rail, Diesel (copy)
250 kgkm
cr_hh
Truck Class 8b HHD Diesel (copy)
1 Item(s)
Used oil collection burdens
0.07 kg
Wastewater to Treatment
1 kg
cr_lc
Local Collection Mixer (copy)

Contribution Analysis

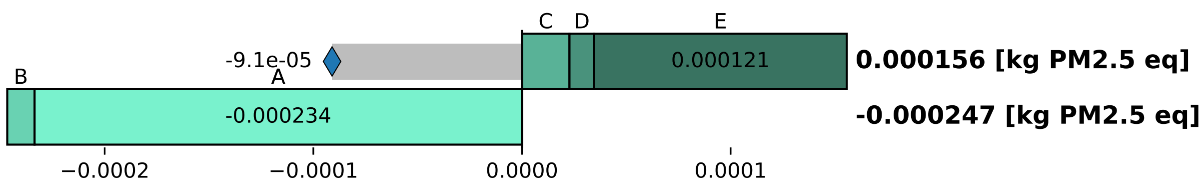
ILCD2011; Climate change; midpoint; GWP100; IPCC2007

GWP 100



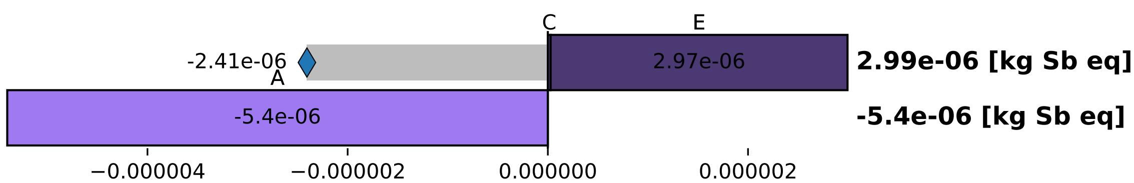
ILCD2011; Respiratory inorganics; midpoint; PM2.5eq

Respiratory



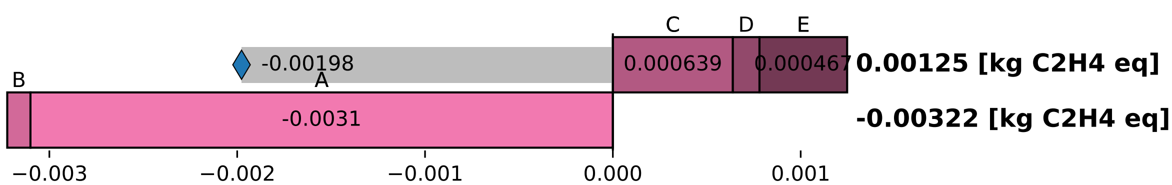
ILCD2011; Resource depletion- mineral; midpoint

Resources



ILCD2011; Photochemical ozone formation; midpoint

POCP



Stage	GWP 100 kg CO2 eq	Respiratory kg PM2.5 eq	Resources kg Sb eq	POCP kg C2H4 eq
A – Displaced Prod.	**-8.70e-01**	**-2.34e-04**	**-5.40e-06**	**-3.10e-03**
B – Displaced Use	**-2.14e-01**	-1.31e-05	–	-1.24e-04
C – Transport	6.10e-02	2.28e-05	2.77e-08	**6.39e-04**
D – Use	**2.13e-01**	1.18e-05	–	1.42e-04
E – Reprocessing	**3.03e-01**	**1.21e-04**	**2.97e-06**	**4.67e-04**
TOTAL:	**-5.063e-01**	**-9.102e-05**	**-2.407e-06**	**-1.977e-03**

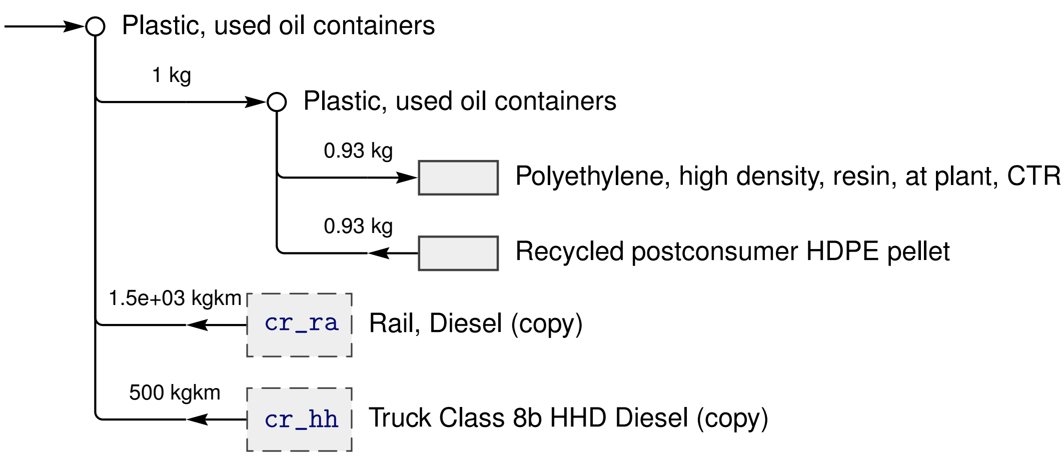
f_pla

B.3 Plastic, used oil containers

Input: 1 kg Plastic, used oil containers

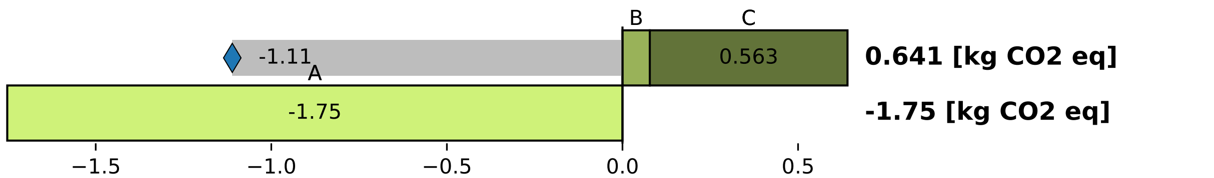
This model fragment includes reverse logistics, reprocessing, and displaced production associated with HDPE oil container recycling. The plastic was assumed shipped 2,000 km, 75% by rail and 25% by heavy truck, to a plastic recycling facility. Mechanical recycling is assumed, with the model adapted from the US LCI database. Treatment chemicals, including detergents, surfactants, and wetting agents, are cut off, except sodium hydroxide is included. Recycling has a yield of 93% and the product is assumed to displace primary HDPE granulate (also modeled from US LCI).

Input	1	kg	Plastic, used oil containers

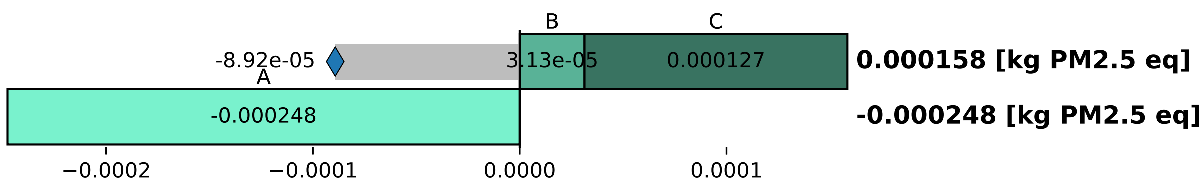


Contribution Analysis

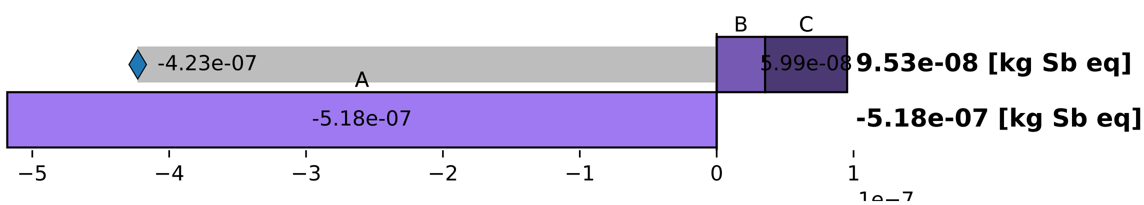
ILCD2011; Climate change; midpoint; GWP100; IPCC2007
GWP 100



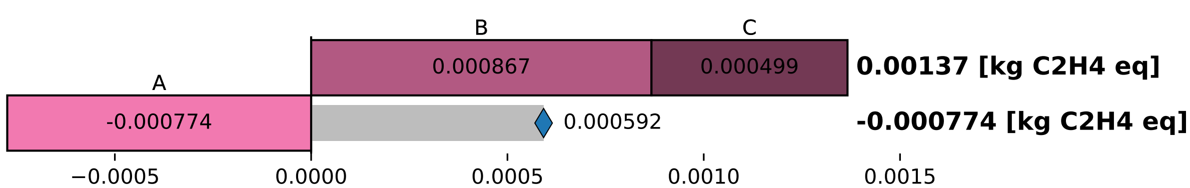
ILCD2011; Respiratory inorganics; midpoint; PM2.5eq
Respiratory



ILCD2011; Resource depletion- mineral; midpoint
Resources



ILCD2011; Photochemical ozone formation; midpoint
POCP



Stage	GWP 100 kg CO2 eq	Respiratory kg PM2.5 eq	Resources kg Sb eq	POCP kg C2H4 eq
A – Displaced Plastic Credit	**-1.75e+00**	**-2.48e-04**	**-5.18e-07**	**-7.74e-04**
B – Transport	7.78e-02	3.13e-05	3.54e-08	**8.67e-04**
C – HDPE Recycling	**5.63e-01**	**1.27e-04**	5.99e-08	**4.99e-04**
TOTAL:	**-1.111e+00**	**-8.921e-05**	**-4.230e-07**	**5.921e-04**

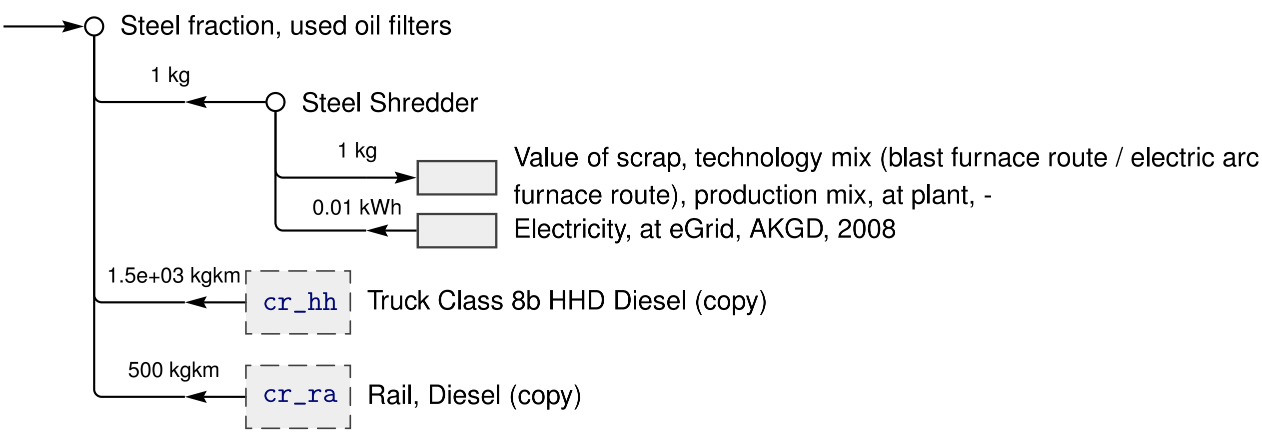
f_ste

B.4 Steel fraction, used oil filters

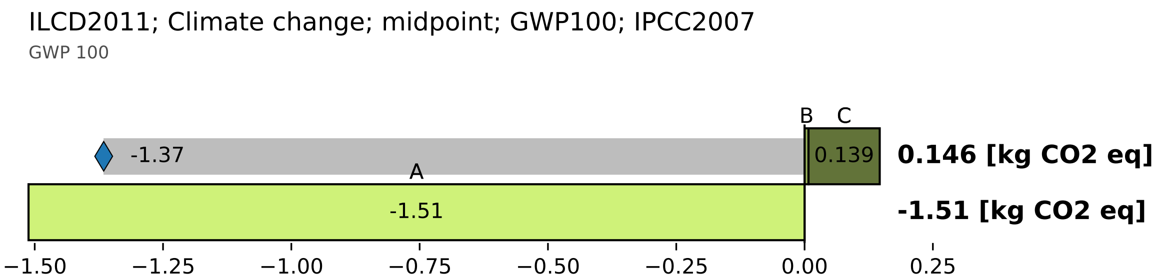
Input: 1 kg Steel fraction, used oil filters

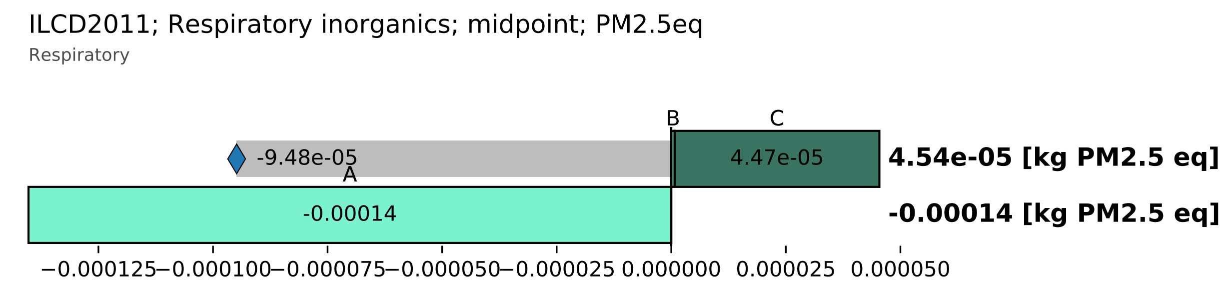
This model fragment includes reverse logistics, reprocessing, and displaced production associated with steel recycling. The steel was assumed shipped 2,000 km, 75% by truck and 25% by rail. Filter processing was assumed to use either a hammermill or shear-type shredder, with an electric power consumption of 10 kWh/ton (Fitzgerald 2009). An electric grid mix to approximate conditions in Alberta was selected. The ecological value of the scrap steel was modeled using the WorldSteel Association's LCA study.

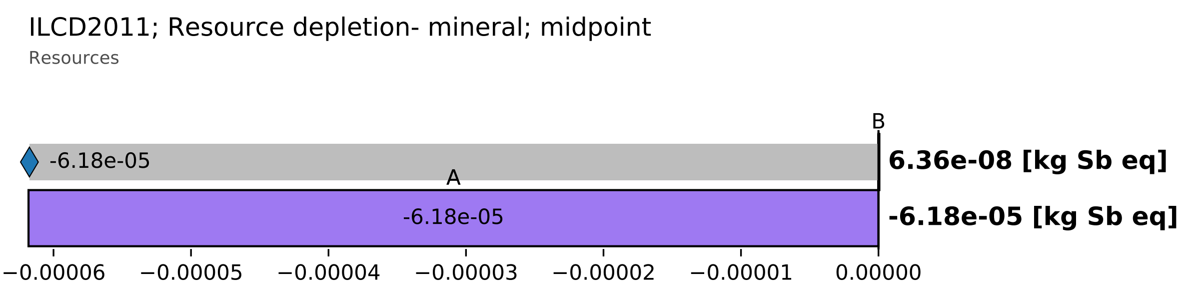
Input	1	kg	Steel fraction, used oil filters

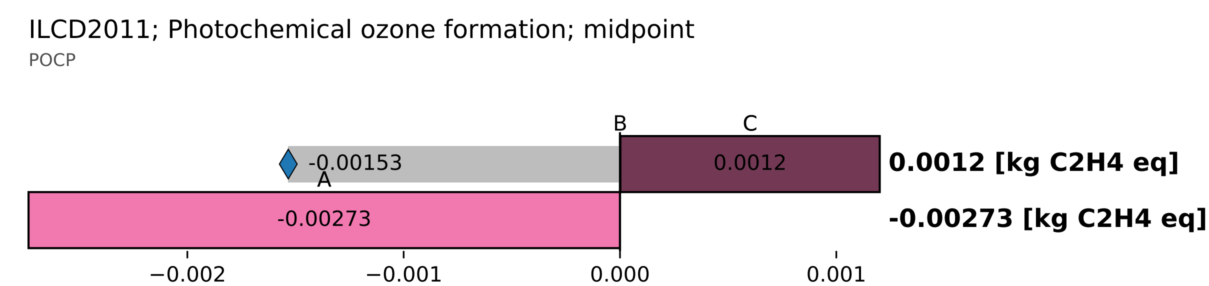


Contribution Analysis









Stage	**GWP 100** kg CO2 eq	**Respiratory** kg PM2.5 eq	**Resources** kg Sb eq	**POCP** kg C2H4 eq
A – Steel Scrap Credit	**-1.51e+00**	**-1.40e-04**	**-6.18e-05**	**-2.73e-03**
B – Steel Shredding	7.64e-03	7.43e-07	8.62e-10	1.85e-06
C – Transport	1.39e-01	**4.47e-05**	6.27e-08	**1.20e-03**
TOTAL:	**-1.366e+00**	**-9.484e-05**	**-6.175e-05**	**-1.533e-03**