
Life Cycle Assessment of Used Oil Management in California

Pursuant to Senate Bill 546 (Lowenthal)



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Table of Contents

Table of Contents	i
Table of Figures	iii
Table of Tables	vi
Abbreviations.....	xii
1 General Aspects.....	1
1.1 Legislative Context.....	3
1.2 Recycling Routes	7
1.3 Literature Review	9
2 Goal	11
3 Scope	11
3.1 The Product System.....	11
3.2 Functional Unit.....	12
3.3 System Boundary.....	12
3.4 Exclusions from the System Boundary.....	13
3.5 Cut-Off Criteria.....	14
3.6 Allocation Procedures.....	14
3.7 Impact Assessment	15
3.8 Data Requirements.....	16
3.9 Assumptions	18
3.10 Limitations.....	19
3.11 Critical Review	20
3.12 Reporting	21
4 Life Cycle Inventory Analysis.....	21
4.1 Reference Flow Modeling	21
4.2 Inventory Design and Life Cycle Stages	24
4.3 Background Processes	35
5 Life Cycle Impact Assessment.....	40
5.1 Base Year and Extreme Scenarios – Informal Management	42
5.2 Base Year and Extreme Scenarios – Formal Management.....	52
5.3 Direct Impact Model Scenarios	85
5.4 DIM Scenario LCIA Graphs.....	107
5.5 Statutory Scenarios	116
6 Life Cycle Interpretation	117

6.1	Identification of Significant Issues	117
6.2	Other Model Uncertainties.....	120
6.3	Conclusions.....	136
7	Critical Review.....	136
8	References	137
9	Appendix A: Material Flow Analysis (MFA) Methodology.....	146
9.1	Introduction.....	146
9.2	Methods	147
10	Appendix B: Combustion Model	153
10.1	Introduction.....	153
10.2	Methodology	155
10.3	Data resources:.....	161
10.4	Results.....	165
10.5	Emission Factors.....	170
11	Appendix C: Informal Management	190
11.1	Dumped used oil.....	190
11.2	Parameter estimates	192
11.3	Modeled processes.....	198
11.4	Summary of informal management	200
12	Appendix D: Displacement Modeling	203
12.1	Determination of Displaced Products	204
13	Appendix E: Closed-Loop Versus Open-Loop Recycling.....	207
14	Appendix F: Data Map and Quality Assessment	211

Table of Figures

Figure 1: Production of Recycled Fuel Oil (RFO).....	7
Figure 2: Production of Marine Distillate Oil (MDO).....	8
Figure 3: Production of Re-Refined Base Oil.....	9
Figure 4: The system boundary of the life cycle assessment of used oil management in CA.	12
Figure 5: Global Warming Potential in kg CO ₂ equivalent for the 2010 base year model.	47
Figure 6: Acidification Potential in H ⁺ moles equivalent for the 2010 base year model.	48
Figure 7: Eutrophication Potential in kg N equivalent for the 2010 base year model.	48
Figure 8: Ecotoxicity Potential in CTUeco equivalent for the 2010 base year model.....	48
Figure 9: Human Health Cancer Potential in cases for the 2010 base year model.	49
Figure 10: Human Health Non-Cancer Potential in cases for the 2010 base year model.	49
Figure 11: Human Health Criteria Air Potential in kg PM ₁₀ equivalent for the 2010 base year.....	50
Figure 12: Smog Creation Potential in kg O ₃ equivalent for the 2010 base year model.....	50
Figure 13: Life cycle impacts for all categories for the six extreme IM scenarios.	51
Figure 14: Global Warming Potential ranges for formal management.....	56
Figure 15: Global Warming Potential for formal management.	58
Figure 16: Acidification Potential ranges for formal management.....	60
Figure 17: Acidification Potential for formal management.	62
Figure 18: Eutrophication Potential ranges for formal management.	63
Figure 19: Eutrophication Potential for formal management.	65
Figure 20: Ecotoxicity Potential ranges for formal management.	67
Figure 21: Ecotoxicity Potential for formal management.....	69
Figure 22: Human Health Cancer Potential ranges for formal management.	70
Figure 23: Human Health (Cancer) Potential for formal management.....	73
Figure 24: Human Health Non-Cancer Potential ranges for formal management.	75
Figure 25: Human Health (Non Cancer) Potential for formal management.	77
Figure 26: Human Health Criteria Air Potential ranges for formal management.	79
Figure 27: Human Health (Criteria Air) Potential for formal management.....	81
Figure 28: Smog Creation Potential ranges for formal management in kg O ₃ equivalent.....	82
Figure 29: Smog Potential for formal management.....	84
Figure 30: Net Global Warming Potential for all scenarios in kg CO ₂ equivalent.	108

Figure 31: Global Warming Potential of Baseline life stages in kg CO ₂ equivalent.	108
Figure 32: Net Acidification Potential for all scenarios in H ⁺ moles equivalent.	109
Figure 33: Acidification Potential of Baseline life stages in H ⁺ moles equivalent.	109
Figure 34: Net Eutrophication Potential for all scenarios in kg N equivalent.	110
Figure 35: Eutrophication Potential of Baseline life stages in kg N equivalent.	110
Figure 36: Net Ecotoxicity Potential for all scenarios in CTUeco equivalents.	111
Figure 37: Ecotoxicity Potential of Baseline life stages in CTUeco equivalents.....	111
Figure 38: Net Human Health Cancer Potential for all scenarios in cases.	112
Figure 39: Human Health Cancer Potential of Baseline life stages in cases.....	112
Figure 40: Net Human Health Non-Cancer Potential for all scenarios in cases.	113
Figure 41: Human Health Non-Cancer Potential of Baseline life stages in cases.	113
Figure 42: Human Health Criteria Potential for all scenarios in kg PM10 equivalent.	114
Figure 43: Human Health Criteria Potential of Baseline life stages in kg PM10 equivalent.....	114
Figure 44: Net Smog Potential for all scenarios in kg O ₃ equivalent.	115
Figure 45: Smog Potential of Baseline life stages in kg O ₃ equivalent.....	115
Figure 46: Comparison of ecotoxicity indicator scores resulting from informal management scenarios.	124
Figure 47: Human health toxicity indicator scores resulting from informal management scenarios.....	126
Figure 48: Ecotoxicity indicator scores for the retention rate sensitivity analysis.....	128
Figure 49: Human health toxicity indicator scores for the retention rate sensitivity analysis.	129
Figure 50: Ecotoxicity indicator scores for the RFO displacement sensitivity analysis.	130
Figure 51 Human health toxicity indicator scores for the RFO displacement sensitivity analysis.....	131
Figure 52: Ecotoxicity indicator scores for the used oil composition sensitivity analysis.....	132
Figure 53: Human health toxicity indicator scores for the used oil composition sensitivity analysis.	133
Figure 54: Information contained in a hazardous waste manifest and used in the MFA.	147
Figure 55: Computation of the facility mass balance from inflows and outflows.	148
Figure 56: Mass balance discrepancy for facilities receiving used oil during 2010.	149
Figure 57: Consolidation versus direct generation for used oil during the MFA period.	151
Figure 58: Used oil disposition facility by NAICS code, 2007-2011.....	152
Figure 59: Tutorial description of tabular emission factor charts.	166
Figure 60: Tutorial description of retention rate charts.	166
Figure 61: Measured emissions of methane in the combustion model.	171

Figure 62: Distribution of emission measurements for carbon monoxide.	173
Figure 63: Histogram of carbon monoxide emission factor measurements.	173
Figure 64: Emission measurements for oxides of nitrogen by fuel.	174
Figure 65: Measured and reported SOx retention rates.	175
Figure 66: Particulate matter emissions by fuel for facilities with no control technology.	177
Figure 67: Particulate matter emission measurements for used oil by facility.	178
Figure 68: Organic emissions by fuel.	180
Figure 69: Polycyclic organic species by source and fuel.	182
Figure 70: Total PAH by fuel by data source.	183
Figure 71: Retention rates for metals, grouped by technology.	185
Figure 72 (a)-(e): Retention rates for selected metals.	188
Figure 73: Chlorine retention rates by facility.	189
Figure 74: Fate and transport model for improperly disposed used oil.	192
Figure 75: Fate and transport model with estimated probability parameters shown.	202
Figure 76: Closed-loop recycling of material application A over four years.	207
Figure 77: Open-loop recycling of material application A into application B over four years.	208

Table of Tables

Table 1: Used Oil Specifications.	3
Table 2: API Base Oil Standards (American Petroleum Institute, 2007).....	5
Table 3: California Waste Codes related to used Oil (22 CCR, Chapter 11).....	6
Table 4: Data sources (a complete data map is located in Appendix F).	17
Table 5: Data quality requirements. Source: Weidema & Wesnæs (1996).	17
Table 6: The California used oil reference flow..	22
Table 7: Quantities of oil sold, lost in use, and available for collection.	24
Table 8: Estimating the water content of used oil collected.	29
Table 9: Combustion emission factors used in the model, in kg/MJ lower heating value.....	30
Table 10: Default retention rates for various emitted substances by technology.....	31
Table 11: Displacement Relationships.....	32
Table 12: U.S. & California Refinery Model Data Sourcing.....	33
Table 13: Inventory parameters for primary production of displaced petroleum products.....	34
Table 14: Grid mix parameters for WECC and U.S. grid.	37
Table 15: Freight Transport Emission Factors.....	39
Table 16: Fuel economy for on-road freight vehicles used in the study, miles per gallon.	39
Table 17: Mass flow inventory for base year with informal management.....	43
Table 18: Global Warming Potential in kg CO ₂ equivalent for base year and extreme IM scenarios.	44
Table 19: Acidification Potential for base year and extreme IM scenarios.	44
Table 20: Eutrophication Potential for base year and extreme IM scenarios.....	44
Table 21: Ecotoxicity Potential for base year and extreme IM scenarios.....	45
Table 22: Human Health Cancer Potential for base year and extreme IM scenarios.....	45
Table 23: Human Health Non-Cancer Potential for base year and extreme IM scenarios.	46
Table 24: Human Health Criteria Air Potential for base year and extreme IM scenarios.	46
Table 25: Smog Creation Potential for base year and extreme IM scenarios.	47
Table 26: Material flows for the 2010 base year model and the three extreme scenarios.	52
Table 27: High, low, and default settings of the retention rates in the combustion model.	53
Table 28: High, low, and default settings of the organic compound emission rates.....	54
Table 29: Parameter settings for the reverse logistics sensitivity scenario.	54
Table 30: Parameter settings for the reverse logistics sensitivity scenario.	54

Table 31: Parameter settings for the used oil composition sensitivity scenario.....	54
Table 32: Global Warming Potential for formal management.....	59
Table 33: Acidification Potential for formal management.	61
Table 34: Eutrophication Potential for formal management.....	66
Table 35: Ecotoxicity Potential for formal management.	68
Table 36: Ecotoxicity Potential Emission Fate Contribution Analysis.....	68
Table 37: Human Health (Cancer) Potential for formal management.	74
Table 38: Human Health (Cancer) Potential Emission Fate Contribution Analysis.....	74
Table 39: Human Health (Non Cancer) Potential for formal management.	78
Table 40: Human Health (Non Cancer) Potential Emission Fate Contribution Analysis.....	78
Table 41: Human Health (Criteria Air) Potential for formal management.....	80
Table 42: Smog Potential for formal management.	85
Table 43: Used oil and secondary product flows for Baseline Scenario.....	86
Table 44: Global Warming Potential for Baseline Scenario.....	86
Table 45: Acidification Potential for Baseline Scenario.....	87
Table 46: Eutrophication Potential for Baseline Scenario.	87
Table 47: Ecotoxicity Potential for Baseline Scenario.	87
Table 48: Human Health (Cancer) Potential for Baseline Scenario.....	87
Table 49: Human Health (Non Cancer) Potential for Baseline Scenario.....	87
Table 50: Human Health (Criteria Air) Potential for Baseline Scenario.	88
Table 51: Smog Potential for Baseline Scenario.	88
Table 52: Used oil and secondary product flows for Scenario 1.	88
Table 53: Global Warming Potential for Scenario 1.....	89
Table 54: Acidification Potential for Scenario 1.	89
Table 55: Eutrophication Potential for Scenario 1.....	89
Table 56: Ecotoxicity Potential for Scenario 1.	89
Table 57: Human Health (Cancer) Potential in cases for Scenario 1.....	89
Table 58: Human Health (Non Cancer) Potential in cases for Scenario 1.....	90
Table 59: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 1.....	90
Table 60: Smog Potential for Scenario 1.	90
Table 61: Used oil and secondary product flows for Scenario 2.	91

Table 62: Global Warming Potential for Scenario 2.....	91
Table 63: Acidification Potential for Scenario 2.	91
Table 64: Eutrophication Potential for Scenario 2.....	91
Table 65: Ecotoxicity Potential for Scenario 2.	92
Table 66: Human Health (Cancer) Potential for Scenario 2.	92
Table 67: Human Health (Non Cancer) Potential for Scenario 2.	92
Table 68: Human Health (Criteria Air) Potential for Scenario 2.....	92
Table 69: Smog Potential for Scenario 2.	92
Table 70: Used oil and secondary product flows for Scenario 3.	93
Table 71: Global Warming Potential for Scenario 3.....	93
Table 72: Acidification Potential for Scenario 3.	93
Table 73: Eutrophication Potential for Scenario 3.....	93
Table 74: Ecotoxicity Potential for Scenario 3.	94
Table 75: Human Health (Cancer) Potential for Scenario 3.	94
Table 76: Human Health (Non Cancer) Potential for Scenario 3.	94
Table 77: Human Health (Criteria Air) Potential for Scenario 3.....	94
Table 78: Smog Potential for Scenario 3.	94
Table 79: Used oil and secondary product flows for Scenario 4.	95
Table 80: Global Warming Potential for Scenario 4.....	95
Table 81: Acidification Potential for Scenario 4.	95
Table 82: Eutrophication Potential for Scenario 4.....	95
Table 83: Ecotoxicity Potential for Scenario 4.	96
Table 84: Human Health (Cancer) Potential for Scenario 4.	96
Table 85: Human Health (Non Cancer) Potential for Scenario 4.	96
Table 86: Human Health (Criteria Air) Potential for Scenario 4.....	96
Table 87: Smog Potential for Scenario 4.	96
Table 88: Used oil and secondary product flows for Scenario 5.	97
Table 89: Global Warming Potential for Scenario 5.....	97
Table 90: Acidification Potential for Scenario 5.	97
Table 91: Eutrophication Potential for Scenario 5.....	98
Table 92: Ecotoxicity Potential for Scenario 5.	98



Table 93: Human Health (Cancer) Potential for Scenario 5.	98
Table 94: Human Health (Non Cancer) Potential for Scenario 5.	98
Table 95: Human Health (Criteria Air) Potential for Scenario 5.	98
Table 96: Smog Potential for Scenario 5.	98
Table 97: Used oil and secondary product flows for Scenario 6.	99
Table 98: Global Warming Potential for Scenario 6.....	99
Table 99: Acidification Potential for Scenario 6.	99
Table 100: Eutrophication Potential for Scenario 6.....	100
Table 101: Ecotoxicity Potential for Scenario 6.	100
Table 102: Human Health (Cancer) Potential for Scenario 6.	100
Table 103: Human Health (Non Cancer) Potential for Scenario 6.	100
Table 104: Human Health (Criteria Air) Potential for Scenario 6.	100
Table 105: Smog Potential for Scenario 6.	100
Table 106: Used oil and secondary product flows for Scenario 7.	101
Table 107: Global Warming Potential for Scenario 7.....	101
Table 108: Acidification Potential for Scenario 7.....	101
Table 109: Eutrophication Potential for Scenario 7.....	102
Table 110: Ecotoxicity Potential for Scenario 7.	102
Table 111: Human Health (Cancer) Potential for Scenario 7.	102
Table 112: Human Health (Non Cancer) Potential for Scenario 7.	102
Table 113: Human Health (Criteria Air) Potential for Scenario 7.	102
Table 114: Smog Potential for Scenario 7.	102
Table 115: Used oil and secondary product flows for Scenario 9.	103
Table 116: Global Warming Potential for Scenario 9.....	104
Table 117: Acidification Potential for Scenario 9.....	104
Table 118: Eutrophication Potential for Scenario 9.....	104
Table 119: Ecotoxicity Potential for Scenario 9.	104
Table 120: Human Health (Cancer) Potential for Scenario 9.	104
Table 121: Human Health (Non Cancer) Potential for Scenario 9.	104
Table 122: Human Health (Criteria Air) Potential for Scenario 9.	105
Table 123: Smog Potential for Scenario 9.	105



Table 124: Used oil and secondary product flows for Scenario 10.	106
Table 125: Global Warming Potential for Scenario 10.....	106
Table 126: Acidification Potential for Scenario 10.....	106
Table 127: Eutrophication Potential for Scenario 10.....	106
Table 128: Ecotoxicity Potential for Scenario 10.	106
Table 129: Human Health (Cancer) Potential for Scenario 10.	106
Table 130: Human Health (Non Cancer) Potential for Scenario 10.	107
Table 131: Human Health (Criteria Air) Potential for Scenario 10.	107
Table 132: Smog Potential for Scenario 10.	107
Table 133: Hypothetical example case to illustrate life cycle impact assessment.	121
Table 134: Cradle-to-gate GHG emissions from primary refining for various LCI databases.....	135
Table 135: California waste codes related to used oil (California Code of Regulations, 2005b).....	146
Table 136: Material Flow Analysis results delivered to the Direct Impacts Model.....	152
Table 137: Summary of fuel-specific emission factors with no pollutant retention.	154
Table 138: Default retention rate values by combustion technology.....	155
Table 139: Average higher heating values of fuels in the MACT database.	160
Table 140: Data sources included in the development of the used oil combustion model.	165
Table 141: Composition measurements of used oil in the study.	168
Table 142: Composition measurements of No. 2 and No. 6 fuels.	169
Table 143: Metals concentration for marine distillate oil produced from recycled oil.....	170
Table 144: Emission Factors for CO ₂	171
Table 145: Emission factors for methane.	172
Table 146: Emission factors for nitrous oxide.	172
Table 147: Emission factors for carbon monoxide.	174
Table 148: Emission factors for oxides of nitrogen.....	174
Table 149: Retention rates for sulfur by technology.....	176
Table 150: Particulate matter emission factors by fuel.....	178
Table 151: Particulate matter retention rates by technology.....	178
Table 152: Emission factors for VOCs (non-methane, non-PAH) by fuel.	180
Table 153: Composite VOC characterization factor calculation.	181
Table 154: Emission factors for PAH by fuel.....	183



Table 155: Composite PAH characterization factor calculation.....	184
Table 156: Retention rates for metals.	185
Table 157: Retention rates for halogens and phosphorus.	189
Table 158: Populations of counties with dry-weather diversions and percentage of coastline diverted... 194	
Table 159: Storm drain filter statistics for two classes of cities.	195
Table 160: Substance removal rate in storm drain filters.	195
Table 161: Substance removal rate at wastewater treatment plant.	196
Table 162: Fate of wastewater treatment plant sewage sludge.	197
Table 163: Process inventory for treatment of 1 kg used oil in wastewater.	199
Table 164: Probability parameter estimates and brief justifications.	201
Table 165: Used Oil Secondary Product Descriptions.....	204
Table 166: Complete process list.	213
Table 167: Pedigree data quality assessment.	213
Table 168: Data quality pedigree rating matrix.	215

Abbreviations

AP	Acidification Potential
CalRecycle	California Department of Resources Recycling and Recovery
CCR	California Code of Regulations
CTUeco	Comparative Toxicity Unit for ecotoxicity (same as PAF m ³ day)
GWP	Global Warming Potential
DIM	Direct Impacts Model
DTSC	California Department of Toxic Substances Control
DWD	Dry Weather Diversion
EP	Eutrophication Potential
ETP	Ecotoxicity Potential
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation model
HDMO	Heavy Duty Motor Oil
HFO	Heavy Fuel Oil
HHCP	Human Health Cancer Potential
HHNCP	Human Health Non Cancer Potential
HHCAP	Human Health Criteria Air Potential
HSC	California Health and Safety Code
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
MDO	Marine Distillate Oil
MFA	Material Flow Analysis
MSW	Municipal Solid Waste
Mgal	Million gallons
NMVOG	Non Methane Volatile Organic Compounds
PAF	Potentially Affected Fraction (measured in m ³ day, PAF m ³ day same as CTUeco)
PCB	Polychlorinated Biphenyls
PCMO	Passenger Car Motor Oil
POTW	Publicly Owned Treatment Works
PM ₁₀	Particles which are 10 micrometers in size or smaller
PM _{2.5}	Particles which are 2.5 micrometers in size or smaller
PM _{2.5-10}	Particles which are 2.5-10 micrometers in size
PRC	California Public Resources Code
RFO	Recycled Fuel Oil
SB	Senate Bill
SCP	Smog Creation Potential
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
t	1 tonne (metric ton) = 1,000 kg
UCSB	University of California, Santa Barbara
UO	Used Oil
U.S. LCI	U.S. Life Cycle Inventory Database
VOC	Volatile Organic Compounds
WECC	Western Electricity Coordinating Council

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1 General Aspects

Petroleum products are among the most significant material flows in the economy (Adriaanse et al., 1997). In 2010 the world production of crude oil was 3.97 billion metric tons (Gt), of which 0.85 Gt was consumed in the United States (International Energy Agency, 2011). The vast majority of this material is combusted in some form as fuel. However, a fraction of crude oil is appropriated for non-combustion uses including petrochemical production, asphalt and paving materials, and lubricating and industrial oils known in aggregate as “lubricants.”

Lubricants are a diverse array of products with demand throughout consumer and industrial activity. The most common application is crankcase lubrication of internal combustion engines, notably in passenger vehicles. Other high-volume lubricant uses include heavy trucks, off-road equipment used in mining and construction, transmissions and gearboxes for engine-powered vehicles, stationary machinery such as generators, and hand tools such as chainsaws. Aside from engine lubrication, lubricants have a broad range of industrial applications including food-grade process oils, hydraulic fluids, dielectric oils, metalworking oils, and many others (Kline & Company Inc., 2012; Rivzi, 2009).

Unlike most petroleum products, lubricants are not intentionally consumed in use in many applications. Instead, they must be rejuvenated or replaced. While some amount of on-site rejuvenation occurs, most lubricants are drained and transported off-site for management. Used oil has a heating value comparable to other petroleum products, giving it intrinsic value as a fuel. However, lubricants often accumulate contaminants during use, including heavy metals from equipment wear, halogenated compounds, and aromatic hydrocarbons. Additionally, some lubricant products are formulated to contain high concentrations of halogens. Consequently, the possible adverse effects of combustion of used oil are of concern. Regulations exist at both the state and federal level that restrict the sale and use of used lubricants. Improper disposal of used oil directly to soil or waterways is environmentally harmful and illegal in California.

The quantity of used oil generated in the U.S. each year is unknown. In 1991, the last year an estimate was conducted, used oil generation in the U.S. was estimated at 5.2 billion liters (GL), of which 3.1 billion liters was recovered (Graziano & Daniels, 1995). The remainder was consumed on-site, used as fuel, or disposed. Nationally, an estimated 2.9 billion liters of used oil was combusted annually in asphalt plants, space heaters, boilers, and other industrial equipment over the mid-1990s (U.S. Department of Energy, 2006a). Aside from direct combustion, used oil can also be processed into a high-grade fuel or re-refined into secondary base oil used for lubricant production (Boughton & Horvath, 2004). All three treatment routes are thought to provide environmental benefits relative to improper disposal of used oil (Fehrenbach, 2005; Pires & Martinho, 2012a).

Re-refining capacity in the U.S. is approximately 700 million liters (ML) per year (Lubes'n' Greases Magazine, 2012). In recent years, there has been considerable investment in expanding re-refining capacity, due in part to the high price of crude oil which increases the economic competitiveness of re-refined base oil (Brown Gibbons Lang & Company, 2011; Challener, 2012).

A typical lubricant product consists primarily of base oil from an oil refinery. The base oil is blended with additives to control viscosity and alter performance characteristics for specific applications. The additive package typically accounts for 5-20 percent of the mass of the product (Leslie R. Rudnick, 2009). Worldwide, additives accounted for about 11 percent of total lubricant demand by mass in 2010, though additive consumption was concentrated in vehicle engine lubricants and metalworking applications (Lubes 'n' Greases Magazine, 2012).

Lubricants are distinct from other petroleum products in that they are not necessarily consumed during use. Thus, end-of-life lubricating oils from non-consumptive use present a recoverable waste stream. However, generation of used oil is highly dispersed, so collection presents logistical difficulties.

Used oil can be used more or less directly as a fuel. Apart of the base oil, used oil contains additives and also contaminants from lubricant use and collection. These substances could cause environmental harm if they are emitted to the atmosphere during direct combustion. Used oil can also be distilled into a high-grade fuel or re-refined into a product that competes with primary base lubricant. Byproducts of the distillation and re-refining processes include primarily asphalt additives, which contain the bulk of the contaminants found in the used oil feedstock (Graziano & Daniels, 1995). Sequestration of these contaminants into asphalt roadways is regarded as environmentally benign. The amount of used oil disposed improperly (i.e. dumped into waterways or buried informally) is unknown. This quantity is difficult to estimate because a substantial portion of oil is consumed during use through combustion, wear, or fugitive emissions.

Engine and transmission lubricants, particularly from automotive applications, are collected and recycled commercially. Little information is available on the fate of industrial lubricants. In 2010, U.S. lubricant sales totaled 8.02 million metric tons (Mt) (Lubes 'n' Greases Magazine, 2012), comparable to U.S. consumption of other recyclable substances, such as polypropylene resin (7.83 Mt in 2010) or aluminum (3.46 Mt in 2010). Nationwide recovery of used oil was last estimated to be 945 million gallons (Mgal), or about 3.12 Mt, in 1995 (U.S. Department of Energy, 2006a). More recent estimates are not available.

California Senate Bill (SB) 546 (Lowenthal, 2009) requires that the Department of Resources Recycling and Recovery (CalRecycle) coordinate, with input from representatives of a broad stakeholder group, a comprehensive Life Cycle Assessment (LCA) of California's used lubricating and industrial oil management process (California Public Resources Code 2013a). CalRecycle's scope of work for the LCA practitioner contract was approved on March 15, 2011 and the University of California, Santa Barbara, (UCSB) was selected as the life cycle assessment (LCA) practitioner. On June 24, 2011, the contract between CalRecycle and UCSB was approved by both parties.

In July 2011, UCSB formed a practitioner team and started to engage with CalRecycle and the used oil stakeholders in order to work toward a goal and scope definition. An initial Goal and Scope Document was presented to CalRecycle, the external reviewers, and the stakeholders on February 6, 2012, and comments were solicited from all involved parties. A draft of the Final Life Cycle Assessment Report was submitted on June 7, 2013, and discussed during a stakeholder meeting on July 9-10, 2013. The final version of the report was submitted on July 26, 2013. A complete life cycle inventory model of the California used oil management system is presented, as well as life cycle assessment results for 10 scenarios. The used oil LCA is being conducted



according to all relevant international standards for Life Cycle Assessments, in particular ISO 14040:2006 and ISO 14044:2006 (International Organization for Standardization (ISO), 2006).

1.1 Legislative Context

1.1.1 Federal Regulation of Used Oil

Waste is regulated in the U.S. by the U.S. Environmental Protection Agency (EPA) under the Solid Waste Disposal Act of 1965, which was amended in 1976 with the Resource Conservation and Recovery Act (RCRA) and later (U.S. Environmental Protection Agency, 2011; Chapter I). RCRA introduced the legal notion of hazardous wastes, along with the requirement that these wastes be tracked from “cradle to grave,” i.e. from the point of waste generation to the point of final disposal. The EPA maintains a list of hazardous waste streams, each of which is denoted by an alphanumeric waste code. Waste codes can be assigned on the basis of a waste’s chemical composition, inherent hazard characteristics, or industrial process of origin. In addition to the federal regulations, several states also regulate different materials as hazardous.

The Used Oil Recycling Act of 1980 directed the EPA to develop regulations to protect the public from the hazards associated with used lubricating oil. Public comments from members of the oil recycling industry expressed concern that classifying used oil as hazardous waste would discourage people from collecting and storing it due to regulatory burdens, and thus adversely affect the recycling rate (50 Fed Reg 230, 1985).

Ultimately, the EPA declined to classify used oil as hazardous. Instead, it established a standard which regulated the flash point, metal content, and total halogen content of used oil to be combusted as fuel (see Table 1). Used oil which meets the list of specifications is presumed to be destined for recycling, and is thus exempt from the hazardous waste management requirements. On-specification, or “on-spec” oil, can be burned freely for energy recovery. Used oil which does not meet the specification shown in Table 1, but which also does not have any other hazard characteristics, is known as off-specification, or “off-spec” used oil. Off-spec oil may only be burned in certain facilities whose emissions are regulated under the Clean Air Act. Any oil disposed without recycling is considered hazardous solid waste and is subject to regulation.

Table 1: Used Oil Specifications.

Constituent/Property	Allowable Level (40 CFR 279.11)	Allowable Level (HSC 25250.1)
Polychlorinated biphenyls	Not detectable ¹	Not detectable ¹
Total Halogens	4000 ppm max. ²	3000 ppm max. ²
Arsenic	5 ppm max.	5 ppm max.
Cadmium	2 ppm max.	2 ppm max.
Chromium	10 ppm max.	10 ppm max.
Lead	100 ppm max.	50 ppm max.
Flash Point	100 F (38 C) min.	100 F (38 C) min.

- 1) 2 ppm is considered the detection limit for PCBs. A PCB concentration of 50 ppm or greater qualifies the oil as toxic waste under the Toxic Substances Control Act (TSCA) (40 CFR 761).

- 2) Oil with a halogen content of 1000 ppm or greater is presumed to be contaminated with halogenated hazardous wastes, and hence regulated as hazardous, unless the burner can demonstrate that the halogen content is non-hazardous.

1.1.2 California Regulation of Used Oil

The California Oil Recycling Enhancement Act, administered by the Department of Resources Recycling and Recovery (CalRecycle), is intended to discourage the illegal disposal of used lubricating oil. Used oil is defined in the California Health and Safety Code, Section 25250, as “any oil that has been refined from crude oil, or any synthetic oil, that has been used, and, as a result of use or as a consequence of extended storage, or spillage, has been contaminated with physical or chemical impurities,” but excludes oils that have a flashpoint of below 100 degrees Fahrenheit or contain concentrations of greater than 5ppm PCBs or 1000ppm halogens (California Health and Safety Code, 2013). It also outlines the fees paid by manufacturers and the incentive payments received by certified collection centers (CCCs) and oil re-refiners.

In October 2009, the California Legislature passed Senate Bill 546 (Lowenthal), which modified the California Oil Recycling Enhancement Act and made significant changes to the fee and incentive structures. SB546 also requires that oil be tested for these hazardous characteristics before leaving the state of California. Another requirement is that a life cycle assessment of used oil management within the state of California was to be completed.

The California Oil Recycling Enhancement Act of 1992 established a fee-return incentive system for engine lubricating oil in an effort to improve the recycling rate for used oil. Manufacturers pay a fee for each unit of oil sold, on a volume basis. Since SB 546, oils made of at least 70 percent re-refined base oil pay a lower fee. Revenues from the fee are used to fund a network of used oil collection centers at service stations and auto parts stores, as well as to promote and support community and county-level recycling enhancement programs (CalRecycle). The state of California distinguishes between “lubricating oils” (oils for use in lubricating internal combustion engines, transmissions, and gearboxes) and “industrial oils” (hydraulic oils, metalworking and cutting fluids, white oils, and others). Lubricating oils are subject to the fee, while industrial oils are not.

1.1.3 Lubricating Oils

Lubricating oil is defined by the state of California to include, but not be limited to, “any 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” (California Public Resources Code, 2013a). Industrial oils are defined by the state of California to include, but not be limited to, “any compressor, turbine or bearing oil, hydraulic oil, metal-working oil, or refrigeration oil” (California Public Resources Code, 2013b). Dielectric oils are specifically excluded from the California industrial oil definition, but were included in the category of industrial oils for the scope of this life cycle assessment. (Note: while the California legislative language makes a distinction between lubricating oils and industrial oils, the two types of oil are commonly both referred to as lubricating oils and will be referred to as such in this report.)

A typical barrel of California crude oil contains 0.9 percent lubricant oils (California Energy Commission, 2004). However, the fraction of crude oil that is suitable for turning into a lubricant

depends greatly on the source of the crude. Some crude oils contain no lubricants whatsoever. Lubricants are a product of conventional petroleum refining, although not all refineries have the technology necessary to produce base oil, the refinery product that is blended to become a finished lubricant.

Petroleum refining involves the heating and distillation of crude oil through different processes designed to separate crude oil fractions based on their boiling ranges. The intermediate refinery product vacuum gas oil comes out of the refinery’s distillation unit and is then hydrotreated, hydrocracked, and hydro-dewaxed to turn it into a base oil (Jones, 2006). Base oils have a range of viscosities and are categorized as Group I through Group V oils based on their viscosity index, saturation, and sulfur content. Higher group numbers are associated with higher quality base oils. Refinery produced base oils tend to be Group I or Group II. It is possible to produce Group III base oils either in a conventional refinery or through a synthetic chemical process. It is not possible to produce Group IV or Group V base oils from a refining process; these are synthetic lubricating oils that require energy intensive laboratory processing.

U.S. refineries produce primarily Group I and II base oils, along with a small amount of Group III (HSB Solomon Associates, 2013). In 2011, about 60 percent of U.S. primary base oil capacity was for Group II/III production, and 40 percent was for Group I (American Fuel & Petrochemical Manufacturers, 2012). The volume of re-refined base oil produced in California in 2012, typically 100 percent Group II, constituted about 4 percent of the total volume of domestically produced and imported primary lubricants sold in the state. Groups IV and V account for only 2 percent of global base oil production (Chevron U.S.A., 2011). The specifications for all five groups are shown in Table 2.

Table 2: API Base Oil Standards (American Petroleum Institute, 2007).

Group	Sulfur, Wt %		Saturates	Viscosity Index
I	>0.03	and/or	<90	80-119
II	≤0.03	and	≥90	80-119
III	≤0.03	and	≥90	≥120
IV	All Polyalpha Olefins (PAOs) (Synthetics)			
V	All Stock Not Included in Groups I-IV [Pale Oils (naphthenics) and Non-PAO Synthetics]			

To create a finished lubricant product, a blender will combine different base oils to achieve the desired viscosity and add a suite of additives to enhance the lubricating properties of the oil needed for its intended use. Industrial oils usually contain only a small amount of additives, about 5 percent of the finished product (U.S. Department of Energy, 2006b). Finished motor oil, on the other hand, usually contains 20-25 percent additives by weight (ibid). The reason motor oils require a larger additive package is that they are expected to function in much more extreme conditions, including extreme cold, heat, and pressure (U.S. Department of Energy, 2006b). Additives serve as detergents, dispersants, oxidation inhibitors, antiwear agents, friction

modifiers, foam inhibitors, extreme pressure agents, anti-corrosives, viscosity modifiers, and more (Lubrizol Corporation, 2011).

1.1.4 California Hazardous Waste Designation

All used oil has been managed as a hazardous waste in California since 1986. As a consequence, transport of used oil must be tracked and reported to the state’s Department of Toxic Substances Control (DTSC) until it is tested by a permitted facility. Oil that is shown to meet the requirements in Table 1 is no longer considered to be hazardous. It is classified as “recycled oil” which can be burned for energy recovery (HSC 25250). Every shipment of used oil between facilities must be reported to the DTSC on a legal form called a hazardous waste manifest. Since late 2006, the DTSC has used the same uniform manifest form that the U.S. EPA mandates for federally regulated hazardous wastes (California Department of Toxic Substances Control, 2007). Waste flows are nominally reported by the original generator of the waste, but large quantities of used oil are consolidated by transporters who operate routine collection routes (California Department of Toxic Substances Control, 2008). These transporters generate consolidated manifests, which list the transporter as the generator of the waste.

Different hazardous wastes are identified through numeric waste codes established by regulation (California Code of Regulations, Title 22, Chapter 11, Appendix XII).

Table 3 shows the three California waste codes included in the study. The descriptions make implicit reference to the statutory definition of used oil. The accurate identification and classification of waste streams as coded hazardous wastes is the responsibility of the waste generator and is to be based on the generator’s expertise and knowledge of the waste’s origin, as well as analytical methods. Waste code 221 embodies all used oil and is mainly made up of spent engine lubricants. Waste codes 222 and 223, both considerably smaller flows, are also thought to contain significant quantities of used oil. Waste code 222 describes sludge from oil/water separators, which are in common use at refineries as well as auto maintenance and other industrial facilities. Waste code 223 is predominantly oily water but also includes solid wastes contaminated with oil.

Table 3: California Waste Codes related to used Oil (22 CCR, Chapter 11).

Code	Description	Mass in 2011 1)	Oil Content 2)
221	Waste Oil and Mixed Oil	480,000 t	95%
222	Oil/Water Separation Sludge	21,000 t	50%
223	Unspecified Oil-containing Waste	75,000 t	15% / 65%

1) Total mass of waste reported on manifests, including double counting. From DTSC Hazardous Waste Tracking System.

2) Assumed average volume fraction of recoverable oil, based on available data and information provided by used oil life cycle assessment project stakeholders. Values may vary on a facility basis.

1.2 Recycling Routes

In the state of California, collected oils that are tested and certified as being non-hazardous may end up in one of three main recycling routes: 1) recycled fuel oil (RFO) production, wherein the used oil is filtered and dewatered and sold as a fuel oil or cutter stock, 2) distillation into a distillate fuel oil, usually blended with other fuels to be burned in marine engines and therefore often referred to as marine distillate oil (MDO), or 3) re-refining, in which the used oil is processed back into a base oil.

1.2.1 Recycled Fuel Oil (RFO) Production

The recycling route that involves the least processing is the production of recycled fuel oil. Used oil is transported to a processing facility and stored in large tanks, where some natural settling of sediments and evaporation of water occurs. It is then typically passed through a mesh strainer to remove large objects and some of the larger sediment particles. The oil is then heated in order to fully evaporate water content that enters the used oil stream during use and collection. At this point, it is ready for sale.

The only inputs to the process are the natural gas or electricity used to heat the oil. No co-products are generated, but some wastewater and tank bottom sludge wastes are created. The wastewater is treated in a wastewater treatment facility and the tank bottoms are landfilled. A process flow diagram representing the processing of used oil into recycled fuel oil is shown in Figure 1.

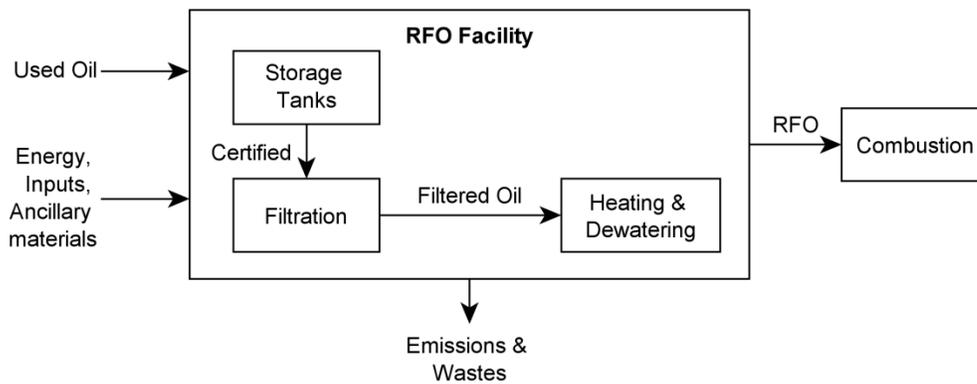


Figure 1: Production of Recycled Fuel Oil (RFO).

1.2.2 Marine Distillate Oil (MDO) Production

Like recycled fuel oil production, marine distillate oil (MDO) production produces a fuel that utilizes the energy content of used lubricating oil. However, it involves significantly more processing steps. The same natural separation of water, oil, and tank bottoms occurs in storage tanks upon the oil's arrival at the production facility, after which the oil is heated and dewatered. The oil then passes through one or more distillation units, and different products are extracted. MDO, a middle-weight distillate fuel oil, accounts for the majority of the output. The fuel that is created from California's used oil stream is typically burned in commercial marine engines as a low sulfur cutter stock. A lighter fuel is also produced which is referred to as "light ends." These are similar to a naphtha or gasoline and contain high levels of sulfur and halogens (Ennis, 2012).

Light ends are sold to facilities with high emission controls such as a waste incinerator or cement plants. The heavy bottom residuals are turned into an “asphalt flux.” This is a high viscosity product that is added to asphalt in road or roofing applications, where it is used to improve the quality of the final product due to the asphalt flux’s lubricating qualities (Ennis, 2012). Additionally, there is typically some amount of ethylene glycol from used antifreeze that has entered the used oil stream during the collection process. This fraction is removed and sold as a co-product.

The various processing steps require energy inputs. In California, processors are most likely to use electricity or natural gas due to emission limits, although in other parts of the country processors may use some of the lighter co-products on-site to generate additional energy inputs. Some chemical inputs may be used in the treatment of the oil. Wastewater and solid waste are also generated from the processing. Wastewater is treated in a wastewater treatment facility, and solid wastes and sludge are landfilled. A process flow diagram representing the processing of used oil into marine distillate oil is shown in Figure 2.

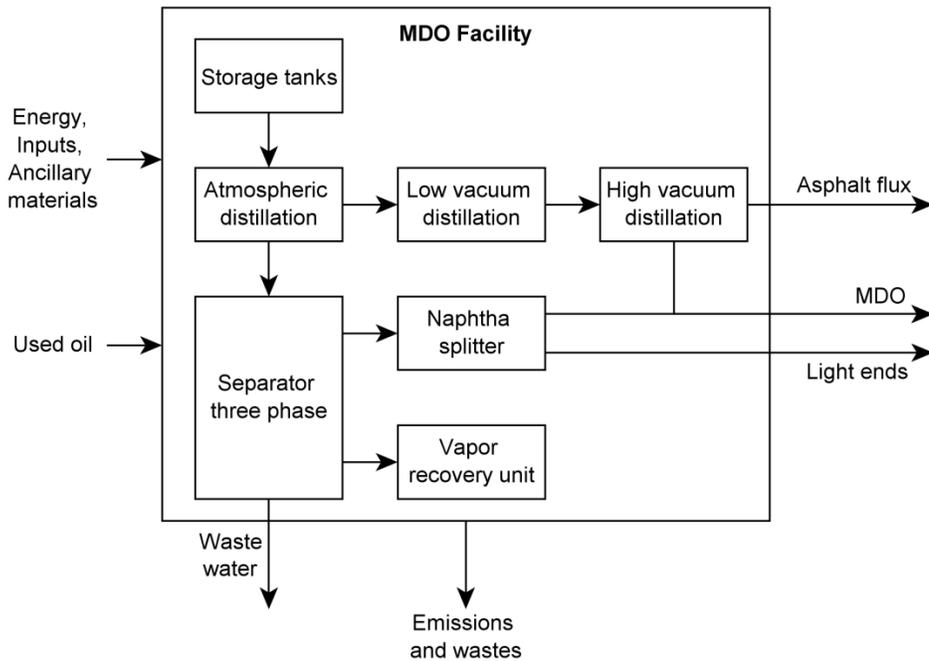


Figure 2: Production of Marine Distillate Oil (MDO).

1.2.3 Re-Refining into Secondary Base Oil

The third route that used oil may take is to be transferred to a facility that turns the highest quality fraction of the used oil stream back into lubricating base oil. As in the previous two routes, the oil is first filtered and dewatered. Like in marine distillate oil production, the oil is then passed through one or more distillation units. It may also be treated in a de-poisoning unit which removes some of the additives and contaminants that may negatively affect the machinery in the following processing steps. It is then passed through a wiped- or thin-film evaporator, which

separates the light and heavy components, and the lube distillate and asphalt flux, respectively. The lube distillate fraction (also called vacuum gas oil) is subsequently treated in a process that exposes it to a proprietary catalyst and hot hydrogen gas. This process removes the majority of the sulfur, nitrogen, chlorine and other remaining additives and contaminants. It also re-saturates the hydrocarbon molecules in order to improve the quality of the lubricant product.

The re-refining process requires energy inputs such as electricity and natural gas. As with the distillation process, facilities whose permits allow for it may also burn light fuels derived from the processing of the used oil. Plants may use various different chemical inputs to treat and de-poison the oil and hydrogen gas for the hydrotreatment process. The catalyst is replaced, on average, every seven years (Hall, 2011). As with marine distillate oil production, the heavy metals in the used oil are sequestered in the asphalt flux. Wastewater is treated either on or off-site, and tank bottoms are landfilled. A process flow diagram representing the processing of used oil into re-refined base oil is shown in Figure 3.

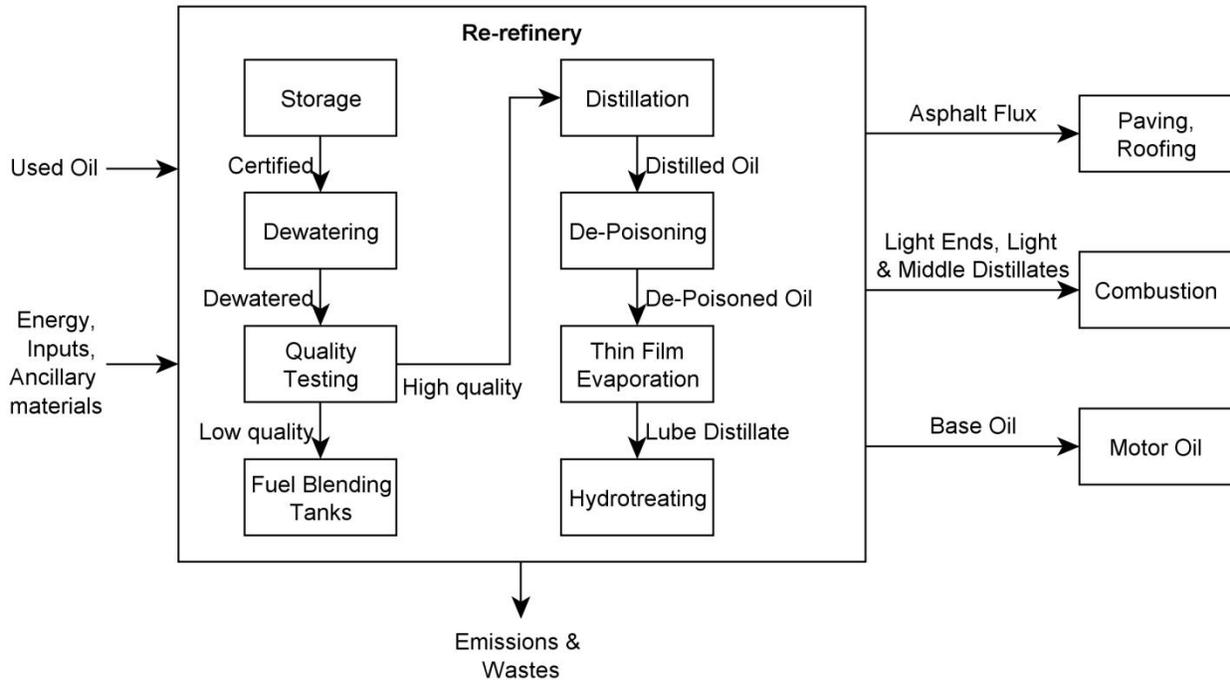


Figure 3: Production of Re-Refined Base Oil.

1.3 Literature Review

A number of studies have assessed the environmental impacts of these different used oil management strategies. Only three are life cycle assessment (LCA) studies that consider the three major disposition routes included in the scope of the current LCA. Boughton & Horvath (2004) performed an analysis of the California used oil management system and found that, in comparing the impacts of re-refining, marine distillate oil production, and combustion of used oil as recycled fuel oil, impacts were dominated by the toxicity impacts of heavy metal emissions

from combustion of recycled fuel oil. Re-refining and marine distillate oil production had similar toxicity impacts, which were lower than those of recycled fuel oil, while recycled fuel oil had a lower overall global warming impact.

The Boughton & Horvath study assumed 100 percent emission of all metals in used oil. Fehrenbach (2005) compared five different re-refining techniques to one another as well as to virgin base oil production and recycled fuel oil combustion. Results showed that all five re-refining techniques had lower impacts than virgin oil production for all impact categories. In only one category, global warming potential, recycled fuel oil combustion resulted in lower impacts than re-refining. In an analysis of the Portuguese used oil management system, Pires & Martinho (2012) compared the impacts of re-refining, recycled fuel oil combustion, marine distillate oil production, and one additional route, clay expansion. Re-refining was shown to have the lowest impact in the categories of abiotic depletion, eutrophication, global warming, and human toxicity. They also found that a simple model of improper disposal, which assumed all uncollected oil was directly emitted to waterways, had the highest overall impacts of all scenarios.

Several more studies have assessed the life cycle impacts of one or more of the disposition routes in question. Kalnes, Shonnard, & Schuppel (2006) compared the re-refining of used oil to combustion of recycled fuel oil in cement kilns and found that re-refining was preferable in terms of cumulative energy demand, acidification, eutrophication, and fossil fuel use, but that combustion was preferable in the category of global warming, assuming that recycled fuel oil displaces coal. Kanokkantapong, et al. (2009) compared acid clay and solvent extraction re-refining technologies, which are not used in California, to the combustion of recycled fuel oil in small boilers, vaporizing burners, atomizing burners, and cement kilns.

Their findings showed that of the five combustion techniques, cement kiln combustion had the lowest global warming and acidification impacts, vaporizing burners had the lowest eutrophication potential, and cement kilns and vaporizing burners had similarly low heavy metal emission levels. Nakaniwa, Yagita, and Inaba (2001) compared the combustion of recycled fuel oil to the combustion of virgin heavy fuel oil in power plants. They found that use of recycled fuel oil reduced energy resource depletion and halved CO₂, SO_x, and NO₂ emissions as compared to the use of virgin heavy fuel oil.

Additionally, there are a few reports that present the state of used oil management for a certain geographical area at a given point in time. A 2008 Lawrence Livermore National Laboratory report describes composition, sources, and volumes of used oil in California; the major disposition routes for used oil in California; and market and regulatory forces that may impact the management system (Lawrence Livermore National Laboratory, 2008).

The report makes the default assumption that re-refining is the “highest and best use” for used oil. In 2006, the U.S. Department of Energy produced a similar report regarding national lubricating oil demand and used oil management practices (U.S. Department of Energy, 2006b). The study considered market forces, and again, made assumptions about which management approach was preferable, favoring re-refining over energy production. Environmental impacts were not directly assessed, but the report presents findings from previous studies. A literature review by Taylor Nelson Sofres Consulting (2001) found that local impacts from re-refining were generally lower than those from incineration, that the environmental impacts of collection and transport are rarely significant in the greater life cycle, and that the fuel that used oil is assumed to displace is a



crucial assumption that can affect the results of a study. This review focused primarily on European management systems.

2 Goal

This life cycle assessment (LCA) is a requirement of SB 546. The goal was to generate a quantitative environmental profile of the management system for all of the used oil generated in California. The results of the LCA, when combined with a closely integrated economic assessment performed by the economic contractor, will provide sufficiently broad information to be used by CalRecycle to fulfill its duties pursuant to Section 48651.5 (b) (1) (D), namely to provide suggestions to the Legislature regarding possible policy changes to promote increased collection and responsible management of used oil. The intended audience of the study is CalRecycle, all industries involved in and affected by the management of used oil generated in California, and the public at large. The results of this study are intended to be used in comparative assertions intended to be disclosed to the public.

The objectives of the LCA are:

- To quantify the potential environmental impacts of managing used oil generated in California, accounting for all relevant life cycle stages such as generation, collection, disposition of the used oil, and use of secondary products.
- To model the California used oil management system in a way that allows sensitivity and scenario analysis with regards to system parameters such as collection rates, reverse logistics, and disposition routes, and modeling assumptions such as allocation procedures and market effects.
- To generate results that can be used by CalRecycle to provide any recommendations for statutory changes that may be necessary to promote increased collection and responsible management of used oil.

3 Scope

3.1 *The Product System*

The studied product system manages the following used oil generated within California state boundaries: Lubricating and industrial oils as defined in Public Resource Code (PRC) 3460 and Health and Safety Code (HSC) 25250.1, as well as used dielectric oil. Used oil is generated when lubricating or industrial oil leaves its intended use phase in a collectable form. All possible fates of used oil generated in California have been included in the analysis. These include: improper disposal; on-site combustion; reprocessing into recycled fuel oil, reprocessing into distillate fuel oil, re-refining into secondary base oil; and onsite rejuvenation. Effects on primary products competing in markets with secondary output products from used oil disposition are also within the scope of this study.

3.2 Functional Unit

The function of the studied product system is the management of used oil generated in California. The functional unit is defined as the management of all used oil generated in California during a calendar year. Material flow analysis (MFA) data have been collected for the years 2007-2011, known as the “MFA Period.” The calendar year 2010 has been chosen as the base year. The inventory model for the calendar year 2010 is called the “Base Year model.” The potential environmental impacts of changes in the used oil management system will be assessed through scenario modeling. The resulting inventory models will be called “Scenarios.” The scenarios will extend over the years 2015-2030, known as the “study period.” The continued operation of the system under “business as usual,” i.e. with no policy or capacity changes, is referred to as the “Baseline Scenario.”

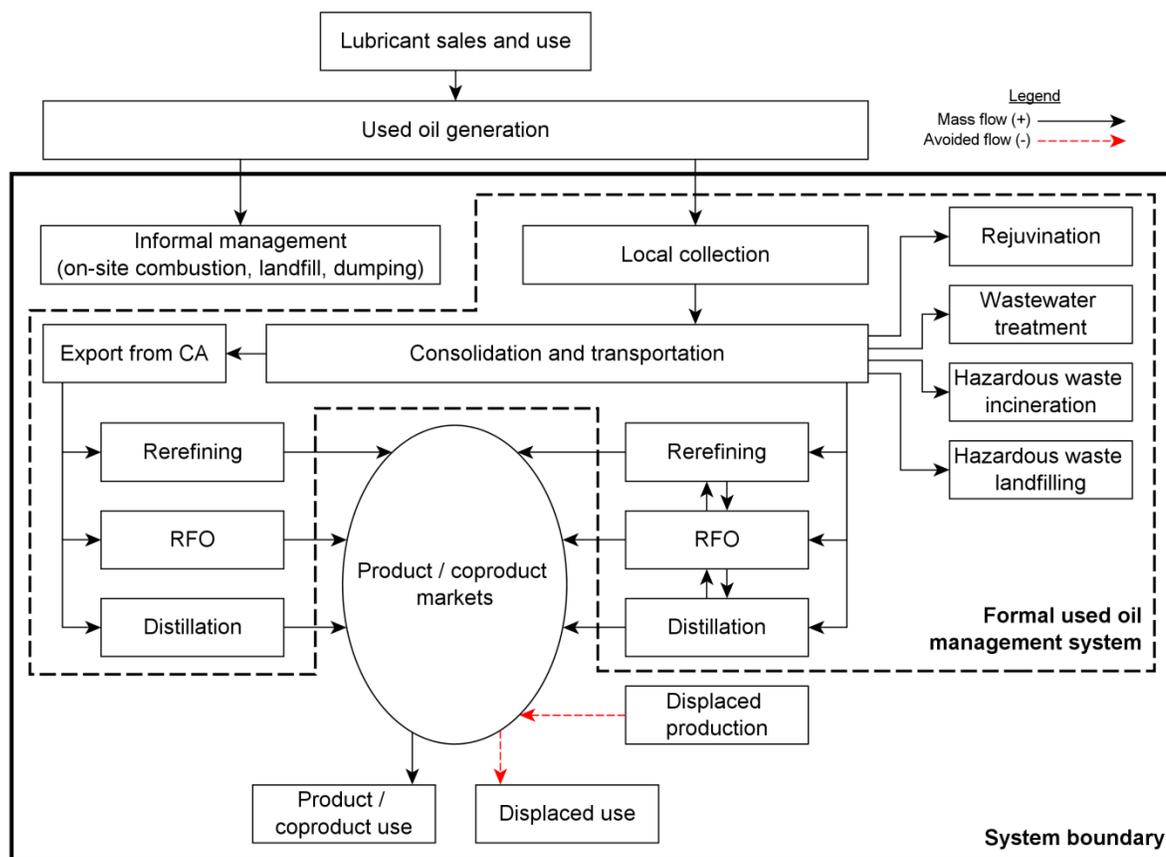


Figure 4: The system boundary of the life cycle assessment of used oil management in California.

3.3 System Boundary

Figure 4 shows a process flow diagram of the life cycle assessment of used oil management in California. In the context of this assessment, California’s used oil management system begins with the generation of collectable used oil within California state boundaries. Processes upstream of used oil generation are outside the boundaries of the studied system. The study follows the generated collectable used oil downstream until it reaches the natural environment, is consumed,

or is reprocessed into secondary products. The system boundary further includes the use of the secondary products and their market effects, in particular their interaction with competing products.

The market effect is modeled as displaced production and displaced use of the products that are being substituted by the secondary products from used oil disposition. Displaced production and use is modeled for all primary products that are understood to compete with the secondary products from used oil re-refining into base oil, used oil distillation into marine distillate oil, conversion of used oil into recycled fuel oil, and used oil combustion at the site of its generation. Displaced production and use is not modeled for dielectric oil rejuvenation, which is regarded as a lifetime extension.

The studied used oil management system is divided into informal and formal management subsystems. The informal management system consists of the following components:

- **Dumping:** The draining of used oil directly onto soil or into waterways.
- **Landfill:** The disposal of oil used into the regular solid waste stream.
- **On-site combustion:** The use of used oil as fuel by the generator at the site of generation.

The formal used oil management system can be divided into the following stages:

- **Collection and Waste Disposal:** The storage and transportation of all collected oil, i.e. oil that is retrieved from a certified collection center or from a facility by a certified hauler; and the direct disposal of used oil not suited to be processed due to its off-specification nature or hazardous components.
- **Used Oil Reprocessing:** Reprocessing of used oil into recycled fuel oil, marine distillate oil, or re-refined base oil.
- **Use of Secondary Products:** The use of all secondary products, such as combustion of marine distillate oil in marine engines or of recycled fuel oil in asphalt kilns.
- **Displaced Primary Production:** The avoided production of primary products that are displaced due to market interactions with secondary products.
- **Displaced Primary Product Use:** The avoided use of primary products that are displaced due to market interactions with secondary products.

3.4 Exclusions from the System Boundary

The study's system boundary was chosen to begin with the generation of used oil. This is in accordance with the statutory requirements of SB 546 as well as standard practice in a life cycle assessment of waste management. Used oil generation was taken to occur when the oil is drained from its point of use. This interpretation is consistent with state and federal laws regarding solid wastes. Thus, life cycle stages prior to used oil generation were excluded. Lubricant sales quantities are used to determine the amount of collectable oil in the material flow analysis, but are out of scope for impact assessment.

Other potentially significant contributors to life cycle impacts were systematically omitted because they were expected to be consistent across all comparison cases, or because the available

inventory data were inadequate to reflect potential differences in comparison cases. These include infrastructure; capital equipment construction, maintenance, and decommissioning; employee activities; and business operations. Non-hazardous and hazardous landfill construction is excepted because the construction of landfill capacity is the primary impact from these activities. The following were excluded from the system boundaries:

- Primary lubricant production and sales
- The primary use phase of lubricating oils prior to becoming used oil
- Impacts incurred during the use phase, including those from drips, leaks, and inadvertent combustion
- The use and end of life of re-refined base oil, asphalt additives, and ethylene glycol; and avoided use and end-of-life of displaced primary analogues. These phases of these secondary and primary products are understood to be identical and thus cancel out.
- Infrastructure and capital goods, except for landfills
- Maintenance, operations, and employee transport.

3.5 Cut-Off Criteria

Processes and life cycle stages that contribute less than 1.5 percent of the total mass and energy to the system are below the cut-off criteria for inclusion. The total exclusions are less than 5 percent. Certain activities were included in the system boundaries of the material flow analysis, but not the life cycle assessment. In other words, data regarding their quantities were collected in service of the functional unit, but the impacts of their life stages were not modeled. Data from the material flow analysis demonstrate that these activities fall below the cut-off threshold. These cut-off processes include:

- Transfer losses during collection and hauling of used oil. As reported in Section 4, these made up 1.35 percent of total used oil collected in the base year.
- Dielectric oil rejuvenation. The quantity of dielectric oil reprocessed in the base year made up approximately 0.93 percent of total used oil collected.

Transfer losses during collection and hauling are assumed to be a combination of leaks and spillage, incidental dewatering, and accounting inconsistencies in hauler data reporting due to inaccuracy in estimation and inter-year delays in reporting of oil movement. Dielectric oil rejuvenation is included in the material flow analysis to reflect industrial oil sales, but its impacts are not modeled because of the small size of the flow and the lack of available inventory data.

3.6 Allocation Procedures

Broadly speaking, this study follows ISO 14044, Section 4.3.4. In particular, allocation was avoided where possible by dividing the unit processes or expanding the product system. Consequential system expansion was used, which required expansion of the used oil management system to include the modeling of market effects and displaced production and use of competing products.

3.7 Impact Assessment

In accordance with ISO 14044, the impact categories used in this life cycle assessment (LCA) reflect a comprehensive set of environmental issues related to the product system being studied, taking the goal and scope into consideration. Mid-point indicators have been used in order to keep the uncertainty of the environmental mechanisms as small as possible. Many suites of impact indicators are readily available in the GaBi6 LCA software used for this study. TRACI 2.0 was selected as the most appropriate set of impact indicators for this LCA. The Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) has been developed by U.S. Environmental Protection Agency (EPA) to assist in impact assessment for sustainability metrics, life cycle assessment, industrial ecology, process design, and pollution prevention (Bare, 2011). TRACI is the only suite of life cycle impact indicators that was developed specifically for the United States.

Toxicity assessment in TRACI 2.0 and 2.1 is based on USEtox, a consensus model developed by UNEP-SETAC that combines the strengths of Caltox, Impact 2002, Uses, and EDIP (Rosenbaum et al., 2008). While TRACI 2.0 contains the full list of USEtox characterization factors, the metal characterization factors have been removed from the subsequent version, TRACI 2.1, as model developers recommend further research on these factors and they are still considered “interim.” The LCA practitioners of this study concluded that for this project the costs of not having characterization factors for metals far outweigh the benefits of excluding these characterization factors. As a result, TRACI 2.0 is used for all toxicity impact assessment categories in this project. Toxicity outcomes of the TRACI 2.0 methodology are assessed through comparison to several other toxicity categories in Section 6. The Global Warming Potential indicator was expanded in TRACI 2.1 to include additional flows and so was used in place of TRACI 2.0. Other categories were drawn from TRACI 2.0. Below is a list of impact categories assessed:

- TRACI 2.1, Global Warming Potential in kg CO₂ eq
- TRACI 2.0, Acidification Potential in hydrogen ion mole equivalents (H⁺ moles eq)
- TRACI 2.0, Eutrophication Potential in kg N eq
- TRACI 2.0, Ecotoxicity Potential in Comparative Toxicity Units (CTUeco)
- TRACI 2.0, Human Health (Cancer) Potential in cases
- TRACI 2.0, Human Health (Non Cancer) Potential in cases
- TRACI 2.0, Human Health (Criteria Air) Potential in kg PM₁₀ eq
- TRACI 2.0, Smog Creation Potential in kg of ground-level ozone equivalent (kg O₃ eq)

The only TRACI 2.0 impact category that is not used is Stratospheric Ozone Depletion, caused by halogenated substances. This impact category was excluded from this LCA project because relevant inventory data was only available for certain process inventory data sets in the study but not others. In the impact categories of ecotoxicity, human health cancer, and human health non-cancer, the impacts from emissions to all three environmental mediums (air, soil, and water) have been aggregated so that each category, ecotoxicity, human health cancer, and human health non-cancer, has just one impact indicator result.

Impacts from land and water use are omitted, other than from water supply and wastewater treatment, because they are absent or inconsistent in the life cycle inventory databases used.

According to ISO 14044, optional elements of impact assessment include normalization, grouping and weighting. Neither normalization nor grouping and weighting are performed in this assessment in order to avoid the value choices necessary for these steps.

3.8 Data Requirements

The life cycle inventory data used for the used oil life cycle assessment is a combination of primary and secondary data. Primary data is defined as data collected directly from the organization in control of the unit processes. Secondary data is defined as data coming from secondary data sources such as existing databases and literature. Given equal data quality and fit, priority has been given to primary data. Secondary data has been used when primary data of appropriate quality and fit was unavailable. Table 4 shows the source of inventory data for the most important unit processes or groups of unit processes that together make up the used oil management system and the affected processes of primary fuels production and use. A complete data map can be found in Appendix C. In addition to process inventory data, a wide range of additional data has been collected such as process activity levels, transportation modes and distances, material compositions, calorific values and other characteristics of products and fuels. This data is discussed in Section 4 of this report, which details life cycle inventory modeling. New process inventories for refinery products were developed through cooperation with PE International. A detailed description of the refinery inventory modeling is available in a separate report (PE International, 2013).

LCA Data Source	Primary data (Stakeholders)	Primary data (State of California)	Secondary data (Industry)	Secondary data (Literature)	Secondary Data (Databases)
<i>Used Oil Management System</i>					
Uncollected Used Oil			X	X	
Unprocessed Reuse	X				
Collection & Hauling	X	X	X		X
Hazardous Waste Disposal	X	X			X
Reprocessing into recycled fuel oil (RFO)	X			X	
Reprocessing into marine distillate oil (MDO)	X			X	
Used oil re-refining	X			X	
<i>Displaced processes (primary production and use of competing primary products)</i>					
Heavy Fuel Oil (HFO)					X
Marine Distillate Oil (MDO)					X
Asphalt					X
Base Oil					X
Number 2 Distillate Oil				X	X
Gasoline					X
Naphtha					X
Natural Gas					X

Table 4: Data sources (a complete data map is located in Appendix F).

Life cycle assessment (LCA) is a data-driven quantitative assessment methodology. While data availability is critical to making the assessment feasible, data quality is what ensures robust results useful for environmental decision support.

Table 5 discusses the data quality requirements used in making data source selections. These categories and their descriptions roughly correspond to a commonly used LCA data quality pedigree matrix (Weidema & Wesnæs, 1996). A detailed quality assessment of all processes used throughout the LCA model is located in Appendix F.

Table 5: Data quality requirements. Source: Weidema & Wesnæs (1996).

Data Quality Category	Requirement
Reliability	Where possible, primary data based on measurements have been used. When these are unavailable, secondary data or engineering models will be used. Data will be verified to extent possible. Data source and verification will be indicated for every process inventory. Data should be from transparent and well-documented sources. When computations or assumptions have been made, they will be explicitly documented.
Completeness	The study will use as many data sources as possible and necessary to ensure completeness of data.
Temporal Correlation	Data should be from a time period that is relevant to current production rates and technologies. In order to account for fluctuations in production over time, data from the years 2006-2010 will be solicited.
Geographic Correlation	Data will be sourced from all areas that receive used oil generated in California. Inventory data for similar processes but different geographic area may be weighted based on the percentage of total used oil volume they receive.
Technological Correlation	Data will be sought that reflects currently used technologies as well as technologies that might be used in the future.

3.9 Assumptions

The life cycle assessment (LCA) report lists and details all assumptions made during any stage of the inventory modeling and impact assessment to the extent possible. Every effort was made to be as transparent as possible about inventory modeling that was based on primary data without revealing protected confidential information. Sensitivity analyses are performed on assumptions that have high uncertainty and large potential impact on results. While specific modeling assumptions are described throughout the report, some of the most important methodological assumptions are described here. Assumptions and default parameter values have been developed in consultation with industry stakeholders.

Several assumptions are fundamental to the model. The first is that the 2010 year is representative of an average year. This assumption is based on primary data to the extent that it was available for past years, and on stakeholder advice. The second is that the inputs and outputs for reprocessing facilities scale linearly between years. This is in accordance with standard LCA methodology. Despite extensive data collection, analysis, and synthesis, this LCA did not yield the information required to detect, let alone model, defensible non-linear input-output relationships. The 2030 baseline and scenario results are dependent on the assumptions about future activities intrinsic to the direct impacts model.

There are also a number of assumptions made regarding the fate of used oil and other secondary products. The amounts of uncollected oil going to onsite combustion, to landfill, and to illegal dumping are unknown and therefore based on best estimates from available information and stakeholder input. The split between combustion of recycled fuel oil in boilers, space heaters, and

direct fired kilns is also uncertain. Uncollected oil burned onsite is assumed to be split between space heaters and boilers; recycled fuel oil to combustion is assumed to be split between boilers and kilns. The split proportions are based on best available industry knowledge. Because differences in the emissions resulting from these combustion technologies primarily relate to emission or retention of heavy metals, the model's sensitivity to these assumptions is captured in the range analysis of retention rates.

Although every effort was made to accurately reflect the relationship between secondary products and the primary products they displace, some assumptions were made regarding the technical similarity between different products for purposes of modeling simplification and due to data availability.

3.10 Limitations

The model is inherently limited by data availability. Limitations during inventory modeling occur when required data is not available or when the available data is not of the required quality. Overall, the quality of the data used in this life cycle assessment (LCA) project is regarded as good. While all efforts were taken to ensure the greatest possible accuracy of the LCA, data uncertainty and limitations limit the conclusions that can be drawn from its results. This is true, in particular, for the combustion emission inventories and the displacement relationships between secondary and primary fuels. The sensitivity of the results with regard to those two model uncertainties are explored in greater detail in the sensitivity analysis.

In general, data on the emissions from landfilling, hazardous waste management and wastewater treatment in the U.S. are not available. Long-term emissions of heavy metals and organic substances from used oil improperly disposed to landfill and heavy metal residues in combustion ash are not included.

Life cycle impact assessment is an inherently uncertain calculation, and category results are limited by the inherent characteristics of the underlying methods. While the severity of impacts due to an emission is clearly dependent on the region in which emissions occur, regionalized impact assessment is not well developed, and information about the locations at which emissions occur was not available for the study. As with all LCA results, the impact category scores should be interpreted as approximate and comparative on an aggregate basis and cannot be used to draw conclusions involving regional specificity.

Emissions from combustion are significant drivers of the study results. The combustion emission model is limited by the availability of data describing combustion emissions from both used oil and fuels whose combustion is displaced. These limitations are discussed in Appendix B. Impacts from organic compounds emitted during combustion are highly uncertain. Halogenated organics were not modeled. Speciation profiles of organics from the combustion of fuels in the study are not available.

Displacement of primary production is another major driver of model results, and by definition accounts for any negative contributions to impact category scores. Displaced refinery products are modeled using results derived from a proprietary refinery model owned by PE International (PE International 2012) and are thus not available for public review. Assumptions about displacement are discussed in Appendix D. The influence of the PE refinery model is discussed in Section 6.

Diesel particulate exhaust, although considered a likely carcinogen by state and federal agencies, is not characterized as toxic in TRACI 2.0 or any other life cycle impact assessment methodology, and so is not modeled in the study.

The material flow of metal contaminants in used oil through the distillation and re-refining process is not modeled because of a lack of data availability. Metal contaminants are generally assumed to be retained in distillation bottoms and are thus contained in asphalt flux. While no inventory data are available, literature sources and regulatory documents suggest that these contaminants are permanently retained in the asphalt (see Appendix D). The rate at which actual contaminants in used oil are retained in asphalt versus ending up in distillate fuel or re-refined base stock is not modeled in the study. The metals content of distillate fuels derived from used oil is not known.

Metal emissions during combustion are estimated using retention rates; however, there is a lack of data on the rate of retention for various metals of environmental concern during combustion. The model's intrinsic retention rate estimates are limited by available data. Metals retained in bottom ash are assumed to be disposed in landfill. Impacts arising from their subsequent environmental fate are not modeled due to data limitations.

Impact assessment conclusions are also limited by the limitations of the TRACI 2.0 characterization model, since development of new characterization models was out of scope for this life cycle assessment (LCA). The characterization factors for toxicity impacts from metals are currently considered "interim" due to uncertainty, and their results should be used with caution. As stated by the authors of the USEtox documentation, characterization factors for metals were "classified as interim due to the relatively high uncertainty of addressing fate and human exposure for all chemicals within these substance groups," (Rosenbaum et al., 2008). However, the significance of metals emissions for the study was such that the interim characterization factors were used rather than omitting the flows entirely. Additionally, aquatic ecotoxicity impacts are based only on freshwater studies and therefore caution should be employed when applying aquatic ecotoxicity characterization factors to seawater emissions (Henderson et al., 2011).

Toxicity results should be interpreted on the basis of order-of-magnitude differences and sensitivities to change rather than actual impacts. Significant elementary flows may not be characterized accurately. The significance of the selection of TRACI 2.0 for toxicity characterization is explored by comparing TRACI results to results from other impact assessment methodologies in Section 6.

3.11 Critical Review

The results of this LCA study will be used in comparative assertions intended to be disclosed to the public. ISO 14044 distinguishes between critical reviews by experts and by panels of interested parties. This study is reviewed by both. Throughout the entire length of the LCA, a comprehensive stakeholder process accompanied the study, and stakeholders provided detailed feedback on a quarterly basis. At the same time, Lifecycle Associates, LLC, was selected as chair of a critical review panel, which consists of six independent reviewers. Feedback was provided by the critical reviewers throughout the project following each major LCA deliverable and was incorporated into model development.

3.12 Reporting

Reporting was done in accordance with ISO 14044 and CalRecycle's scope of work for the life cycle assessment (LCA) practitioner contract. The practitioner submitted a draft study report, whose results were reviewed by the CalRecycle project team, the critical review panel, and the stakeholders, and the results were presented at a facilitated stakeholder meeting for comment. Each major deliverable was posted by CalRecycle on its website for public comment. The practitioner has responded to and incorporated, where appropriate, any comments from CalRecycle, the critical review panel, and the stakeholders. Full responses to comments and rationale for any actions taken have been publicly provided.

This report constitutes the final LCA study report to CalRecycle. The report will be a topic of discussion at a CalRecycle public meeting, and, although comments will be invited and noted, the Contractor is not expected to further modify the report based on the comments from this public meeting. The Contractor is expected to attend the CalRecycle public meeting for the purpose of responding to questions on the LCA study from CalRecycle management or the public.

All reports are written with the goal of providing the highest possible transparency regarding all data, models, parameter values, and assumptions, while safeguarding the confidentiality requirements of all primary data providers. Non-disclosure agreements have been executed between the practitioner and primary data providers prior to any primary data collection. No results derived from confidential data have been published without prior clearance from the primary data provider.

4 Life Cycle Inventory Analysis

This section describes the inventory modeling for the base year model and the scenarios of California's used oil management system. Inventory models are required for all processes shown as boxes in the process flow diagram depicted in Figure 4. The resulting process inventories also require activity levels for the base year model and each scenario. Since the functional unit of this LCA is the management of all used oil generated in California during a calendar year, the activity levels have to be derived from a statewide material flow analysis (MFA). The activity levels for the base year model, which represent estimates of the amount of used oil generated and processed in the state, come from records of hazardous waste hauling over the period of 2007-2011, including the base year of 2010 (see Appendix A). This is known in the report as the "MFA period." The activity levels for the 20-year baseline and alternate scenarios come from the Direct Impacts Model constructed by the economic contractor.

4.1 Reference Flow Modeling

The model is built around a yearly measurement of a reference flow, representing all used oil generated in California during a calendar year. The magnitude of this flow is not known. In order to describe the functional unit for the project, it was necessary to estimate the quantity of used oil generated in California for each year of interest. A material flow analysis of used oil generated in California was conducted using hazardous waste hauling data over the MFA period. The MFA methodology is documented in full in Appendix A. In brief, the net quantity of oil-containing waste received by each facility included in the manifest record was estimated based on a mass balance of inflows and outflows from that facility. The amount of oil contained in each shipment

of waste was estimated based on the waste code. Facility-specific knowledge was used to estimate the fate of oil delivered to each facility. The material flow analysis (MFA) results were used to set the activity levels of facility unit processes in the life cycle inventory model. The amounts of secondary products and wastes generated by the used oil system are determined by the output characteristics and process yields of the unit processes in the life cycle assessment (LCA) model.

A summary of the outcome of the combined MFA and LCA models is shown in Table 6. Important results from the MFA included the total amount of oil collected, the amount exported, the amount thought to be burned as recycled fuel oil, and unrecoverable losses and wastes. For information about the assumed water content of different waste codes, please refer to Table 8.

Table 6: The California used oil reference flow. 2010 is the reference year used to develop the base year inventory model.

Million Gallons	2007	2008	2009	2010	2011	Notes
Waste Code 221	109.25	105.34	96.11	96.52	93.26	Waste oil and Mixed oil
Waste Code 222	5.44	4.48	4.91	4.84	4.55	Oil-water separator sludge
Waste Code 223	11.51	11.44	10.93	12.35	13.28	Other oil-containing waste
Total	126.20	121.26	111.95	113.72	111.09	
Processed in-state	101.77	101.67	97.78	100.49	96.32	
Exported	24.4	19.6	14.2	13.2	15.3	
RFO to combustion	40.2	34.4	29.1	23.3	27.5	De-watered; in-state plus exports
Other Products	66.1	69.6	74.1	76.0	73.0	Re-refined base lubricant, light fuels, asphalt additives
Wastes and Losses	20.0	17.3	8.7	14.4	10.5	Mostly wastewater to treatment
Yield (volumetric)	84.2%	85.7%	92.2%	87.3%	90.5%	
Hazardous wastes	5.4	10.1	6.9	5.8	5.5	x 1000 metric tons

It is helpful to bear in mind that some life stages are included in the study as part of the material flow analysis (MFA) for reference flow calculation purposes but are not included in the life cycle

impact analysis, i.e. their potential environmental impacts are not included within the scope of analysis.

4.1.1 Integration with the Economic Model

The Direct Impacts Model (DIM) developed by the economic contractor was used for three key components of the reference flow model. First, the DIM was used to estimate primary sales and the collectable fraction of lubricating and industrial oils for all years in the study. The difference between the quantity of collectable used oil generated and the quantity of used oil collected was taken to be oil managed on-site, either combusted or improperly disposed. Second, because empirical estimates for used oil collection were available only for the years 2007-2011, used oil collection rates for the years 2012-2030 were estimated by the DIM. Third, the DIM was used to estimate the likely secondary products of used oil management for the years 2012-2030.

Combined material flow analysis (MFA) and life cycle assessment (LCA) results from 2007-2011 were used to calibrate the DIM. The results delivered to the DIM are shown in Appendix A, Table 136. These values were used to calibrate the DIM and to provide indirect information about the used oil reprocessing market. The DIM was then used to project MFA results over the period from 2013-2030 for the baseline model and for each modeled scenario. MFA outcomes from the DIM were then input into the LCA to model the prospective environmental impacts over the study period.

4.1.2 Lubricant Sales and Use

The consumption of lubricants in California is included within the scope of the MFA but not the environmental impact assessment. This quantity provides the interface between the LCA model and the DIM, which includes estimates of lubricant sales by sector, and factors for losses-in-use, producing an estimate of collectable used oil for each scenario year. The DIM distinguishes three categories of oil demand: passenger car motor oil, heavy duty motor oil, and industrial oil. For each category, the DIM estimated the quantity of demand for new lubricants and the proportion of oil lost in use for a number of different use cases. Taken in aggregate, these values can be used to estimate a loss fraction for each of the three categories. Table 7 provides estimated loss fractions for different categories of lubricants during the base year.

The fraction of lubricant sales not lost in use is the amount of collectable used oil in a given model year. The difference between collectable used oil and collected used oil (from the MFA and the DIM) was considered to be informally managed. During the MFA period, the quantity of used oil collected is calculated from manifest records; thus, the amount of uncollected used oil to informal management is the difference between a DIM-derived quantity (collectable used oil) and a data-derived quantity (used oil formally managed in California). After the MFA period, both these quantities are output from the DIM; thus the amount of used oil to informal management is entirely determined by the DIM.

Table 7: Quantities of oil sold, lost in use, and available for collection in the combined model. Figures reflect the 2010 base year.

Demand Category	Demand 2010 (Mgal)	Loss Fraction	Collectable used oil 2010 (Mgal, dry)
Passenger Car Motor Oil	80.39	0.19	65.1
Heavy Duty Motor Oil	43.57	0.35	28.3
Industrial Oil	82.70	0.58	34.7
Total:	206.66	0.38	128.1

Sales volumes reported by the Direct Impacts Model (DIM) were derived from a lubricant sales report by a consulting firm (Kline, 2013). Sales estimates are also available from CalRecycle, but these figures were found to be unreliable after consultation with Kline, CalRecycle, and stakeholders.

The CalRecycle definitions of lubricating and industrial oils (California Code of Regulations, section 18601) differ from those used in the study. The first two categories in Table 7 correspond roughly to “lubricating oils” as understood by CalRecycle, while the third category corresponds to “industrial oils.” The correspondence is inexact because several oils regarded as “lubricating oils” by CalRecycle, including railroad oils, marine oils, and other industrial engine oils, are included in Kline’s definition of industrial oils. Commercial hydraulic oils for engines and tractors, regarded as “industrial oils” by CalRecycle, are included in Kline’s definition of lubricating oils. Although dielectric oils are not included in CalRecycle’s regulatory authority, they are included in Kline’s industrial oil and in the material flow analysis (MFA) and DIM. In all cases, the DIM used the Kline category definitions for oils. In the MFA, CalRecycle category definitions for lubricating and industrial oils were encountered during interpretation of used oil hauling reports; on these occasions, the collection estimates were adjusted to correspond to Kline’s categories during calibration of the DIM.

4.2 Inventory Design and Life Cycle Stages

The inventory model follows the material flow of used oil from the point it is generated (drained from a vehicle or piece of equipment, or removed from use at an industrial facility) to the point where it is finally consumed or disposed. Products of used oil recycling are assumed to displace comparable products in the market, thus leading to avoided primary production.

The six life cycle stages of the model contain the following unit processes:

- **Informal Management:** includes on-site combustion for energy recovery, used oil to landfill, and direct dumping into soil or waterways;
- **Collection and Waste Management:** includes truck and rail transport, hazardous waste landfilling, hazardous waste incineration, and waste water treatment;
- **Reprocessing of Used Oil:** includes rerefining, distillation, and recycled fuel oil production;

- **Use of Secondary Products:** includes combustion of all secondary fuels in boiler, direct fired burner, atomizing/vaporizing space heater, or marine engine;
- **Displaced Primary Production:** includes production of all avoided primary refinery products, natural gas, and electricity;
- **Displaced Primary Product Use:** includes combustion of all avoided primary refinery products and natural gas in boiler, direct fired burner, atomizing/vaporizing space heater, or marine engine.

The use phase of fuel products is modeled because fuels produced from used oil-derived fuels may have different characteristics and environmental impacts than the fuels they displace. The use and end-of-life stages of re-refined lubricants, asphalt products, and ethylene glycol are assumed to be identical to those of the displaced products and are not modeled.

4.2.1 Informal Management

This stage represents the disposition for collectable used oil that was not collected in the formal management system. The magnitude of the flow entering this stage equals the difference between collectable used oil, augmented to have the correct water content, and the quantity of wet oil reported on manifests. This value equaled about 36 million gallons (Mgal) in 2010. Three informal management fates of used oil were considered in the model: On-site combustion, landfill, and dumping (the latter two collectively known as “improper disposal”).

Among the informal disposition routes, used oil deposited in landfill is the route for which quantities are most accurately known. The most recent California waste management study involving extraction and analysis of 751 samples of municipal solid waste in landfills estimated the quantity of used oil deposited in landfills at approximately 4,000 metric tons (t) per year (including oil in filters, assuming 25 percent of the total mass of oil filters in landfill) (Adams, Kuehl, & Leary, 2009).

All recoverable used oil that is generated in California in any given year and that is neither collected by authorized used oil haulers nor landfilled is assumed to either be combusted directly at the site of generation or dumped. Therefore, the quantity of used oil modeled in on-site combustion and dumping is inferred rather than calculated directly. There is not sufficient data available to estimate the actual split between on-site combustion and dumping; therefore, a bias-free assumption of 50 percent to each route was used. Thus, of the ~112,000 t of uncollected recoverable used oil generated in the 2010 base year, 4,000 t were landfilled, and on-site combustion and dumping each received 50 percent of the remainder (54,000 t).

On-site combustion was modeled identically to recycled fuel oil combustion in space heaters and small boilers with no control technology (see Appendix B for details on combustion modeling). Details on the model of illegal dumping are provided in Appendix C.

A summary of the dumping model parameter names, estimates for probability values, and brief justifications are provided in Appendix C, Table 164. The fate and transport diagram is repeated, complete with estimated parameters, in Appendix C, Figure 75. Based on a total of ~112,000 t uncollected recoverable used oil in the 2010 base year, the informal management model results in the following fates:

- 54,000 metric tons (t) to on-site combustion
- 3,690 t to fresh water
- 15,800 t to sea water
- 16,840 t to agricultural soil
- 13,510 t to industrial soil
- 5,840 t through wastewater treatment
- 7,550 t to municipal solid waste landfills (direct flow plus filtered contaminants)
- 263 t to incineration (extracted from municipal solid waste flow, plus 3 percent of wastewater treatment biosolids)

4.2.2 Collection, Hauling, and Waste Management

This stage includes all processes related to collecting and consolidating used oil and delivering it to facilities where it is recycled or disposed. The material flow analysis model is implemented in this stage. Distinct processes and dispositions in this stage are described below. Detailed information about the process inventory data used is given in the relevant parts of section 4.3. The activity levels of various waste management disposition routes for the 2010 base year were typical of the material flow analysis period and were used throughout future years in the study period to maintain consistency of comparison with the base year.

LOCAL COLLECTION

All used oil was assumed to undergo a collection process, modeled as the operation of local liquid transport trucks operating short distance collection routes commonly referred to as “milk runs.” The collector travels to different generator facilities in sequence to receive used oil that has accumulated and delivers it to a central location.

Local collection is modeled as occurring in either “small” (1,500 gallons or roughly 5 t payload capacity) or “medium” (3,500 gallons or roughly 11.5 t) trucks. Collection transport distances were modeled analytically and calibrated using operator data. A collection truck following a route was assumed to begin and end at the same point and to travel in sequence to a number of facilities. Then the total distance traveled by the truck is given by

$$D = d \times (C/q + 1),$$

where D is the total trip distance, d is the average distance between facilities, C is the truck’s capacity, and q is the average pickup size. If the truck is assumed to begin empty and return full, then the average utilization of the truck over the full route is 0.5, and the total freight services delivered by the truck are

$$F = D \times C \times 0.5 = dc \times C,$$

where dc represents a characteristic hauling distance per kilogram of used oil collected. The calibrated distance between stops was taken to be 30 km based on confidential information received from one hauler and one operator of quick-lube facilities as well as geographic

information and communication with stakeholders. For small trucks, $C/q = 4$ was assumed, leading to a characteristic distance of 75 km. For medium trucks, $C/q = 12$ was assumed, leading to a characteristic distance of 190 km. The fraction of oil collected by medium trucks was taken to be 30 percent.

INTER-FACILITY TRANSPORT

The used oil material flow analysis was based on manifest records of used oil hauling within the state of California during the analysis period. Because each manifest record includes a start location (generator facility), an end location (a transfer, storage, and disposal facility), and a quantity of waste hauled, it was possible to compute the total freight services required during manifested used oil transport. For each year of the material flow analysis period the total amount of freight required was measured and divided by the total amount of oil collected to determine an average transport distance for each gallon of used oil collected. For the 2010 base year, this transport distance was 361 km.

Inter-facility transport was assumed to be accomplished by a combination of medium trucks (Class 6 – 32 percent), large (combination) trucks (Class 8b – 67 percent), and rail (1 percent), based on observations of the distribution of load sizes and distances reported on the manifests.

RECYCLED OIL EXPORT

Once oil has been tested and shown to be nonhazardous, or once oil is exported from the state of California, it is no longer reported on a manifest. Oil exported and destined for out-of-state recovery was assumed to require additional freight transport to reach its destination. A portion of loads shipped nearby were assumed to travel by class 8 truck and loads traveling a longer distance would go by rail. Based on capacity-weighted average of distances from the California border to known facilities, it was assumed that all oil destined for recycled fuel oil and 20 percent of oil destined for re-refining was transported by truck an average distance of 500 km to nearby facilities. The remaining 80 percent of oil destined for re-refining was assumed to be transported an average of 3,500 km by rail.

TRANSFER LOSSES

Facilities were classified in the material flow analysis according to the relative amounts of used oil they reported generating and receiving. When the quantity of used oil generated was less than the quantity received and the deficiency was smaller than 10 percent of the total amount received, the deficiency was interpreted as an incidental loss during transfer. The quantity of transfer losses ranged from 0.5-1.5 percent of total used oil collected over the material flow analysis period. Transfer losses totaled 1.35 percent in 2010; this value was used for all study years. For more information, please see Appendix A. Transfer losses were attributed to a combination of leaks and spillage, incidental dewatering, and accounting discrepancies during handling. Because some of the quantity of transfer losses can be attributed to routes with no environmental impact, and because the entire amount was below the cutoff threshold, transfer losses were not assigned any environmental impacts.



DIELECTRIC FLUID REJUVENATION

Oil delivered on a manifest to a facility known to be engaged primarily in transformer or transformer oil rejuvenation was designated as dielectric fluid for rejuvenation. This quantity was estimated at between 1 million-1.5 million gallons per year over the material flow analysis period. Substantial portions of dielectric fluid are rejuvenated on-site without entering the hazardous waste management system, and other facilities aside from the ones noted in the study may be engaged in dielectric fluid rejuvenation. For these reasons, the estimated amount should be taken as a lower bound. 0.93 percent of total used oil collected was designated for dielectric fluid rejuvenation in 2010; this value was used for all study years.

HAZARDOUS WASTE LANDFILL

Oil delivered to known hazardous waste landfill facilities, or delivered on a manifest that reported management method code H132 “Landfill or Surface Impoundment,” was interpreted as being delivered to a hazardous waste landfill. In 2010, 0.53 percent of all used oil collected was designated for hazardous waste landfill. In addition to used oil sent directly to landfill on a manifest, solid wastes were generated from the processing of some used oil originating in industrial facilities. Confidential data on the quantity of hazardous waste generated in this manner were provided by one facility and were used to estimate the size of this additional flow. The flow totaled an additional 0.79 percent of all used oil collected in 2010, leading to a total hazardous waste generation of 1.32 percent of all used oil collected. This value was used for all study years.

HAZARDOUS WASTE INCINERATION

Oil delivered on a manifest that reported management method code H040 “Destructive Incineration” was interpreted as being incinerated without energy recovery. In 2010, 0.19 percent of all used oil collected was designated for hazardous waste incineration; this value was used for all study years.

WASTEWATER TREATMENT

Oil delivered on a manifest that reported management method code H135 “Discharge to POTW/NPDES” was interpreted as being delivered to waste water treatment without oil recovery. In 2010, 5.6 percent of all waste code 221, 222, 223 collections was designated for wastewater treatment in 2010; this value was used for all study years. This quantity excludes the water content of used oil recovered at reprocessing facilities.

WATER CONTENT FEEDBACK

Used oil generation was estimated based on demand and loss rates, and used oil collection was estimated based on actual reports of waste oil hauling. Because demand quantities describe dry used oil and collection quantities describe mixtures of oil and water, it was necessary to introduce a correction to the used oil generation estimate that accounted for water content. The water content of used oil collected was estimated by waste code and is described in Table 8.

Table 8: Estimating the water content of used oil collected.

Waste Stream	Water Fraction
Waste Code 221 (Waste oil and mixed oil)	5%
Waste Code 222 (oil-water separator sludge)	50%
Waste Code 223 (other oil-containing waste)	35% — wastes destined for energy recovery; 85% — other wastes
Total collected used oil, 2010	16.5%
Total collected used oil, 2012-2030	Determined in DIM

4.2.3 Used Oil Reprocessing

The three used oil disposition routes that have been modeled here are:

- Distillation of used oil into so-called marine distillate oil and various co-products;
- Re-refining of used oil into re-refined base oil and various co-products
- Recycling of used oil into so-called recycled fuel oil

The inventory models of these three reprocessing routes are based on primary data collected from re-refining, marine distillate oil, and recycled fuel oil facilities in California and out-of-state. All primary data collection was subject to non-disclosure agreements. Concise technical descriptions of the processes are provided in section 1.2.

Each reprocessing process modeled included only intermediate flows and waste outputs to waste management. Intermediate inputs are connected to upstream cradle-to-gate inventory processes of energy and material input production. Secondary product outputs are connected to inventory models of the use phase and inventory models of displaced production and use processes. Waste outputs are connected to inventory models of the respective waste management processes.

4.2.4 Use of Recycled Products

The use phase of the co-products of recycled oil is thought to be a significant driver of environmental impacts (Boughton & Horvath, 2004; Fehrenbach, 2005). Because of the inadequacy of existing life cycle inventory data resources to describe used oil combustion, it was necessary to develop an in-depth parametric combustion model for the study. Combustion of used oil, recycled fuel oil, and distillate co-products are modeled and compared to the combustion of primary fuels thought to be displaced by these co-products, including No. 2 distillate, No. 6 residual oil, and natural gas. Marine distillate oil produced from used oil was assumed to combust identically to primary marine distillate, except for differences due to fuel composition. Details of the combustion model's design and construction are provided in Appendix B.

The combustion model is designed around a set of fuel-specific emission factors for eight key combustion pollutants, and technology-specific retention rates for several selected elements and compounds whose emission factors are dependent on fuel composition. The retention rates

indicate the amount of a given substance that is retained within the combustion equipment or otherwise mitigated prior to release to the environment. A retention rate of zero corresponds to full emission of the constituent substance. Emission factors for metals and phosphorus are determined by applying the retention rate directly to the concentration of the respective substances in the fuel. Emission factors for SO_x are determined by first converting elemental sulfur to the equivalent mass of SO₂, and then applying the retention rate. Halogens are limited to chlorine and fluorine in the data, both of which are converted to simple acids prior to applying retention rates. Particulates are assigned a maximal emission factor per fuel which is then mitigated according to the technology-specific retention rate. Table 9 reports the combustion emission factors used in the study, along with their default values in the model for each fuel.

Table 10 provides a list of retention rates and their default values in the model. The retained portion of each material was assumed to be incorporated into fly and/or bottom ash or captured in a control device. The resulting residual materials were assumed to be permanently sequestered as hazardous waste and were assigned no environmental impact potential.

No new primary data collection was performed in the development of the combustion model. The modeling of fuel combustion was thus limited by data availability and relevance. Because of the importance of combustion emissions to the model outcome and the uncertainty inherent in the data, sensitivity analysis was performed on both emission factors and retention rates. Upper and lower bounds for emission factors and retention rates were established based on primary data. Table 9 displays important emission factors for different fuel and combustion technology combinations, and Table 10 contains the retention rates assumed for different flow types across the five included technologies.

Table 9: Combustion emission factors used in the model, in kg/MJ lower heating value.

kg/MJ LHV	RFO	No 2 Distillate	No 6 Residual oil	Natural Gas	Light Ends	Marine Distillate	Bunker Fuel
Technology	All	All	All	All	All	All	All
CH4	3.1E-06	3.2E-06	3.1E-06	1.1E-06	3.1E-06	3.7E-07	4.0E-07
CO2	7.2E-02	7.4E-02	7.7E-02	5.5E-02	7.2E-02	7.4E-02	7.9E-02
N2O	6.1E-07	6.4E-07	6.2E-07	1.1E-07	6.3E-07	5.1E-06	5.5E-06
CO	3.4E-06	3.3E-06	3.5E-06	2.9E-06	2.7E-05	7.0E-05	6.0E-05
NOx	7.3E-05	3.7E-05	1.7E-04	1.6E-05	6.8E-05	9.3E-04	1.4E-03
SOx*	1.8E-04	7.7E-05	4.9E-04	3.5E-07	3.9E-07	8.9E-05	1.7E-03
PM Total*	5.8E-05	1.5E-06	2.0E-05	6.5E-07	2.2E-07	6.5E-05	4.0E-05
PM10*	4.6E-05	7.4E-07	1.7E-05	6.5E-07	2.2E-07	3.3E-05	3.5E-05
NMVOC	3.1E-06	1.4E-06	4.0E-06	4.5E-06	1.8E-06	3.7E-05	4.0E-06
PAH	1.9E-08	1.2E-08	3.7E-09	2.9E-10	1.1E-08	7.9E-07	8.4E-07

*Note: PM Total, PM10, and SO_x emission factors are modified by retention rates.

Table 10: Default retention rates for various emitted substances by technology. Rates based on highly limited or no data are marked with a dagger symbol †.

	Metals	PM	Halogens	Sulfur	Phosphorus
Boiler	0.85	0.2	0.1 [†]	0.15	0.5 [†]
Atomizing Heater	0.4	0	0.1 [†]	0.05	0.5 [†]
Vaporizing Heater	0.998	0.95	0.1 [†]	0.35	0.99
Baghouse	0.99	0.98	0.2 [†]	0.6	0.5 [†]
Marine	0.4 [†]	0	0.1 [†]	0.02	0 [†]

4.2.5 Displaced Production and Use of Primary Products

In a consequential life cycle assessment, it is assumed that the benefits of recycling will result from secondary products displacing primary products that otherwise would have been produced. In other words, the secondary product results in an overall reduction in primary production. A displacement rate of less than 1 implies that primary production has not been completely avoided by the secondary product and overall production for the market has increased. The impacts of this avoided primary production, or “avoided burden,” can be subtracted from those of the recycling system to determine the overall environmental impact of the system. If in any impact category the impacts of primary production are lower than those of the recycling system, then there can be no environmental benefit from recycling for that impact category.

In the present study, the co-products of used oil displace both fuels and nonfuel products from crude oil refineries and natural gas. Through system expansion, the study performs a comparison of the life cycle impacts of used oil recycling plus the direct impacts of combustion of co-products, versus the avoided life cycle impacts of displaced production plus the avoided direct impacts of combustion of displaced fuels.

Table 11 displays the displacement relationships currently represented in the baseline model. Secondary products are those products that result from the management of California’s used oil. Secondary combustion describes the process that is used to model the use phase of a given product category, specifically fuels, since these are the only products for which the use phase is modeled. Displaced production refers to the production of the primary product that the secondary product is understood to compete with in the marketplace. Displaced combustion is the avoided use phase of that product or products.

For each product, the sulfur content and lower heating value are provided when available. The displacement rate is the ratio of secondary product to primary product, either on a per kg or per MJ basis, as specified beneath. More information about the selection of displaced products is provided in Appendix D.

Table 11: Displacement Relationships. Displaced combustion was assumed to occur in the same facility type as secondary combustion.

Secondary Product	%S	LHV (MJ/kg)	Secondary Combustion	Displaced Product	% S	LHV (MJ/kg)	Disp. Rate MJ/MJ
Base Oil	N/A	N/A	N/A	Base Oil	N/A	N/A	1*
Light Ends	Unk	44	Light Ends in Kiln	No 2 Distillate	0.001	43.9	1
Light Distillates	0.3	43	No 2 Distillate in Boiler	No 2 Distillate	0.2	43	1
Middle Distillates	0.05	43	No 2 Distillate in Boiler	No 2 Distillate	0.2	43	1
Marine Distillate	0.2	43	MDO in Marine Engine	No. 2 Distillate	0.2	43	1
Asphalt Flux	N/A	N/A	N/A	Bitumen	N/A	N/A	1*
Ethylene Glycol	N/A	N/A	N/A	Ethylene Glycol	N/A	N/A	.7*
Used Oil – Onsite Combustion	0.4	41.4	RFO in 50% Space Heater / 50% Boiler	No 2 Distillate	0.2	43	0.5/0.33
				No 6 Residual	1.16	40.4	0.5/0.33
				Natural Gas	0.001	49	0.5/0.33
RFO	0.4	41.4	RFO in 60% Kiln / 40% Boiler	No 2 Distillate	0.2	43	0.33
				No 6 Residual	1.16	40.4	0.33
				Natural Gas	0.001	49	0.33

*Indicates displacement rate is on a kg/kg basis.

Two displacement rates are listed for the displaced primary products from onsite combustion. This is because the used oil that is combusted in small space heaters is assumed to displace only No. 2 distillate and natural gas due to technical constraints, whereas combustion in boilers is assumed to also be capable of displacing No. 6 residual oil, using a 50/50 and a three-way split, respectively.

Additionally, the improper disposal of used oil also results in an avoided burden. About 2.2 percent of the used oil that ends up in wastewater treatment plants or landfills is assumed to be directly incinerated for energy in municipal solid waste incineration facilities. This energy production is assumed to displace an equal amount of electricity production on a per MJ basis.

DISPLACED PRODUCTION OF REFINERY PRODUCTS

PE International was commissioned to develop custom U.S. and California refinery models to describe displaced petroleum products production for the project (PE International, 2013). These two models are rooted in PE International’s European refinery model as modified to reflect U.S. and California product slates, technologies, and emissions profiles.

Table 12 lists the sources of data used in the California and U.S. refinery modeling.

Table 12: U.S. & California Refinery Model Data Sourcing (PE International, 2013)

Refinery Model Data Sourcing	
Crude Oil Properties	U.S. Energy Information Administration, California Energy Commission (CEC) Petroleum Industry Information Reporting Act (PIIRA) database
Refinery Modeling	Expert judgment, PE Proprietary Data
Refinery Production Slate and Product Qualities	U.S. Energy Information Administration, California Energy Commission, International Maritime Organization, Expert judgment
Emissions	U.S. EPA — Greenhouse Gas Data Sets, with reference to 2010 U.S. EPA —The National Emissions Inventory, with reference to 2008 U.S. EPA — Toxics Release Inventory (TRI), with reference to 2010

The refinery model life cycle inventory covers the entire supply chain of the refinery products from cradle to gate. Emissions are allocated to refinery products based on emission mass and product energy content. Products are assigned an emission allocation for each unit process they pass through based on mass, and the emissions are aggregated over the whole refinery. In this way, products that pass through more unit processes and require more energy during production are allocated a larger assignment of emissions.

The unit processes provided in the California and U.S. refineries are partially aggregated, allowing the user to choose their preferred source of crude oil, electricity, and natural gas. This methodology also permits the model to be tailored to production location and to vary with time. Process inventory summaries are reported in Table 13. The crude oil input process includes transport of crude oil to a U.S. or California refinery. In the final inventory model, in order to ensure comparability between in-state and out of state production, only U.S. refinery processes were used due to differences in data sourcing between U.S. and California model development.

Table 13: Inventory parameters for primary production of displaced petroleum products.

Displaced Product	Functional Unit	Crude Oil Input kg	Electricity MJ	Natural Gas kg	Water kg
Group II Base Oil	1 kg – CA	1.08	0.286	0.113	0.323
	1 kg – U.S.	1.04	0.57	0.0869	0.313
Bitumen	1 kg – CA	1.01	0.0527	0.00825	0.303
	1 kg – U.S.	0.992	0.101	0.00306	0.298
Diesel	1 kg – CA	1.11	0.144	0.0477	0.332
	1 kg – U.S.	1.12	0.198	0.0199	0.336
Gasoline	1 kg – CA	1.11	0.133	0.0561	0.388
	1 kg – U.S.	1.10	0.235	0.037	0.437
Heavy Fuel Oil – <0.3% sulfur	1 kg – CA	0.998	0.132	0.0507	0.299
	1 kg – U.S.	0.99	0.212	0.0234	0.297
Heavy Fuel Oil – >0.3% sulfur	1 kg – CA	0.979	0.132	0.0507	0.294
	1 kg – U.S.	0.972	0.212	0.0234	0.292
Bunker Fuel – 3.5% sulfur	1 kg – CA	0.979	0.132	0.0507	0.294
	1 kg – U.S.	0.972	0.212	0.0234	0.292

DISPLACED PRODUCTION OF NATURAL GAS

In 2010, natural gas was more expensive than recycled fuel oil. Stakeholder feedback indicated that facilities such as stationary hot mix asphalt plants may switch between natural gas and recycled fuel oil depending on price and technological feasibility. Therefore, natural gas is included in the modeling of recycled fuel oil displacement. Displaced production of natural gas was modeled using the PE Professional Database for maximal comparability between avoided products. The process was modified to include a 1.9 percent methane leakage rate based on more recent studies regarding leaks during extraction and transport of natural gas using modern shale gas extraction techniques (Howarth 2011, Burnham 2012).

DISPLACED COMBUSTION

Because the combustion emissions of used oil products were thought to be different from those of displaced primary products, it was necessary to model the combustion of both co-products and displaced products in a way that was mutually compatible and comparable. The combustion

model discussed in Section Use of Recycled Products 4.2.4 was used to model combustion of both co-products and displaced products.

4.3 Background Processes

Background processes can be defined as processes for which elements of the reference flow, in this case used oil and used-oil-derived products, are not inputs or outputs. The following section describes the process inventories used in background modeling for this life cycle assessment (LCA).

4.3.1 The U.S. LCI Inventory Model

The U.S. Life Cycle Inventory database (U.S. LCI), maintained by the National Renewable Energy Laboratory, was used for the core processes of electricity production, fuels production, and natural gas distribution. The core inventory model consists of 35 unit processes drawn from U.S. LCI describing the extraction, refining, and combustion of several different types of fossil energy, uranium extraction, and refining, and transport by train, truck, barge, and ocean freighter. Taken together, the processes can be used to construct a cradle-to-gate inventory model for any given output. Data for the U.S. LCI model were developed by Franklin Associates. The U.S. LCI model was used to describe electricity production and distribution, natural gas production and distribution, diesel fuel production and combustion, and propane (LP gas) production and combustions. Combustion of used oil co-products and displaced products were modeled in a customized model developed specifically to meet the needs of this LCA project (see Section 4.2.4).

The U.S. LCI model has several notable omissions. Electricity generation from non-fossil fuel sources is not modeled. Waste generation is reported but waste disposal processes are not included. Natural gas distribution is modeled, but the database does not include a process for transport of natural gas by pipeline. All processes exclude water use, land use, and infrastructure.

4.3.2 Modifications and Enhancements of the U.S. LCI Model

The U.S. LCI model was supplemented with cradle-to-gate processes for electricity production from renewable sources, including photovoltaic, wind, geothermal, and hydroelectric power, all drawn from the PE Professional Database.

A model for natural gas distribution by pipeline was constructed based on a publication by Franklin Associates in which the other U.S. LCI processes were described (Franklin Associates LLC, 2007). According to this reference, natural gas distribution by pipeline requires 773 BTU per ton-mile, equivalent to 0.0155 Nm³ of natural gas combustion per metric ton-kilometer of natural gas distribution.

4.3.3 Electricity Production and Distribution

Emission estimates resulting from electricity consumption are sensitive to fuel types and generation technologies. Because the study analyzes processes that occur in different geographic and temporal settings it is important to consider how these generation method(s) differ by region and change over time. Two electricity grid mix time series were created to analyze the processes captured by the study.

The 10-Year Regional Transmission Plan for the Western Electricity Coordination Council (WECC) was used to determine California's future electricity grid mixes. California is not an electricity island. The state is connected with other western states for reliability purposes and is a net importer of electricity. Changes that occur in other states will likely have an effect on the emissions intensity of California electricity use and therefore future WECC mixes are used. The 10-Year Regional Transmission Plan has multiple grid mix scenarios and the 2020 State-Provincial Steering Committee reference case was used to develop this time series (Western Electricity Coordinating Council, 2011). This case accounts for state renewable portfolio standards while incorporating expected savings from energy efficiency programs and policies. Linear extrapolation between the 2010 and 2020 mix was used to forecast the remaining years examined by this study.

For processes occurring outside the state of California, the United States average electricity grid mix was used. The time series used in this study is based on the reference case developed by the Energy Information Agency (EIA) and reported in their Annual Energy Outlook (U.S. Energy Information Administration, 2012).

Grid mixes used in the study are reported in Table 14.

Table 14: Grid mix parameters for WECC and U.S. grid.

WECC Grid Mix	2010	2015	2020	2025	2030
Transmission loss	0.07471	0.07471	0.07471	0.07471	0.07471
Biomass	0.01285	0.01347	0.01410	0.01473	0.01535
Coal	0.28771	0.27971	0.27170	0.26770	0.26369
Geothermal	0.02035	0.02702	0.03370	0.03704	0.04038
Heavy_Fuel_Oil	0.00540	0.00540	0.00540	0.00540	0.00540
Hydro	0.22801	0.23419	0.24037	0.24345	0.24654
Lignite	0.00000	0.00000	0.00000	0.00000	0.00000
Natural Gas	0.32098	0.29073	0.26049	0.24536	0.23024
Nuclear	0.09468	0.08342	0.07215	0.06652	0.06089
Solar	0.00117	0.01459	0.02802	0.03473	0.04144
Wind	0.02769	0.05004	0.07239	0.08357	0.09475
Unspec. Fossil	0.00115	0.00142	0.00168	0.00150	0.00131
U.S. Average Grid Mix	2010	2015	2020	2025	2030
Transmission loss	0.08969	0.08969	0.08969	0.08969	0.08969
Biomass	0.00738	0.00959	0.01710	0.01957	0.01762
Coal	0.42257	0.35574	0.36148	0.36880	0.36303
Geothermal	0.00412	0.00498	0.00630	0.00785	0.00979
Heavy Fuel Oil	0.00896	0.00669	0.00655	0.00635	0.00616
Hydro	0.06716	0.07882	0.07755	0.07596	0.07547
Lignite	0.02604	0.02513	0.02421	0.02329	0.02237
Natural Gas	0.23799	0.27208	0.25677	0.25028	0.26581
Nuclear	0.19556	0.19995	0.20462	0.20137	0.19139
Solar	0.00024	0.00034	0.00172	0.00167	0.00180
Wind	0.02485	0.04028	0.03899	0.04022	0.04184
Unspec. Fossil	0.00512	0.00640	0.00471	0.00465	0.00471

4.3.4 Freight Transport

Vehicle emission factor time series for this study were developed using the California Emissions Factors (EMFAC) model developed by the California Air Resources Board (California Air Resources Board, 2013). EMFAC is the state-of-the-art tool for assessing emissions from mobile sources in California. EMFAC models forecast improvements in vehicle emission rates over time by accounting for the effects of truck and bus regulations, the Paveley Clean Car Standard (Assembly Bill 1493, 2002, and amendments), and the Low Carbon Fuel Standard. The model can be used at a high resolution level to develop emission inventories for specific vehicle types in specific regions of California. For the present model, an aggregate approach was used to establish statewide average emission inventories for each of the vehicle classifications used in the used oil transport model. Emission factors on a mass per fuel energy content functional unit were

developed for each of the years analyzed in the study using a LHV for diesel of 128,450 btu/gal, annual average seasonal data, and average speed profiles, while taking into account fleet turnover.

Table 15 shows the emission factors used in the study. The emissions analyzed were a direct output of the EMFAC model with the exception of methane (CH₄) and nitrous oxide (N₂O). These emissions factors were determined as specified by CARB, which uses specific fractions of other factors. CH₄ is measured as a direct fraction of total greenhouse gases while N₂O is determined from the amount of diesel fuel consumed.

While EMFAC models improvements in emissions over time, it does not assess changes in fuel economy, so emerging national standards were used. In 2011 the first federal regulations for heavy duty vehicle fuel economy were passed. These standards were developed by the U.S. EPA and the National Highway Transportation Safety Administration and call for improvements in fuel economy in Class 3 trucks by 15 percent and 20 percent for Class 6 and 8 by 2018 (49 CFR sections 523, 534-535). Using the 2010 fuel economy estimated by for EMFAC as a reference for Class 6 and 8 Trucks and estimating the fuel economy of the Class 3 truck from the Transportation Energy Data Book, it was assumed that that in 2030 all trucks are compliant with this standard (Davis, Diegel, & Boundy, 2012). Linear interpolation was used to approximate fuel economy in intervening years. Table 16 reports fuel economy used in the model.



Table 15: Freight Transport Emission Factors.

[kg / MJ LHV]									
Class 3 Truck	CO	CO2	Nox	PM10	PM2.5	Sox	N20	CH4	VOC
2010	9.08E-05	7.51E-02	4.91E-04	1.35E-05	7.81E-06	4.52E-07	2.45E-06	8.56E-07	1.84E-05
2015	9.15E-05	7.51E-02	3.81E-04	1.33E-05	7.40E-06	4.66E-07	2.45E-06	7.88E-07	1.70E-05
2020	8.59E-05	7.51E-02	2.75E-04	1.29E-05	6.91E-06	4.82E-07	2.45E-06	6.44E-07	1.39E-05
2025	7.92E-05	7.51E-02	1.88E-04	1.27E-05	6.50E-06	4.97E-07	2.45E-06	5.00E-07	1.08E-05
2030	7.62E-05	7.51E-02	1.38E-04	1.27E-05	6.37E-06	5.13E-07	2.45E-06	4.11E-07	8.85E-06
Class 6 Truck	CO	CO2	Nox	PM10	PM2.5	Sox	N20	CH4	VOC
2010	8.46E-05	7.51E-02	5.35E-04	2.82E-05	2.14E-05	7.10E-07	2.45E-06	1.19E-06	2.56E-05
2015	4.45E-05	7.51E-02	3.33E-04	1.65E-05	1.04E-05	7.43E-07	2.45E-06	5.70E-07	1.23E-05
2020	3.36E-05	7.51E-02	1.71E-04	1.35E-05	7.48E-06	7.71E-07	2.45E-06	3.89E-07	8.38E-06
2025	3.17E-05	7.51E-02	8.70E-05	1.31E-05	6.81E-06	8.02E-07	2.45E-06	3.53E-07	7.60E-06
2030	3.34E-05	7.51E-02	8.49E-05	1.37E-05	7.12E-06	8.37E-07	2.45E-06	3.72E-07	8.01E-06
Class 8 Truck	CO	CO2	Nox	PM10	PM2.5	Sox	N20	CH4	VOC
2010	1.25E-04	7.51E-02	6.28E-04	2.27E-05	1.87E-05	7.12E-07	2.45E-06	1.30E-06	2.80E-05
2015	7.68E-05	7.51E-02	3.99E-04	9.77E-06	6.65E-06	7.55E-07	2.45E-06	7.33E-07	1.58E-05
2020	7.91E-05	7.51E-02	2.74E-04	8.45E-06	5.32E-06	7.89E-07	2.45E-06	7.23E-07	1.56E-05
2025	8.01E-05	7.51E-02	1.59E-04	8.38E-06	5.16E-06	8.20E-07	2.45E-06	7.21E-07	1.55E-05
2030	8.18E-05	7.51E-02	1.45E-04	8.47E-06	5.13E-06	8.55E-07	2.45E-06	7.31E-07	1.57E-05

Table 16: Fuel economy for on-road freight vehicles used in the study, miles per gallon.

	Class 3	Class 6	Class 8
2010	12.12	8.51	5.53
2015	12.58	8.94	5.81
2020	13.03	9.37	6.09
2025	13.49	9.79	6.36
2030	13.94	10.22	6.64

4.3.5 Chemical Production

The production of chemical inputs used by recycling facilities was primarily modeled using PE International’s professional database. PE International’s database was chosen as a default because

the production of all primary refinery products being displaced was modeled by PE. Therefore, the use of its material input processes ensured the greatest comparability between the secondary and primary products.

Appropriate PE processes were available for all of the following inputs: process water, hydrogen, liquid nitrogen, sodium hydroxide, hydrochloric acid, and sodium chloride. No PE process was available for sodium hypochlorite production, so an Ecoinvent process was substituted.

4.3.6 Waste Management

Several solid and liquid wastes result from the processing of used oil. Once again, preference was given to the PE International Professional Database in order to ensure comparability with primary production processes. Landfill of inert waste and waste water treatment processes were both available from PE. However, the PE databases did not contain any processes representing the treatment and disposal of hazardous waste. Therefore, Ecoinvent processes for disposal to hazardous waste incineration and disposal of hazardous waste to underground deposit were used instead.

The Ecoinvent process for hazardous waste incineration of used mineral oil was modified in order to ensure that it accurately represented the composition of waste that results from the used oil system. Used oil is considered off-specification and unfit for re-processing in California if its total halogen content is above 1,000 ppm or if its PCB content is above 50 ppm (California Code of Regulations, 2005a). Since no halogens were included in the original Ecoinvent used mineral oil incineration process, halogen flows and quantities were taken from the process for combustion of an equal quantity of average hazardous waste under the assumption that these flows are representative of the halogenated emissions that are likely to be emitted by a hazardous waste incineration facility.

5 Life Cycle Impact Assessment

This section reports and discusses the impact assessment results of the life cycle inventory model of used oil management in California under various assumptions including:

- The 2010 base year model;
- Four hypothetical extreme informal management scenarios in which all the used oil collected and reprocessed in 2010 is assumed to be informally managed;
- Three hypothetical extreme formal management scenarios in which all the used oil collected and reprocessed in 2010 is sent to just one of the three disposition routes;
- The 2015, 2020, and 2030 scenario years of the baseline model and the 10 scenarios from the Direct Impacts Model.

The baseline scenario is also called the “no change” or “business as usual” scenario. Extreme scenarios are intended to highlight differences between the different routes. However, they are not intended to necessarily reflect achievable conditions in any way. Both capacity constraints, in terms of California re-processing facility capacity, and technical limitations, in terms of the appropriateness of different loads of used oil to different re-processing routes, would apply in a

real-world scenario. The flow quantities and activity levels of the baseline scenario are taken from the Direct Impacts Model (see Section 4.1.1).

The used oil management system is divided into informal and formal management. Informal management is further divided into used oil dumping, used oil landfill/incineration, displaced processes due to secondary products from landfill/incineration, onsite combustion of used oil, and displaced production and combustion of primary fuels due to onsite used oil combustion. Formal management consists of five life cycle stages: Collection, reprocessing, use of secondary products, displaced production, and displaced use. In sum, the six life cycle stages reflected in the impact model graphs are:

1. **Informal Management:** includes dumping, landfill and incineration, onsite combustion, and displacement due to onsite combustion and incineration
2. **Collection and Waste Management:** includes collection, inter-facility transport, and treatment of hazardous waste and wastewater generated during collection and transfer.
3. **Reprocessing of Used Oil:** includes the production and use of all energy and ancillary material inputs into used oil reprocessing as well as the transportation and waste management processes that occur during used oil reprocessing.
4. **Use of Secondary Products:** accounts for the combustion of all secondary fuel products from used oil reprocessing. This includes the main secondary products, marine distillate oil and recycled fuel oil, as well as all co-products that are sold as fuel.
5. **Displaced Primary Production:** includes the production of all fuels that are assumed to be displaced by the secondary fuels from used oil reprocessing.
6. **Displaced Primary Product Use:** includes the combustion of all fuels that are assumed to be displaced by the secondary fuels from used oil reprocessing.

Each figure shows life cycle stages from top to bottom in a “waterfall” layout. Positive numbers on the graph denote incurred impacts from processes with positive activity levels. Negative numbers represent avoided impacts from processes which displace production and use of primary products. Each bar is labeled with the magnitude of the impact in the respective life cycle stage (not the cumulative impact). Labels on small bars are offset for visual clarity.

Each subsequent bar begins at the level where the previous bar ended, so that by following the bars from top to bottom, one can see the cumulative impact at each life cycle stage. The thick pink line at the end of the fifth bar shows the net impacts of formal used oil management, calculated as the sum of incurred and avoided impacts. This layout shows the contribution that each life cycle stage makes to the overall impact, and also highlights the difference between incurred impacts (positive numbers) and avoided impacts (negative numbers). The scale of all the graphs within each impact category is identical across the four scenarios, meaning that impacts between scenarios can be compared visually using bar length. The order of magnitude of the indicator results is given on the right hand side of the x-axis.



5.1 Base Year and Extreme Scenarios – Informal Management

This section reports the life cycle impact assessment results of the 2010 base year model with informal management impacts shown, as well as the impacts of several different extreme informal management scenarios.

The base year as reported in all other analyses assumes that 4 percent of informally managed oil is landfilled, and the remaining quantity is split 90/10 between dumping and onsite combustion, which equates to an 87/9/4 dumping/onsite combustion/landfill split. The results of assuming a 50/50 split between dumping and onsite combustion in the base year are also reported here in order to gauge the sensitivity of the base year model to this assumption, which equates to a 48/48/4 dumping/onsite combustion/landfill split. In addition, there are four extreme informal management scenarios:

- No Management 87/9/4: All collected used oil is sent to informal management route; 4 percent is landfilled. Of the remaining oil, 90 percent is dumped and 10 percent is combusted onsite.
- No Management 48/48/4: All collected used oil is sent to informal management route; 4 percent is landfilled. Of the remaining oil, 50 percent of the oil is dumped, and 50 percent is combusted onsite.
- No Management 45/5/50: All collected used oil is sent to informal management route; 45 percent of the oil is dumped, 5 percent is combusted onsite, and 50 percent is sent to landfill.
- No Management 25/25/50: All collected used oil is sent to informal management route; 25 percent of the oil is dumped, 25 percent is combusted onsite, and 50 percent is sent to landfill.

Mass flow inventory inputs and secondary products for the base year and extreme informal management scenarios are shown in Table 17. In the 2010 base year, an estimated 435 million kg of dry collectable used oil were generated. Of this, 16.5 percent, or 63.7 million kg, was estimated to be water. Of the collected used oil, 354 million kg were reprocessed through the three disposition routes in the base year. However, in informal management, the entire quantity of collectable dry used oil is assumed to be informally managed. Table 26 shows the mass flow inventory quantities for the base year and extreme informal management scenarios.

Table 17: Mass flow inventory for base year with informal management shown and extreme informal management scenarios.

[million kg]	Base Year		No Management			
	87/9/4	48/48/4	87/9/4	48/48/4	45/5/50	25/25/50
Collectable Dry Used Oil	435	435	435	435	435	435
Collected UO Water Content	64	64	0	0	0	0
Recycled Oil Reprocessed	354	354	0	0	0	0
UO to Informal Management	112	112	435	435	435	435
Used Oil Dumped to Soil	49	27	188	105	98	54
Used Oil Dumped to Water	49	27	188	105	98	54
Used Oil Landfilled	4	4	16	16	218	218
UO to Incineration	0.5	0.3	1.9	1.2	5.6	5.2
UO to Onsite Combustion	11	54	42	209	22	108
Waste to Disposal	27	27	0	0	0	0
Secondary Products						
Re-refined Base Oil	51	51	0	0	0	0
Light Fuel	121	121	0	0	0	0
RFO to Combustion	41	41	0	0	0	0
Asphalt Product	81	81	0	0	0	0
Ethylene Glycol	0.4	0.4	0	0	0	0

All life cycle impacts results are reported for both the 2010 base year and the extreme informal management scenarios in Table 18 through Table 25, with one table per impact category. Table headers are shaded to match the colors in the corresponding bar charts. Waterfall graphs are shown in Figure 5 through Figure 12 for the base year only, with informal management impacts included. They display a contribution analysis of the impact of each life stage of the used oil management system for the 2010 base year model, including informal management. Range charts show the life cycle impacts of the 2010 base year and extreme informal management scenarios in Figure 13.

Each chart includes a bar for the impacts of the base year, with impacts bound by a 50/50 dumping/onsite combustion assumption on one side and a 90/10 dumping/combustion assumption on the other, a bar for no management with 4 percent landfilled and the remaining oil split by a 50/50 dumping/onsite combustion assumption on one side and a 90/10 dumping/combustion assumption on the other, and a bar assuming 50 percent landfilling with the remaining oil split by a 50/50 dumping/onsite combustion assumption on one side and a 90/10 dumping/combustion assumption on the other.

Table 18: Global Warming Potential in kg CO₂ equivalent for base year with informal management shown and extreme informal management scenarios.

[kg CO ₂ -Equiv.]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	5.1E+06	2.8E+06	2.0E+07	1.1E+07	1.0E+07	5.7E+06
Landfill:incurred	2.2E+06	1.6E+06	8.7E+06	6.3E+06	4.7E+07	4.6E+07
Landfill:disp	-5.0E+05	-3.3E+05	-1.9E+06	-1.3E+06	-6.8E+06	-6.5E+06
Onsite:use	3.2E+07	1.6E+08	1.3E+08	6.3E+08	6.5E+07	3.2E+08
Onsite:Disp:use	-3.0E+07	-1.5E+08	-1.2E+08	-5.8E+08	-6.0E+07	-3.0E+08
Onsite:Disp:prod	-6.9E+06	-3.5E+07	-2.7E+07	-1.3E+08	-1.4E+07	-7.0E+07
Used Oil Management	6.1E+08	6.1E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-5.1E+08	-5.1E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-1.9E+08	-1.9E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	-8.5E+07	-1.1E+08	8.9E+06	-7.3E+07	4.2E+07	-5.5E+05

Table 19: Acidification Potential in H⁺ moles equivalent for base year with informal management shown and extreme informal management scenarios.

[H ⁺ moles-Equiv.]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	4.8E+04	2.7E+04	1.9E+05	1.0E+05	9.6E+04	5.4E+04
Landfill:incurred	2.5E+05	1.7E+05	9.9E+05	6.5E+05	3.5E+06	3.3E+06
Landfill:disp	-2.2E+05	-1.5E+05	-8.7E+05	-5.7E+05	-3.0E+06	-2.9E+06
Onsite:use	5.7E+06	2.9E+07	2.2E+07	1.1E+08	1.1E+07	5.7E+07
Onsite:Disp:use	-3.6E+06	-1.8E+07	-1.4E+07	-6.9E+07	-7.2E+06	-3.6E+07
Onsite:Disp:prod	-1.4E+06	-7.1E+06	-5.5E+06	-2.7E+07	-2.8E+06	-1.4E+07
Used Oil Management	2.6E+08	2.6E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-2.2E+08	-2.2E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-5.6E+07	-5.6E+07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	-2.2E+07	-1.9E+07	3.1E+06	1.4E+07	2.0E+06	7.7E+06

Table 20: Eutrophication Potential in kg N equivalent for base year with informal management shown and extreme informal management scenarios.

[kg N-Equiv.]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	2.6E+05	1.5E+05	1.0E+06	5.7E+05	5.3E+05	2.9E+05
Landfill:incurred	4.3E+01	2.8E+01	1.7E+02	1.1E+02	5.9E+02	5.6E+02

Landfill:disp	-5.5E+01	-3.6E+01	-2.1E+02	-1.4E+02	-7.5E+02	-7.1E+02
Onsite:use	6.5E+03	3.3E+04	2.5E+04	1.3E+05	1.3E+04	6.6E+04
Onsite:Disp:use	-1.0E+03	-5.2E+03	-4.1E+03	-2.0E+04	-2.1E+03	-1.1E+04
Onsite:Disp:prod	-8.6E+02	-4.3E+03	-3.3E+03	-1.7E+04	-1.7E+03	-8.6E+03
Used Oil Management	2.5E+05	2.5E+05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-2.1E+05	-2.1E+05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-2.8E+04	-2.8E+04	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	2.8E+05	1.8E+05	1.0E+06	6.6E+05	5.4E+05	3.4E+05

Table 21: Ecotoxicity Potential in CTUeco for base year with informal management shown and extreme informal management scenarios.

[CTUeco]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	1.5E+09	8.3E+08	5.8E+09	3.2E+09	3.0E+09	1.7E+09
Landfill:incurred	8.4E+05	5.5E+05	3.3E+06	2.2E+06	1.2E+07	1.1E+07
Landfill:disp	-3.1E+05	-2.0E+05	-1.2E+06	-7.9E+05	-4.2E+06	-4.0E+06
Onsite:use	7.4E+07	3.7E+08	2.9E+08	1.4E+09	1.5E+08	7.4E+08
Onsite:Disp:use	-1.6E+06	-8.0E+06	-6.2E+06	-3.1E+07	-3.2E+06	-1.6E+07
Onsite:Disp:prod	-2.0E+06	-9.8E+06	-7.6E+06	-3.8E+07	-3.9E+06	-2.0E+07
Used Oil Management	1.4E+08	1.4E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-1.8E+07	-1.8E+07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-7.7E+07	-7.7E+07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	1.6E+09	1.2E+09	6.1E+09	4.6E+09	3.1E+09	2.4E+09

Table 22: Human Health Cancer Potential in cases for base year with informal management shown and extreme informal management scenarios.

[cases]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	8.0E-01	4.4E-01	3.1E+00	1.7E+00	1.6E+00	8.9E-01
Landfill:incurred	1.7E-04	1.1E-04	6.7E-04	4.4E-04	2.3E-03	2.2E-03
Landfill:disp	-1.3E-04	-8.4E-05	-5.0E-04	-3.3E-04	-1.8E-03	-1.7E-03
Onsite:use	1.3E-02	6.7E-02	5.2E-02	2.6E-01	2.7E-02	1.3E-01
Onsite:Disp:use	-7.0E-03	-3.5E-02	-2.7E-02	-1.3E-01	-1.4E-02	-7.0E-02
Onsite:Disp:prod	-1.8E-03	-8.8E-03	-6.8E-03	-3.4E-02	-3.5E-03	-1.8E-02
Used Oil Management	6.4E-01	6.4E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-3.6E-01	-3.6E-01	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-7.0E-02	-7.0E-02	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	1.0E+00	6.8E-01	3.1E+00	1.8E+00	1.6E+00	9.4E-01

Table 23: Human Health Non-Cancer Potential in cases for base year with informal management shown and extreme informal management scenarios.

[cases]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	1.3E+03	7.4E+02	5.2E+03	2.9E+03	2.7E+03	1.5E+03
Landfill:incurred	1.0E-01	6.5E-02	3.9E-01	2.6E-01	1.4E+00	1.3E+00
Landfill:disp	-1.8E-02	-1.2E-02	-7.1E-02	-4.7E-02	-2.5E-01	-2.4E-01
Onsite:use	6.7E+01	3.4E+02	2.6E+02	1.3E+03	1.3E+02	6.7E+02
Onsite:Disp:use	-5.9E-01	-3.0E+00	-2.3E+00	-1.2E+01	-1.2E+00	-6.0E+00
Onsite:Disp:prod	-2.4E-01	-1.2E+00	-9.2E-01	-4.6E+00	-4.7E-01	-2.4E+00
Used Oil Management	6.3E+01	6.3E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-1.3E+01	-1.3E+01	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-8.9E+00	-8.9E+00	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	1.4E+03	1.1E+03	5.5E+03	4.2E+03	2.8E+03	2.2E+03

Table 24: Human Health Criteria Air Potential in kg PM₁₀ equivalent for base year with informal management shown and extreme informal management scenarios.

[kg PM10-Equiv.]	Base Year-87/9/4	Base Year-48/48/4	No Management-87/9/4	No Management-48/48/4	No Management-45/5/50	No Management-25/25/50
Dumping	1.8E+02	9.7E+01	6.8E+02	3.8E+02	3.5E+02	2.0E+02
Landfill:incurred	8.2E+02	5.4E+02	3.2E+03	2.1E+03	1.1E+04	1.1E+04
Landfill:disp	-6.5E+02	-4.3E+02	-2.5E+03	-1.7E+03	-9.0E+03	-8.5E+03
Onsite:use	6.0E+04	3.0E+05	2.3E+05	1.2E+06	1.2E+05	6.0E+05
Onsite:Disp:use	-1.2E+04	-6.1E+04	-4.7E+04	-2.4E+05	-2.5E+04	-1.2E+05
Onsite:Disp:prod	-5.0E+03	-2.5E+04	-1.9E+04	-9.7E+04	-1.0E+04	-5.0E+04
Used Oil Management	8.3E+05	8.3E+05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-6.7E+05	-6.7E+05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-2.2E+05	-2.2E+05	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	-1.6E+04	1.5E+05	1.7E+05	8.2E+05	8.8E+04	4.3E+05

Table 25: Smog Creation Potential in kg O₃ equivalent for base year with informal management shown and extreme informal management scenarios.

[kg O ₃ -Equiv.]	Base Year -87/9/4	Base Year -48/48/4	No Manage- ment- 87/9/4	No Manage- ment - 48/48/4	No Manage- ment- 45/5/50	No Manage- ment- 25/25/50
Dumping	-6.7E+01	-3.7E+01	-2.6E+02	-1.4E+02	-1.4E+02	-7.5E+01
Landfill:incurred	7.3E+03	4.8E+03	2.8E+04	1.9E+04	1.1E+05	1.0E+05
Landfill:disp	-2.7E+04	-1.8E+04	-1.1E+05	-7.0E+04	-3.8E+05	-3.6E+05
Onsite:use	8.1E+05	4.1E+06	3.1E+06	1.6E+07	1.6E+06	8.1E+06
Onsite:Disp:use	-5.7E+05	-2.9E+06	-2.2E+06	-1.1E+07	-1.2E+06	-5.8E+06
Onsite:Disp:prod	-3.3E+05	-1.7E+06	-1.3E+06	-6.4E+06	-6.6E+05	-3.3E+06
Used Oil Management	1.2E+08	1.2E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced use	-1.2E+08	-1.2E+08	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Displaced production	-1.0E+07	-1.0E+07	0.0E+00	0.0E+00	0.0E+00	0.0E+00
Net Total	-4.9E+06	-5.3E+06	-4.5E+05	-1.9E+06	-4.6E+05	-1.2E+06

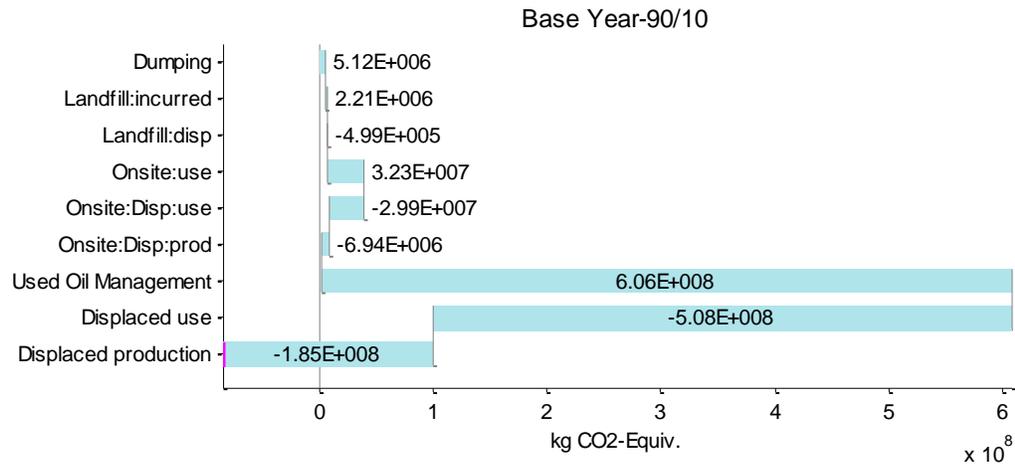


Figure 5: Global Warming Potential in kg CO₂ equivalent for the 2010 base year model.

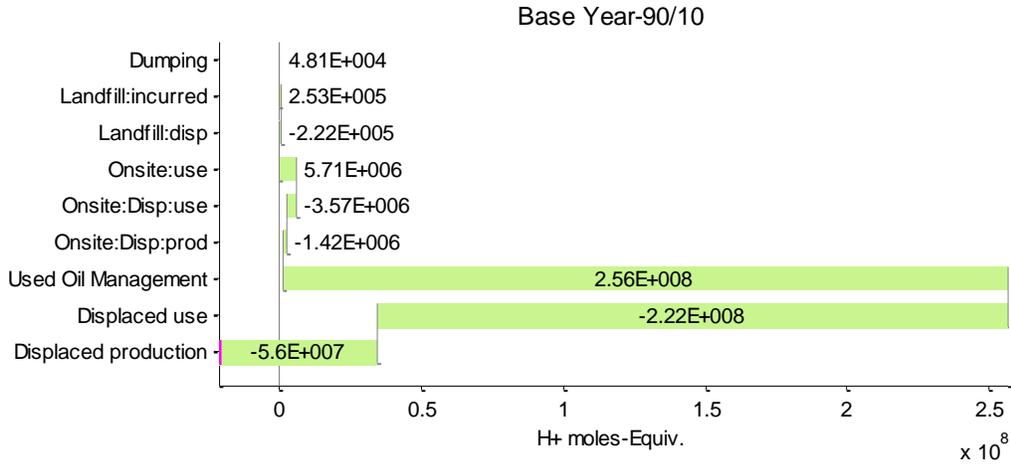


Figure 6: Acidification Potential in H+ moles equivalent for the 2010 base year model.

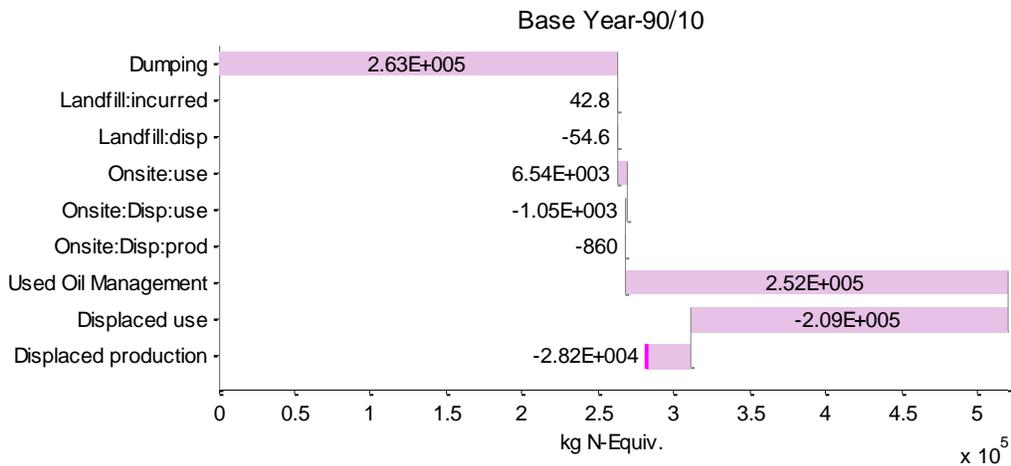


Figure 7: Eutrophication Potential in kg N equivalent for the 2010 base year model.

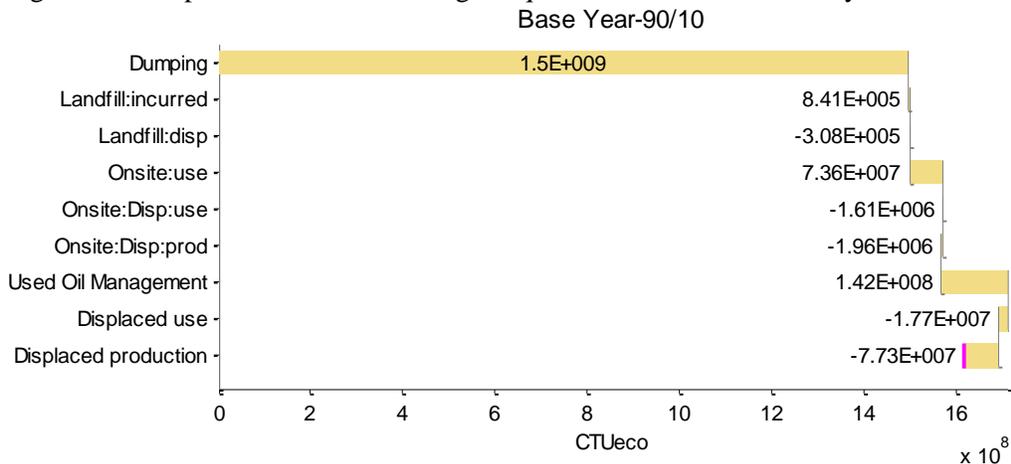


Figure 8: Ecotoxicity Potential in CTUeco equivalent for the 2010 base year model.

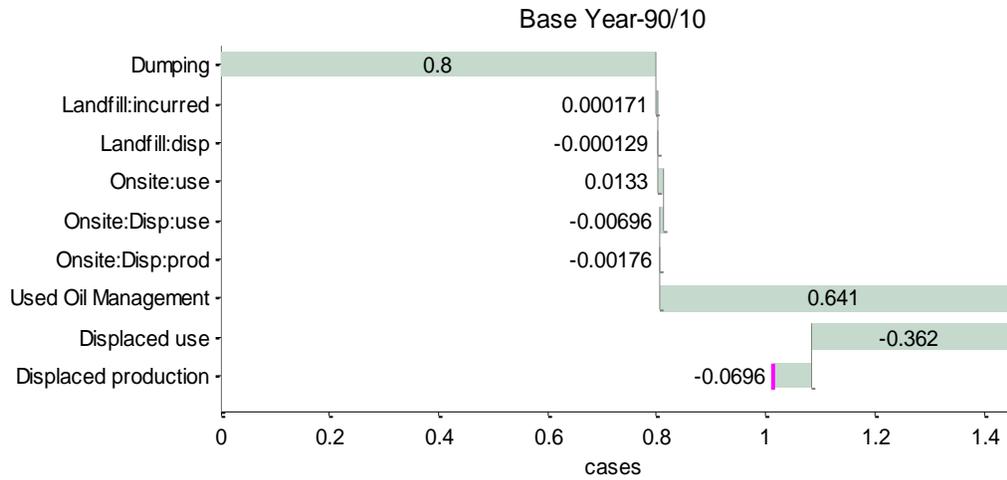


Figure 9: Human Health Cancer Potential in cases for the 2010 base year model.

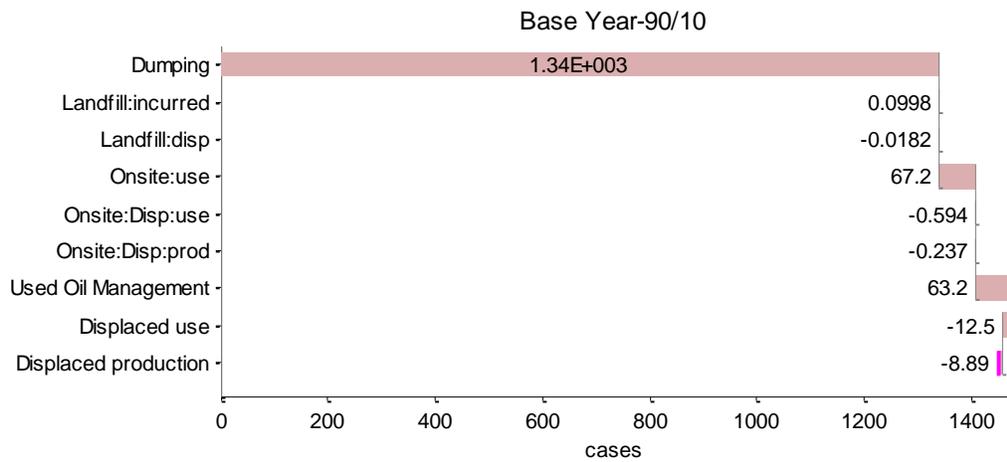


Figure 10: Human Health Non-Cancer Potential in cases for the 2010 base year model.

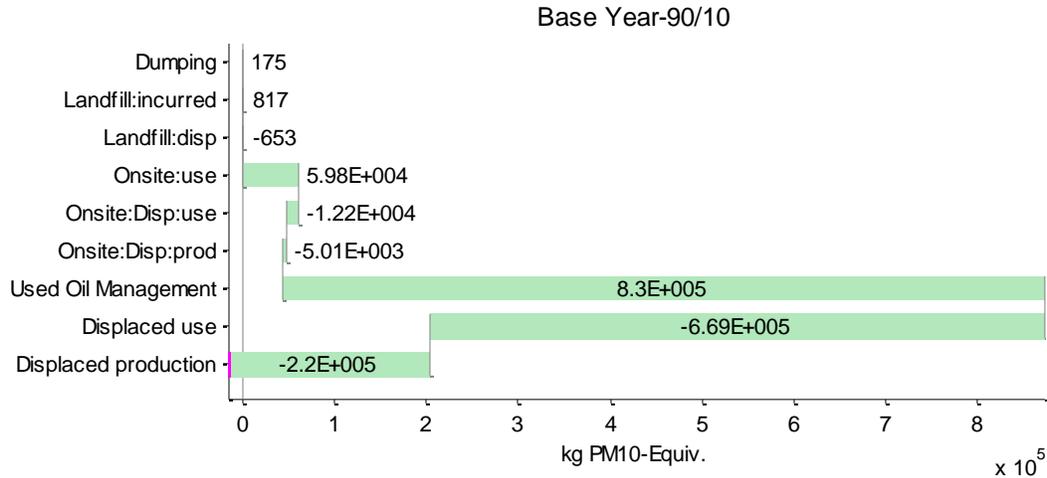


Figure 11: Human Health Criteria Air Potential in kg PM₁₀ equivalent for the 2010 base year.

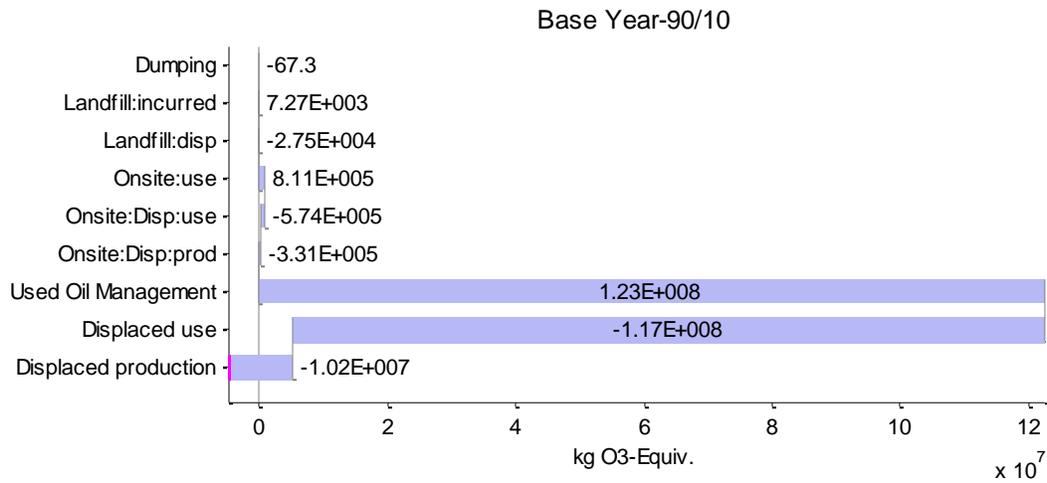


Figure 12: Smog Creation Potential in kg O₃ equivalent for the 2010 base year model.

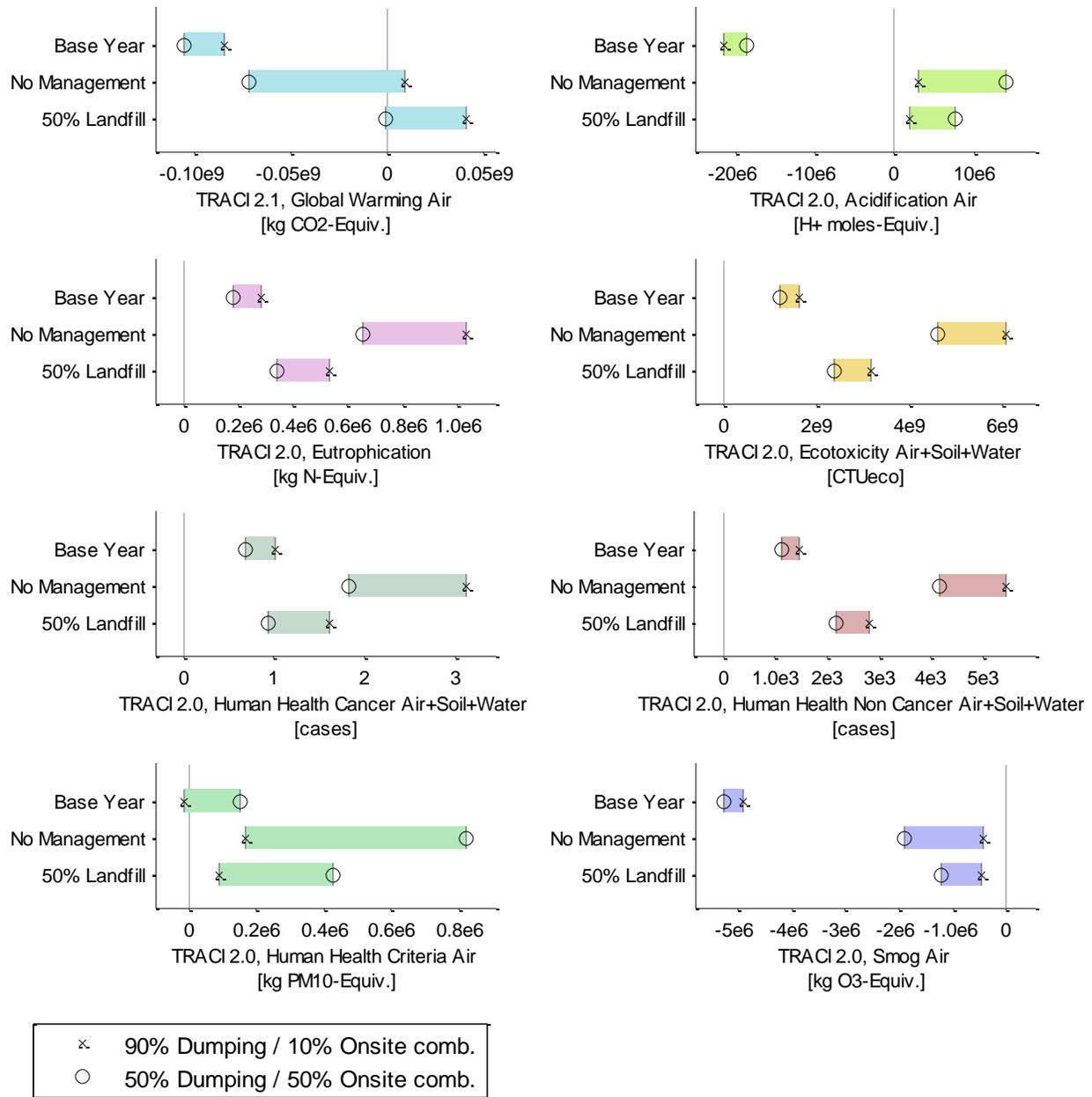


Figure 13: Life cycle impacts for all categories for the six extreme informal management scenarios, showing sensitivity to the dumping/on-site combustion split.

5.2 Base Year and Extreme Scenarios – Formal Management

This section reports the life cycle impact assessment results of the 2010 base year model and the three extreme scenarios. Results are reported both in tables and with waterfall graphs. There is one table and one figure for each impact categories. In each waterfall figure, the 2010 base year impacts are shown at the top, followed by re-refining of all used oil collected and reprocessed in 2010, distillation into marine distillate oil of all used oil collected and reprocessed in 2010, recycling into recycled fuel oil of all used oil collected and reprocessed in 2010.

Table 26 presents the mass flow inventory for the 2010 base year and the three extreme formal management scenarios. In the 2010 base year, an estimated 435 million kg of dry collectable used oil were generated, and 386 kg of wet used oil were collected through California’s formal used oil management system. Of this, 16.5 percent, or 63.7 million kg, was estimated to be water. Thus 112 million kg of collectable dry oil were not collected, equating to a collection rate of 74 percent. Of the collected used oil, 353 million kg were reprocessed through the three disposition routes (see Table 26). Table 26 shows the secondary product types and quantities that were produced in 2010. It also shows the hypothetical secondary product portfolio that would be generated if all 353 million kg of wet used oil were to be processed by only one of the three disposition routes.

These extreme scenarios do not take any technical, economic, logistical, capacity or feasibility constraints into account. The displaced primary product types and quantities at the bottom of the table are derived from the default displacement assumption (see Chapter 12: Appendix D).

Table 26: Material flows for the 2010 base year model and the three extreme scenarios.

[all in million kg]	2010 Base Year	Extreme ReRe	Extreme MDO	Extreme RFO
Collectable Dry Used Oil	435	435	435	435
Used Oil Collected	386	386	386	386
Collected UO Water Content	64	64	64	64
Used Oil Reprocessed	354	357	357	357
Secondary Production				
Re-refined Base Oil	51	231	0	0
Light Fuel	121	24	179	0
RFO to Combustion	41	0	0	325
Asphalt Product	81	46	109	0
Ethylene Glycol	0.4	4.9	0	0
Displaced Production				
Avoided Base Oil	51	231	0	0
Avoided No 2 Distillate	134	24	179	104
Avoided No 6 Residual Oil	14	0	0	111
Avoided Natural Gas	11	0	0	92
Avoided Bitumen	81	46	109	0
Avoided Ethylene Glycol	0.3	3.5	0	0

Life cycle impact results for the 2010 base year and extreme formal management scenarios are discussed by impact category. For each impact category two sets of results have been generated:



1. Possible ranges of results showing sensitivity to six sets of modeling assumptions:
 - SA1. Retention rates in the combustion emission model
 - SA2. Absolute levels of organic compound emissions in the combustion model
 - SA3. Displacement assumption regarding recycled fuel oil
 - SA4. Transportation distances in the reverse logistics model
 - SA5. Natural gas leakage during natural gas production and distribution
 - SA6. Used oil composition
2. Contribution analysis of the results with all modeling assumptions in default settings

The parameter settings used to calculate the possible ranges of results are shown in Table 27 through Table 31.

Table 27: High, low, and default settings of the retention rates in the combustion model.

Retention rates (SA1)	Low	Default	High
Metals			
Atomizing burner	0	0.4	0.8
Boiler	0.2	0.85	0.95
Kiln / baghouse	0.95	0.99	0.999
Marine engine	0	0.4	0.6
Vaporizing burner	0.75	0.998	0.999
Halogens			
Burners, marine engine	0	0.1	0.2
Boiler	0	0.1	0.5
Kiln / baghouse	0	0.2	0.7
Phosphorus			
Atomizing burner, boiler, Kiln / baghouse	0	0.5	0.99
Marine engine	0	0	0.2
Vaporizing burner	0	0.99	0.999
Particulate matter			
Atomizing burner	0	0	0.5
Boiler	0	0.2	0.6
Kiln / baghouse	0.92	0.98	0.99
Marine engine	0	0	0.5
Vaporizing burner	0.75	0.95	0.99
Sulfur			
Atomizing burner	0	0.05	0.2
Boiler	0	0.15	0.5
Kiln / baghouse	0.25	0.6	0.75
Marine engine	0	0.02	0.2
Vaporizing burner	0.15	0.35	0.5

Table 28: High, low, and default settings of the organic compound emission rates in the combustion model.

Organic compound emission factors (SA2)	Default	Low	High
Non methane volatile organic compounds (NMVOC)			
Bunker fuel combustion	1.6E-04	1.E-04	3.2E-03
Marine distillate combustion	1.6E-03	3.E-04	3.2E-03
Natural gas combustion	2.2E-04	3.E-05	4.E-02
No 2 combustion	6.0E-05	4.E-05	3.E-04
No 6 combustion	1.6E-04	1.E-04	2.E-03
Used oil combustion	1.3E-04	1.E-05	1.E-03
Polycyclic aromatic hydrocarbons (PAH)			
Bunker fuel combustion	3.E-05	3.E-06	3.E-03
Marine distillate combustion	3.E-05	3.E-06	3.E-03
Natural gas combustion	1.4E-08	1.4E-09	1.4E-06
No 2 combustion	5.E-07	5.E-08	5.E-05
No 6 combustion	2E-07	2E-08	2E-05
Used oil combustion	8.E-07	8.E-08	8.E-05

Table 29: Parameter settings for the reverse logistics sensitivity scenario.

Reverse Logistics (SA4)		Default	Hi Collect	Low Collect	Hi Collect + Freight	Low Collect + Freight
Distance (medium trucks)	km	190	380	75	380	75
Distance (small trucks)	km	75	150	40	150	40
Export fraction by truck		0.24			0.15	0.5
Export rail distance	km	3500			5000	2500
Export truck distance	km	500			1000	250
Reverse Logistics distance	km	361			540	240

Table 30: Parameter settings for the reverse logistics sensitivity scenario.

Natural Gas Leakage (SA5)	Default	Low	High
Fraction of natural gas production leaked to atmosphere	0.019	0.005	0.05

Table 31: Parameter settings for the used oil composition sensitivity scenario.

Used Oil Composition (SA6)	Default	Bottom 1/4	Top 1/4
Aluminum	2.77E-06	1.00E-06	3.12E-05
Antimony	1.09E-05	7.45E-07	1.50E-05
Arsenic	6.93E-07	1.18E-07	6.93E-07
Barium	1.35E-06	1.00E-06	5.42E-06
Beryllium	1.92E-07	7.90E-08	2.50E-07
Boron	4.77E-05	2.75E-06	4.80E-05
Cadmium	6.90E-07	7.57E-08	1.00E-06
Calcium	2.46E-03	1.14E-03	3.01E-03
Chlorine	2.16E-04	7.86E-05	2.90E-04
Chromium	1.32E-06	5.20E-07	2.45E-06
Cobalt	8.21E-06	4.81E-06	1.16E-05
Copper	9.97E-06	1.00E-06	4.26E-05
Halogens	2.94E-04	2.55E-04	3.40E-04

Hydrocarbons	9.44E-01	9.68E-01	9.33E-01
Iron	1.55E-05	8.00E-06	3.98E-05
Lead	8.79E-06	1.00E-06	2.95E-05
Magnesium	1.63E-05	7.00E-06	2.02E-04
Manganese	4.89E-06	2.71E-07	4.89E-06
Mercury	9.08E-08	2.00E-09	1.47E-07
Molybdenum	1.00E-04	1.00E-06	1.25E-04
Nickel	1.09E-06	5.00E-07	1.92E-06
Nitrogen	4.07E-04	2.75E-04	5.35E-04
Org_Halogens	3.64E-04	2.35E-04	5.73E-04
Oxygen	1.18E-02	1.18E-02	1.18E-02
Phosphorus	8.42E-04	6.60E-04	9.80E-04
Sediment	2.13E-03	1.30E-03	2.25E-03
Selenium	5.28E-07	1.00E-07	7.65E-07
Silicon	1.39E-05	8.00E-06	9.73E-05
Silver	4.94E-07	4.00E-07	1.83E-06
Sodium	7.96E-06	4.00E-06	8.70E-05
Sulfur	3.51E-03	2.80E-03	4.37E-03
thallium	3.15E-05	3.15E-05	3.15E-05
Tin	2.27E-06	1.00E-06	3.99E-06
titanium	1.72E-06	1.00E-06	4.33E-06
Vanadium	5.00E-07	0.00E+00	1.46E-05
Zinc	1.03E-03	8.04E-04	1.22E-03

Contribution analyses are reported both in tables and with waterfall graphs to visualize them. There is one table and one figure for each of the eight chosen impact categories. Table headings are shaded to match the colors in the corresponding bar charts. In each figure, the 2010 base year impacts are shown at the top, followed by re-refining of all used oil collected and reprocessed in 2010, distillation into marine distillate oil of all used oil collected and reprocessed in 2010, recycling into recycled fuel oil of all used oil collected and reprocessed in 2010. The formal used oil management consists of five life cycle stages: Collection and waste management, reprocessing, use of secondary products, displaced production, and displaced use.

In the graphs that follow, informal management is not included in the graphs because it does not vary with changing assumptions about the formal management stages of the system. Informal management is identical in the base year model and the three extreme scenarios and is discussed extensively in section 5.1.

5.2.1 Global Warming (GWP)

In all impact indicator suites, global warming potential is reported in kilograms of carbon dioxide equivalents (kg CO₂ eq) over a 100-year time horizon. Emissions that contribute to this impact category include CO₂, methane (CH₄), and nitrous oxide (N₂O).

Figure 14 shows the range of global warming potential impacts for the base year and three extreme formal management scenarios. In the 2010 base year model the global warming potential (GWP) of collection and waste disposal is 36 million kg CO₂ eq. In all extreme scenarios the GWP of collection and hazardous waste disposal is 33 million kg CO₂ eq. The lower value is due to the extreme scenario assumption that all collected used oil is processed in state.

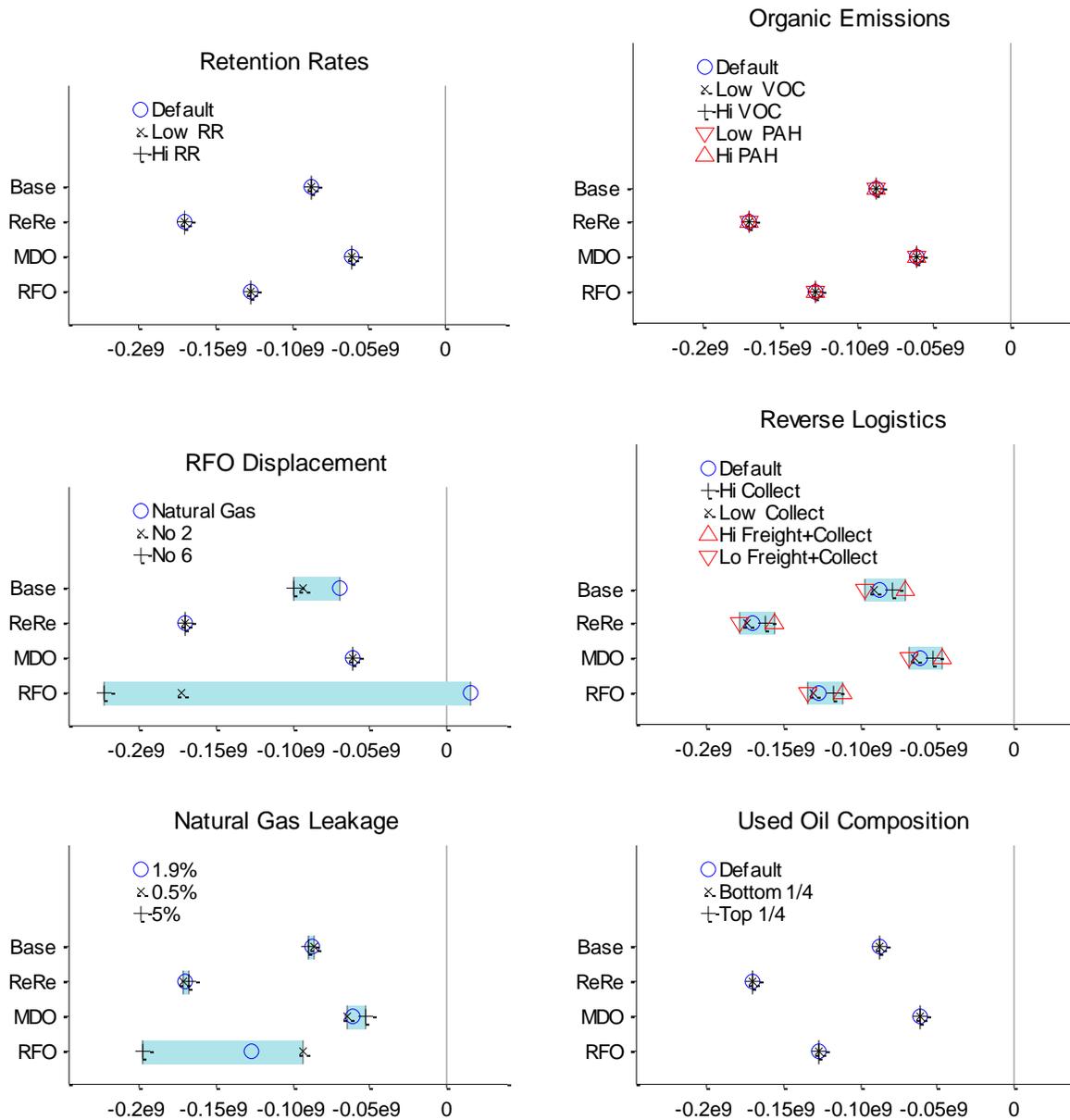


Figure 14: Global Warming Potential ranges for formal management in kg CO₂ equivalent.

In the extreme re-refining scenario, the global warming potential (GWP) of re-refining is 0.29 kg CO₂ eq per kg of processed used oil, or 105 million kg CO₂ eq in total. The GWP of 76 million kg CO₂ from the combustion of the 23 million kg of secondary fuels is roughly equal to the avoided GWP from avoided combustion of the 23 million kg of displaced primary fuels, which are

assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided GWP from displaced production of primary products is 0.86 kg CO₂ eq per kg of processed used oil. The remainder comes in roughly equal parts from displaced asphalt and distillate fuels production. The total avoided GWP from displaced production is 309 million kg CO₂ eq. In the extreme re-refining scenario the net total GWP of California's formal used oil management system, i.e. the sum of collection and processing minus displaced production and use, is

$$(33 + 105 + 76 - 76 - 309) \text{ million kgCO}_2\text{eq} = -171 \text{ million kgCO}_2\text{eq}.$$

In the extreme marine distillate oil scenario, the GWP of reprocessing is 0.14 kg CO₂ eq per kg of processed used oil, or 50 million kg CO₂ eq in total. The GWP of 581 million kg CO₂ from the combustion of the secondary fuels, almost all of which is marine distillate oil, is identical to the avoided GWP from avoided combustion of the 196 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided GWP from displaced production of primary products is 0.40 kg CO₂ eq per kg of processed used oil, 67 percent of which comes from displaced production of distillate fuels and 24 percent of which comes from displaced production of asphalt. The total avoided GWP from displaced production is 144 million kg CO₂ eq. In the extreme marine distillate oil scenario the net total GWP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus displaced production and use, is

$$(33 + 50 + 581 - 581 - 144) \text{ million kgCO}_2\text{eq} = -61 \text{ million kgCO}_2\text{e}.$$

In the extreme recycled fuel oil scenario, the GWP of re-reprocessing is 0.004 kg CO₂ eq per kg of processed used oil, or 1.4 million kg CO₂ eq in total. The GWP from the combustion of the 325 million kg of recycled fuel oil is 972 million kg CO₂ eq. The avoided GWP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 929 million kg CO₂ eq. The avoided GWP from displaced production of these primary fuels is 204 million kg CO₂ eq or 0.572 kg CO₂ eq per kg of processed used oil. In the extreme recycled fuel oil scenario the net total GWP of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(33 + 1 + 972 - 929 - 204) \text{ million kgCO}_2\text{eq} = -127 \text{ million kgCO}_2\text{eq}.$$

With the exception of the extreme re-refining scenario, the use and displaced use stages have the largest impacts. These are driven by the emissions of carbon dioxide, methane, and nitrous oxide during combustion of secondary fuels and the avoided combustion of displaced fuels. Out of the four scenarios, the use stage in the extreme recycled fuel oil scenario has the highest incurred global warming impacts. However, the avoided production and use impacts are even larger, resulting in a net negative impact. The extreme re-refining scenario has the lowest net global warming impacts, followed by the extreme recycled fuel oil scenario.

For all four scenarios, the net impacts are negative, meaning that all California used oil management scenarios avoid more global warming emissions than they produce. The highest incurred impacts are in the extreme recycled fuel oil scenario, while the lowest incurred impacts take place in the extreme re-refining scenario. Extreme re-refining results in the greatest net avoided global warming impacts.

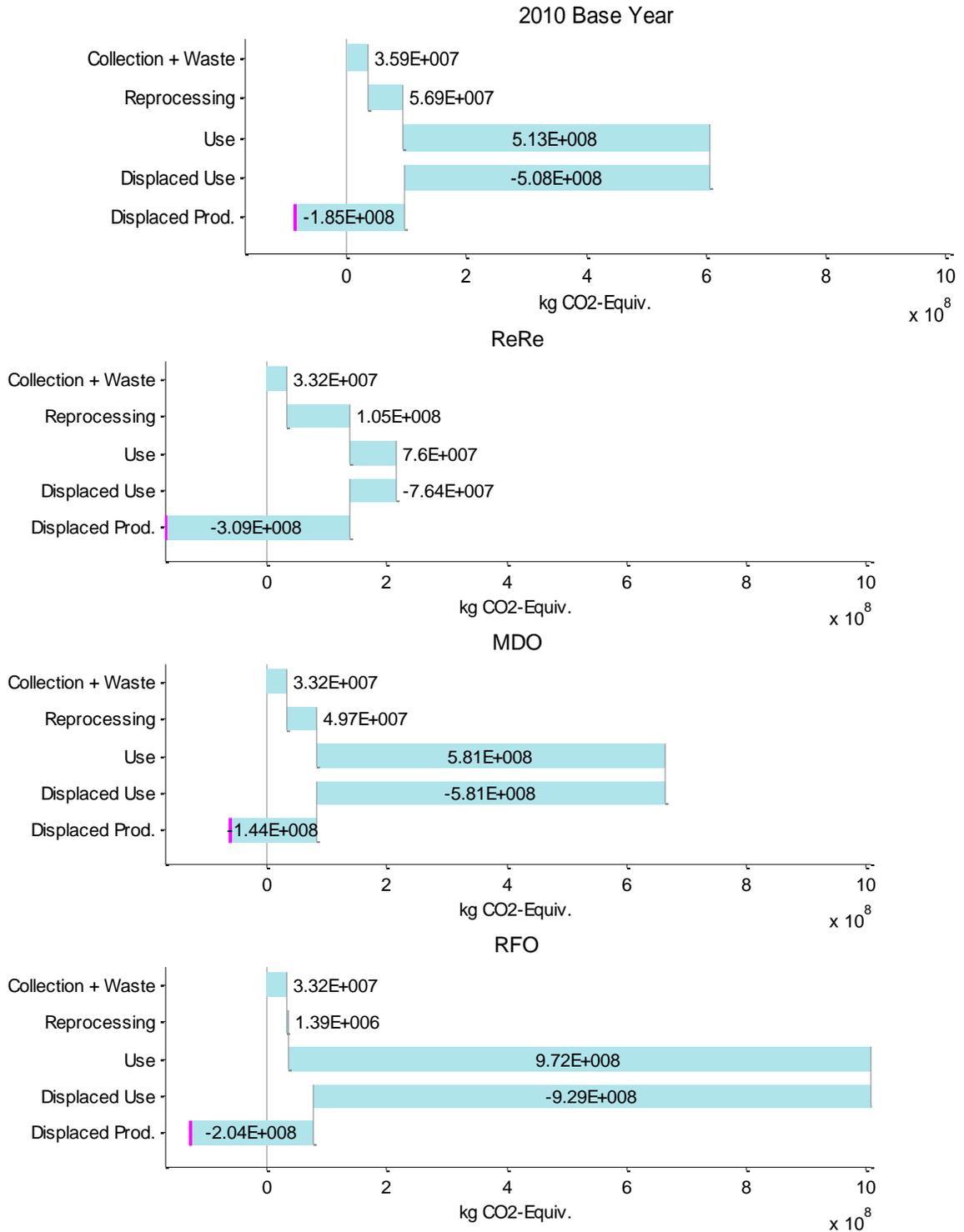


Figure 15: Global Warming Potential in kg CO₂ equivalent for the 2010 base year model and the three extreme reprocessing scenarios.

[all in kg CO ₂ eq]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	3.59E+07	3.32E+07	3.32E+07	3.32E+07
Reprocessing	5.69E+07	1.05E+08	4.97E+07	1.39E+06
Use of sec. products	5.13E+08	7.60E+07	5.81E+08	9.72E+08
Displaced use	-5.08E+08	-7.64E+07	-5.81E+08	-9.29E+08
Displaced production	-1.85E+08	-3.09E+08	-1.44E+08	-2.04E+08
Net results	-8.75E+07	-1.71E+08	-6.10E+07	-1.27E+08

Table 32: Global Warming Potential in kg CO₂ equivalent for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

5.2.2 Acidification (AP)

In TRACI 2.0, acidification potential (AP) is reported in hydrogen ion mole equivalents (H⁺ moles eq). Emissions that contribute to this impact category include ammonia (NH₃), sulfur oxides (SO_x), and nitrogen oxides (NO_x).

Figure 16 shows the range of acidification potential impacts for the base year and three extreme formal management scenarios. In the 2010 base year model, the AP of collection and hazardous waste disposal is 12 million H⁺ moles eq. In all extreme scenarios the AP of collection and hazardous waste disposal is 11 million H⁺ moles eq. The lower value is due to the extreme scenario assumption that all collected used oil is processed in-state.

In the extreme re-refining scenario, the acidification potential (AP) of reprocessing is 0.10 H⁺ moles eq per kg of processed used oil, or 37 million H⁺ moles eq in total. With 4.9 million H⁺ moles eq, the AP from the combustion of the 23 million kg of secondary fuels is almost the same as the avoided AP from avoided combustion of the 23 million kg of displaced primary fuels, which is 5 million H⁺ moles eq. The avoided AP from displaced production of primary products is 0.25 H⁺ moles eq per kg of processed used oil, 87 percent of which comes from displaced base oil production. The remainder comes in roughly equal parts from displaced asphalt and distillate fuels production. The total avoided AP from displaced production is 88 million H⁺ moles eq. In the extreme re-refining scenario the net total AP of California's formal used oil management systems, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(11 + 37 + 5 - 5 - 88) \text{ million } H^+ \text{ moles eq} = -40 \text{ million } H^+ \text{ moles eq.}$$

In the extreme marine distillate oil scenario, the AP of reprocessing is 0.06 H⁺ moles eq per kg of processed used oil, or 20 million H⁺ moles eq in total. The AP of 319 million H⁺ moles eq from the combustion of the secondary fuels, almost all of which is marine distillate oil, is identical to the avoided AP from avoided combustion of the 196 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided AP from displaced production of primary products is 0.14 H⁺ moles eq per kg of processed used oil. The total avoided AP from displaced production is 48 million H⁺ moles eq. In the extreme marine distillate oil scenario the net total AP of California's formal used oil management system, i.e. the sum of collection, processing and use minus avoided production and use, is

$$(11 + 20 + 319 - 319 - 48) \text{ million } H^+ \text{ eq} = -18 \text{ million } H^+ \text{ eq.}$$



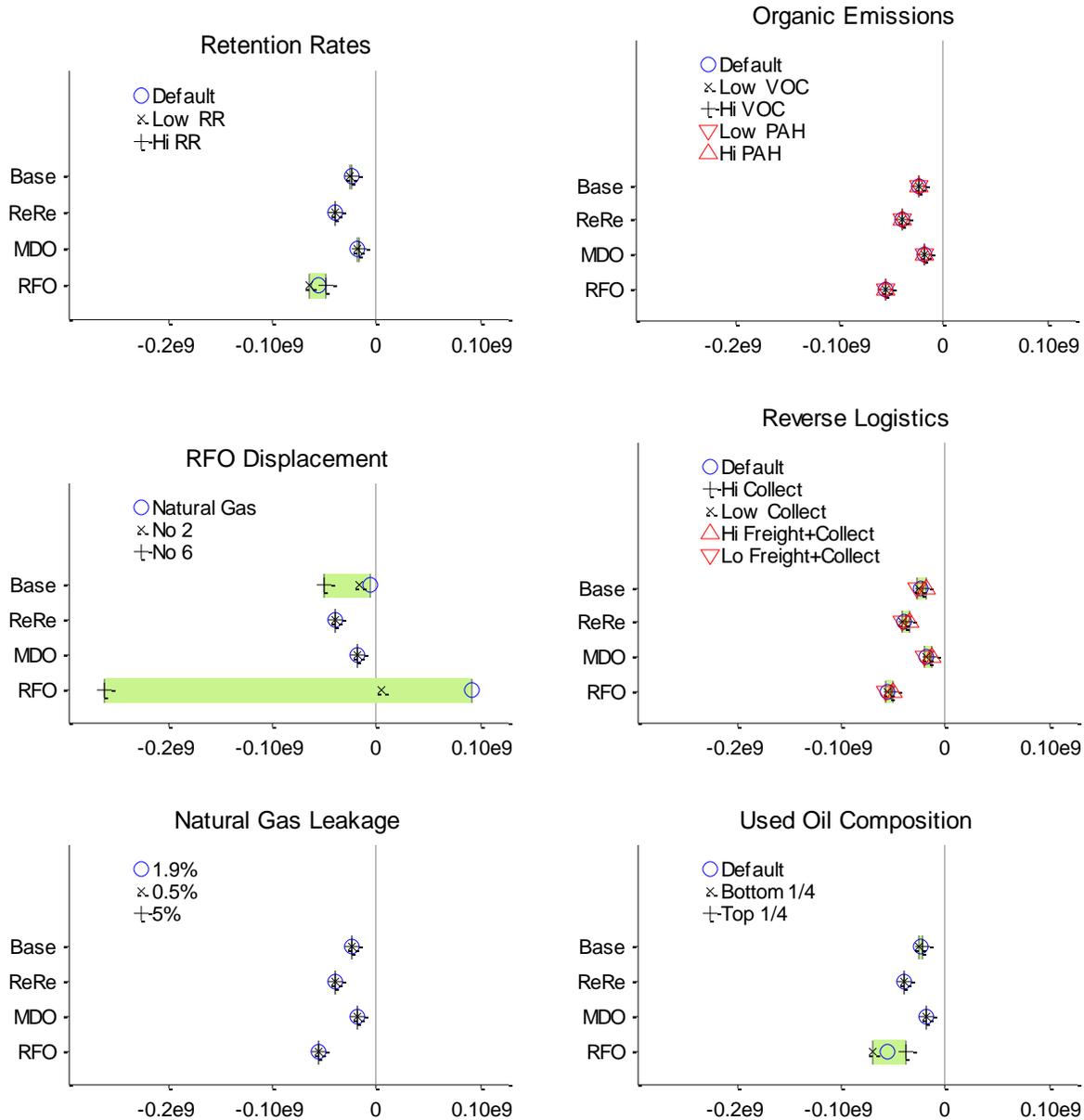


Figure 16: Acidification Potential ranges for formal management in moles H⁺ equivalent.

In the extreme recycled fuel oil scenario, the acidification potential (AP) of re-reprocessing is 0.002 H⁺ moles eq per kg of processed used oil, or 0.6 million H⁺ moles eq in total. The AP from the combustion of the 325 million kg of recycled fuel oil is 126 million H⁺ moles eq. The avoided AP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 130 million H⁺ moles eq. The avoided AP from displaced production of these primary fuels is 46 million H⁺ moles eq or 0.129 H⁺ moles eq per kg of processed used oil. In the extreme recycled fuel oil scenario, the net total acidification potential of California's formal used oil management system, i.e. the sum of used oil

collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is.

$$(11 + 1 + 126 - 130 - 46) \text{ million } H^+eq = -38 \text{ million } H^+eq.$$

Acidification impacts from all life cycle stages of the used oil management system are primarily driven by SO_x emissions, and secondarily driven by NO_x emissions. In all four scenarios except extreme re-refining, the use of secondary products and displaced use stages have the largest acidification impacts. The acidification impacts of re-refined base oil production are low, as are the emissions associated with its use. The extreme re-refining scenario provides the greatest net avoided burden due to the low impacts of secondary products in comparison to the production of primary products.

For all four scenarios, the net impacts are negative, meaning that all California used oil management scenarios avoid more acidification impacts than they produce. The highest incurred impacts happen in the extreme marine distillate oil scenario, followed by the 2010 base year. The extreme re-refining scenario has the lowest net impact.

[all in H+ moles eq]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	1.20E+07	1.06E+07	1.06E+07	1.06E+07
Reprocessing	2.23E+07	3.74E+07	2.01E+07	6.35E+05
Use of sec. products	2.21E+08	4.92E+06	3.19E+08	1.09E+08
Displaced use	-2.22E+08	-5.08E+06	-3.19E+08	-1.30E+08
Displaced production	-5.60E+07	-8.77E+07	-4.82E+07	-4.60E+07
Net results	-2.24E+07	-3.99E+07	-1.77E+07	-5.53E+07

Table 33: Acidification Potential in H+ moles equivalent for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

5.2.3 Eutrophication (EP)

In TRACI 2.0, eutrophication potential (EP) is reported in terms of kilograms of nitrogen equivalents (kg N eq). Most substances that contribute to eutrophication impacts contain nitrogen or phosphorus. Emitting a given substance to water has a higher eutrophication impact than emitting it to air.

Figure 18 shows the range of eutrophication potential impacts for the base year and three extreme formal management scenarios.

In the 2010 base year model, the eutrophication potential (EP) of collection and hazardous waste disposal is 15,000 kg N eq. In all extreme scenarios, the EP of collection and hazardous waste disposal is 13,000 kg N eq. The lower value is due to the extreme scenario assumption that all collected used oil is processed in-state.

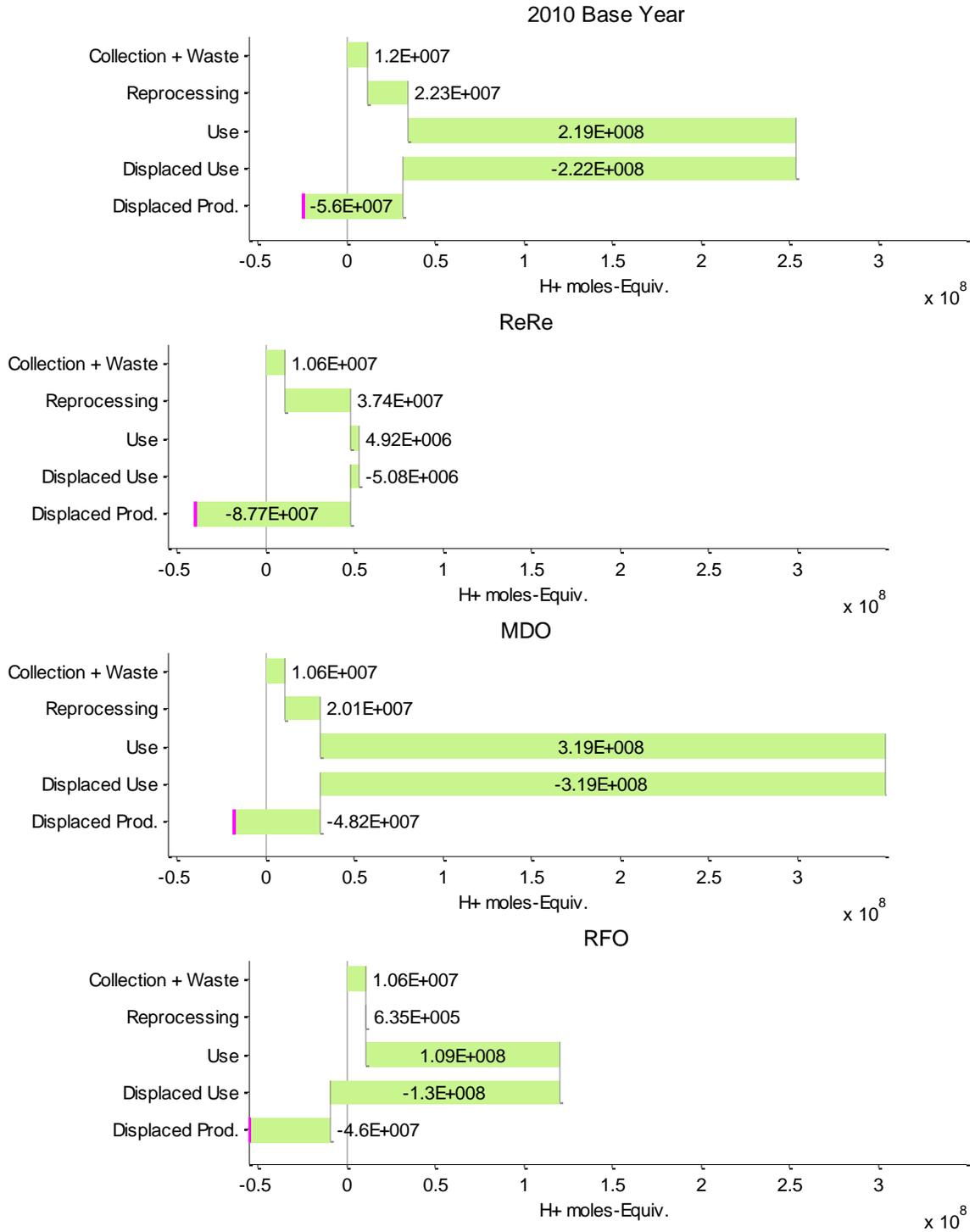


Figure 17: Acidification Potential in H+ moles equivalent for the 2010 base year model and the three extreme reprocessing scenarios.

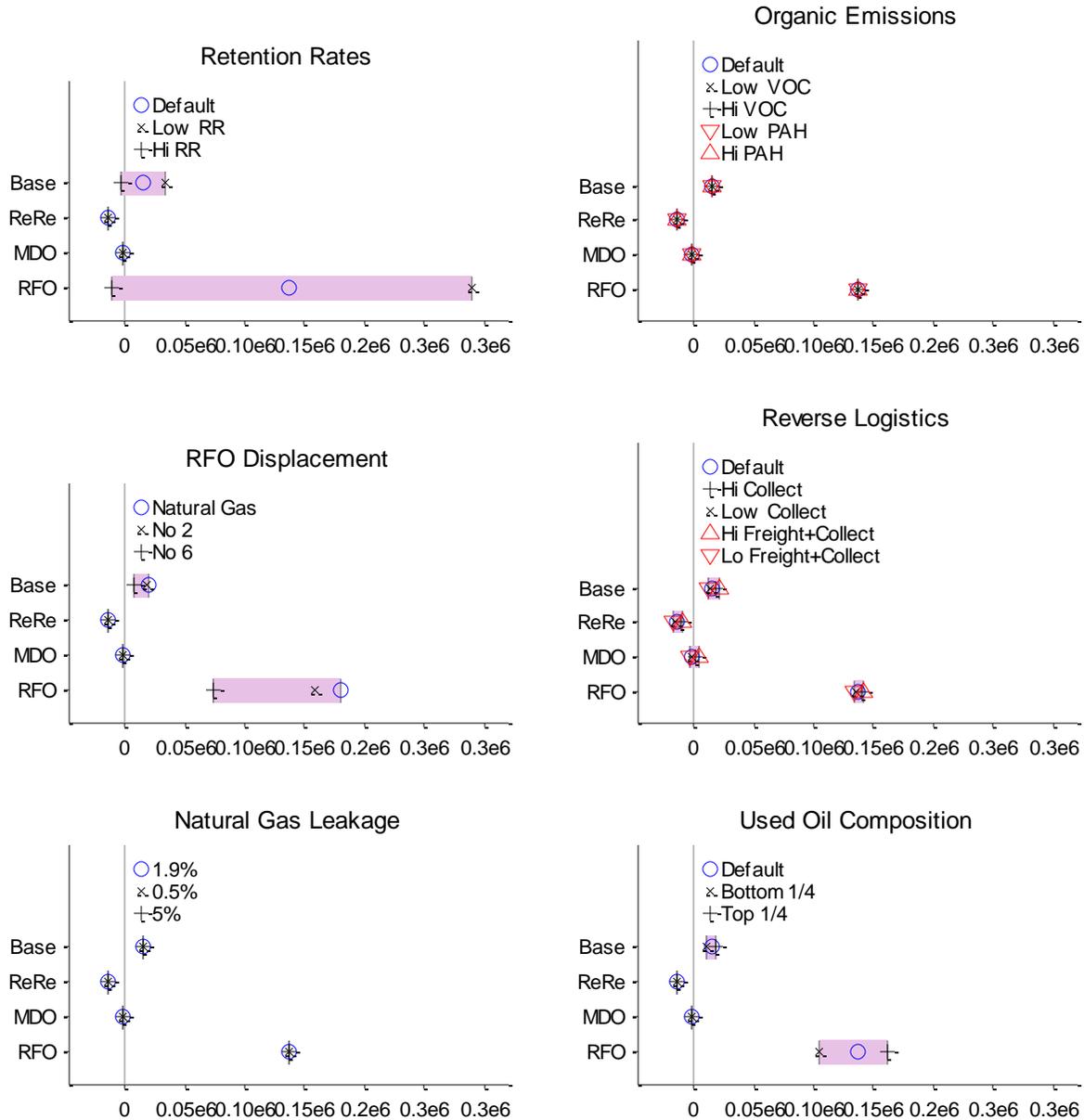


Figure 18: Eutrophication Potential ranges for formal management in kg N equivalent.

In the extreme re-refining scenario, the eutrophication potential (EP) of reprocessing is 4.61E-05 kg N eq per kg of processed used oil, or 16,000 kg N eq in total. The EP of 2,000 kg of N eq from the combustion of the 23 million kg of secondary fuels is roughly equal to the avoided EP from avoided combustion of the 23 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided EP from displaced production of primary products is 1.23E-04 kg N eq per kg of processed used oil, 86 percent of which comes from displaced base oil production. The second largest fraction is 7 percent and comes from displaced asphalt. The total avoided EP from displaced production is 44,000 kg N eq. In the

extreme re-refining scenario the net total eutrophication potential (EP) of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(13 + 16 + 2 - 2 - 44) \text{ thousand } N \text{ eq} = -14 \text{ thousand } N \text{ eq}.$$

In the extreme marine distillate oil scenario, the EP of reprocessing is $2.6E-05$ kg N eq per kg of processed used oil, or 9,000 kg N eq in total. The EP of 315,000 kg N eq from the combustion of the secondary fuels, almost all of which is marine distillate oil, is identical to the avoided EP from avoided combustion of the 196 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided EP from displaced production of primary products is $6.7E-05$ kg N eq per kg of processed used oil, 63 percent of which comes from displaced production of distillate fuels and 25 percent of which comes from displaced production of asphalt. The total avoided EP from displaced production is 24,000 kg N eq. In the extreme marine distillate oil scenario the net total EP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(13 + 9 + 315 - 315 - 24) \text{ thousand } kg \text{ N eq} = -2 \text{ thousand } kg \text{ N eq}.$$

In the extreme recycled fuel oil scenario, the EP of re-reprocessing is $1.7E-06$ kg N eq per kg of processed used oil, or 591 kg N eq in total. The EP from the combustion of the 325 million kg of RFO is 197,000 kg N eq. The avoided EP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 47,000 kg N eq. The avoided EP from displaced production of these primary fuels is 27,000 kg N eq or $-7.4E-05$ kg N eq per kg of processed used oil. In the extreme recycled fuel oil scenario, the net total EP of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(13 + 1 + 197 - 47 - 27) \text{ thousand } kg \text{ Neq} = 137 \text{ thousand } kg \text{ Neq}.$$

Extreme marine distillate oil shows high eutrophication impacts result from its use phase, which are equally balanced by avoided burdens. This incurred impact is due to NO_x emissions to air from marine distillate oil combustion. NO_x emissions from marine engine combustion appear to be quite high, on average, in source reports. The extreme recycled fuel oil scenario also has significant eutrophication impacts during its use phase. These are the result of phosphorus emissions to air during recycled fuel oil combustion. The phosphorus emissions from recycled fuel oil are the result of the high levels of phosphorus in used oil as compared to displaced petroleum products given that phosphorus is a typical lubricant additive.

The net eutrophication impacts are positive for the base year and extreme recycled fuel oil scenarios, and negative for extreme re-refining and extreme marine distillate oil, indicating disposition route choice may influence whether the used oil system has a net environmental benefit or burden in this category. The highest incurred impacts happen in the extreme marine distillate oil scenario. The extreme re-refining scenario has the lowest net impacts, followed by the extreme marine distillate oil scenario.

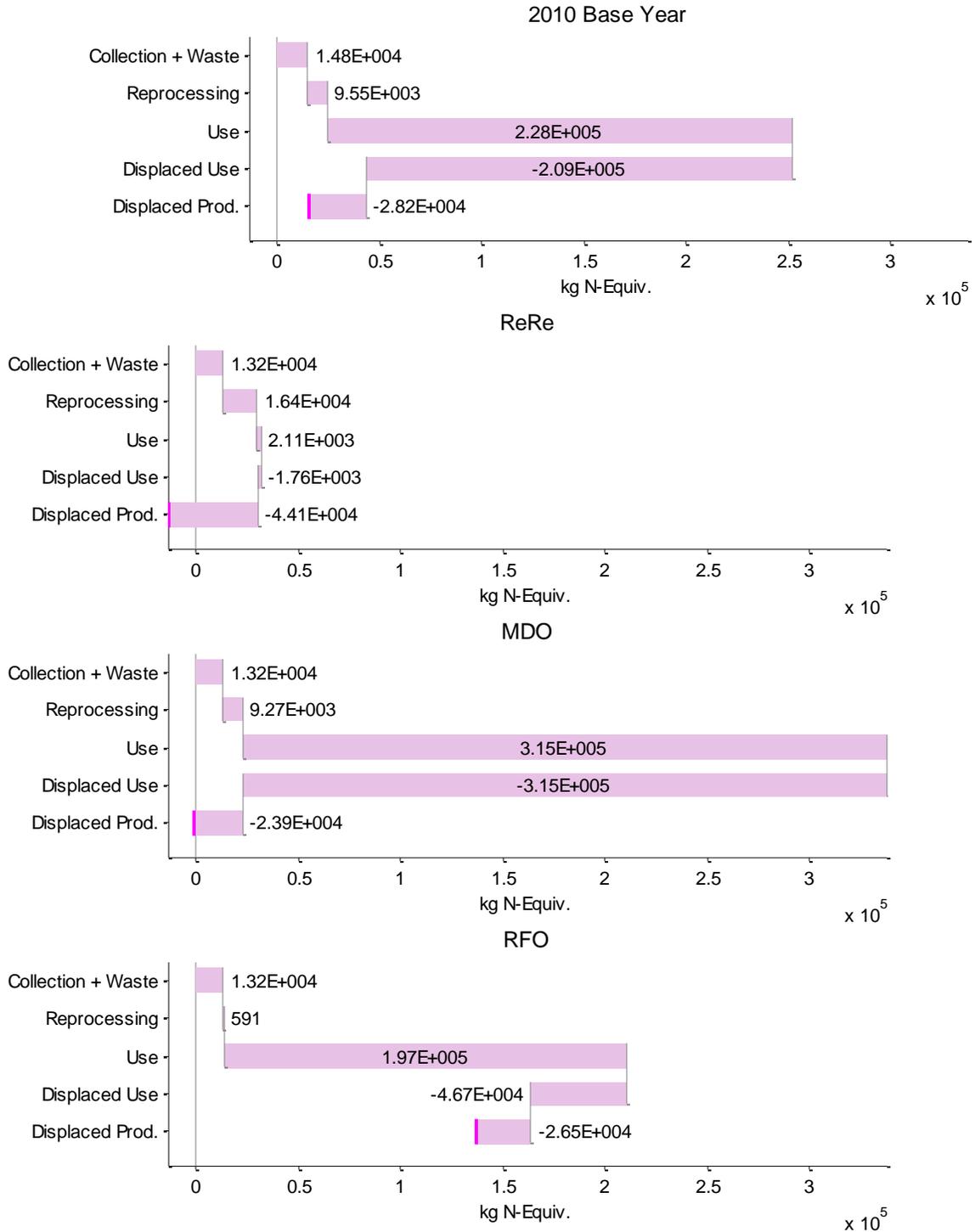


Figure 19: Eutrophication Potential in 10^8 kg CO₂ equivalent for the 2010 base year model and the three extreme reprocessing scenarios.

[all in kg N eq]	2010 Base	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	1.48E+04	1.32E+04	1.32E+04	1.32E+04
Reprocessing	9.55E+03	1.64E+04	9.27E+03	5.91E+02
Use of sec. products	2.28E+05	2.11E+03	3.15E+05	1.97E+05
Displaced use	-2.09E+05	-1.76E+03	-3.15E+05	-4.67E+04
Displaced production	-2.82E+04	-4.41E+04	-2.39E+04	-2.65E+04
Net results	1.50E+04	-1.40E+04	-1.26E+03	1.37E+05

Table 34: Eutrophication Potential in kg N equivalent for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

5.2.4 Ecotoxicity (ETP)

In TRACI 2.0, which uses the USEtox characterization model, ecotoxicity potential (ETP) is reported in terms of the potentially affected fraction (PAF) of species, integrated over time and volume (PAF m³ day). Its unit is also called CTU_{eco}, where CTU stands for comparative toxicity unit. Ecotoxicity impacts are reported as the aggregate of ecotoxicity impacts from emissions to air, land, and water.

Figure 20 shows the range of ecotoxicity potential impacts for the base year and three extreme formal management scenarios.

In the 2010 base year model the ETP of collection and hazardous waste disposal is 20 million CTU_{eco}. In all extreme scenarios, the ETP of collection and hazardous waste disposal is also 20 million CTU_{eco}. The lower value is due to the extreme scenario assumption that all collected used oil is processed in-state.

In the extreme re-refining scenario, the ETP of reprocessing is 0.3 CTU_{eco} per kg of processed used oil, or 108 million CTU_{eco} in total. The ETP of 0.5 million kg CTU_{eco} from the combustion of the 23 million kg of secondary fuels is almost the same as the ETP from avoided combustion of the 23 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided ETP from displaced production of primary products is 0.41 CTU_{eco} per kg of processed used oil, 89 percent of which comes from displaced base oil production. The remainder comes in roughly equal parts from displaced asphalt and distillate fuels production. The total avoided ETP from displaced production is 148 million CTU_{eco}. In the extreme re-refining scenario, the net total ETP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(20 + 108 + 0.5 - 0.5 - 148) \text{ million CTU}_{eco} = -19 \text{ million CTU}_{eco}.$$



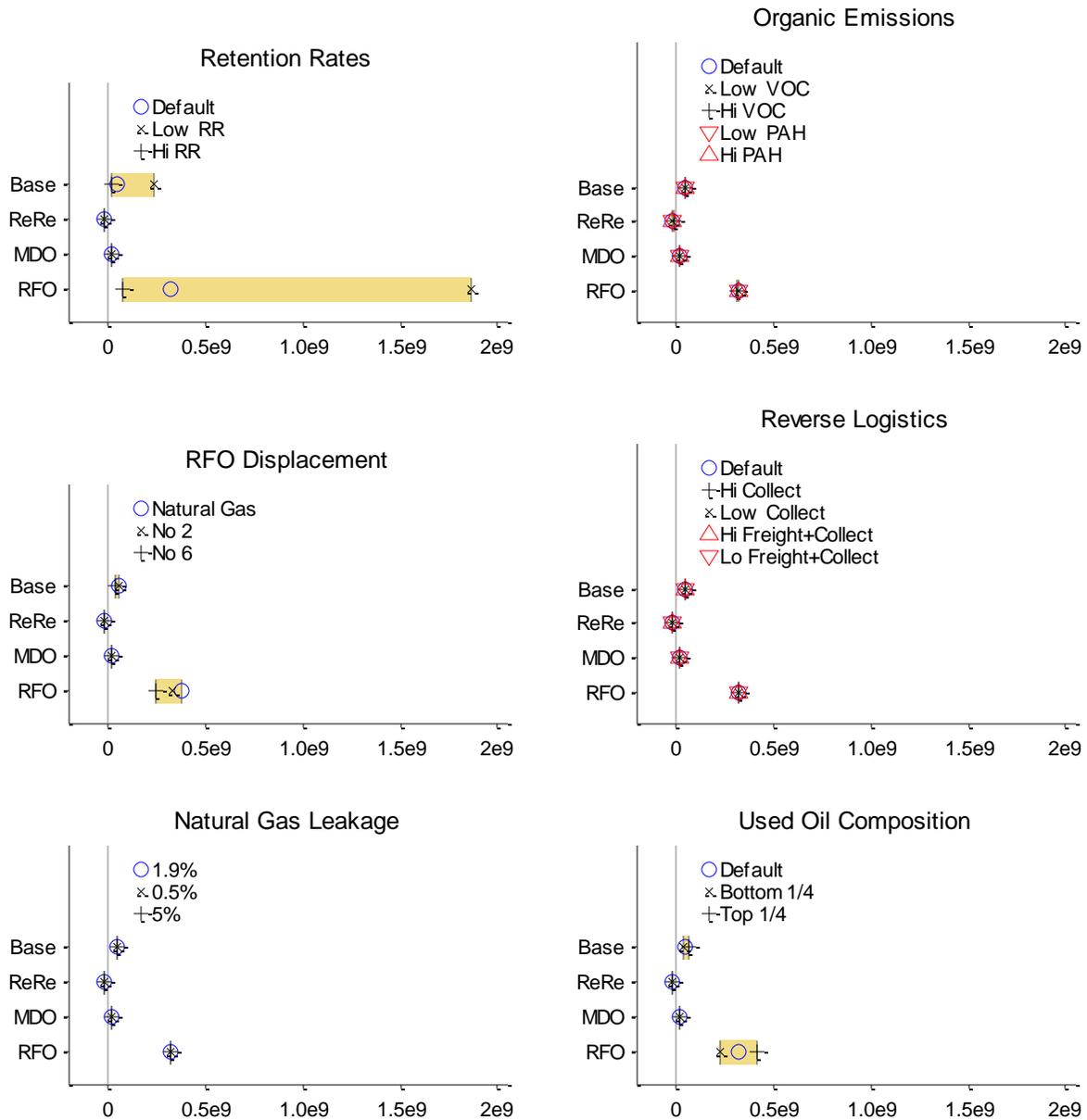


Figure 20: Ecotoxicity Potential ranges for formal management in CTUeco equivalent.

In the extreme marine distillate oil scenario, the ecotoxicity potential (ETP) of re-processing is 0.16 CTUeco per kg of processed used oil, or 58 million CTUeco in total. The 15 million CTUeco from the combustion of the 196 million kg of secondary fuels are somewhat less than the avoided 21 million CTUeco from avoided combustion of the 196 million kg of displaced primary fuels. The avoided ETP from displaced production of primary products is 0.16 CTUeco per kg of processed used oil. The total avoided ETP from displaced production is 58 CTUeco. In the extreme marine distillate oil scenario the net total ETP of California's formal used oil

management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(20 + 58 + 15 - 21 - 58) \text{ million CTUeco} = 15 \text{ million CTUeco.}$$

In the extreme recycled fuel oil scenario, the ecotoxicity potential (ETP) of re-reprocessing is 0.003 CTUeco per kg of processed used oil, or 0.9 million CTUeco in total. The ETP from the combustion of the 325 million kg of recycled fuel oil is 390 million CTUeco. The avoided ETP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 31 million CTUeco. The avoided ETP from displaced production of these primary fuels is 63 million CTUeco or 0.177 kg CTUeco kg of processed used oil. In the extreme recycled fuel oil scenario the net total ETP of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(20 + 1 + 390 - 31 - 63) \text{ million CTUeco} = 316 \text{ million CTUeco.}$$

Recycled fuel oil combustion also exhibits significant ETP, as does onsite combustion, which is essentially the same process. This is largely due to zinc that is emitted to air during combustion. Net ecotoxicity impacts are negative for the extreme re-refining scenario, and positive for the other three scenarios. The highest incurred impacts occur during the recycled fuel oil use phase.

While ecotoxicity impacts are here reported as the combined impacts of emissions to air, water, and soil,

Table 36 shows the percentage of the total impact that was contributed by emissions to each of the three environmental fates.

[all in CTUeco]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	2.04E+07	2.03E+07	2.03E+07	2.03E+07
Reprocessing	6.30E+07	1.08E+08	5.83E+07	9.34E+05
Use of sec. products	5.89E+07	5.00E+05	1.57E+07	3.90E+08
Displaced use	-1.77E+07	-5.11E+05	-2.13E+07	-3.12E+07
Displaced production	-7.73E+07	-1.48E+08	-5.76E+07	-6.33E+07
Net results	4.73E+07	-1.94E+07	1.55E+07	3.16E+08

Table 35: Ecotoxicity Potential in CTUeco for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

[% Contribution]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Air	-10%	-1%	-17%	3%
Soil	-1%	0%	-1%	-1%
Water	111%	101%	118%	98%

Table 36: Ecotoxicity Potential Emission Fate Contribution Analysis.

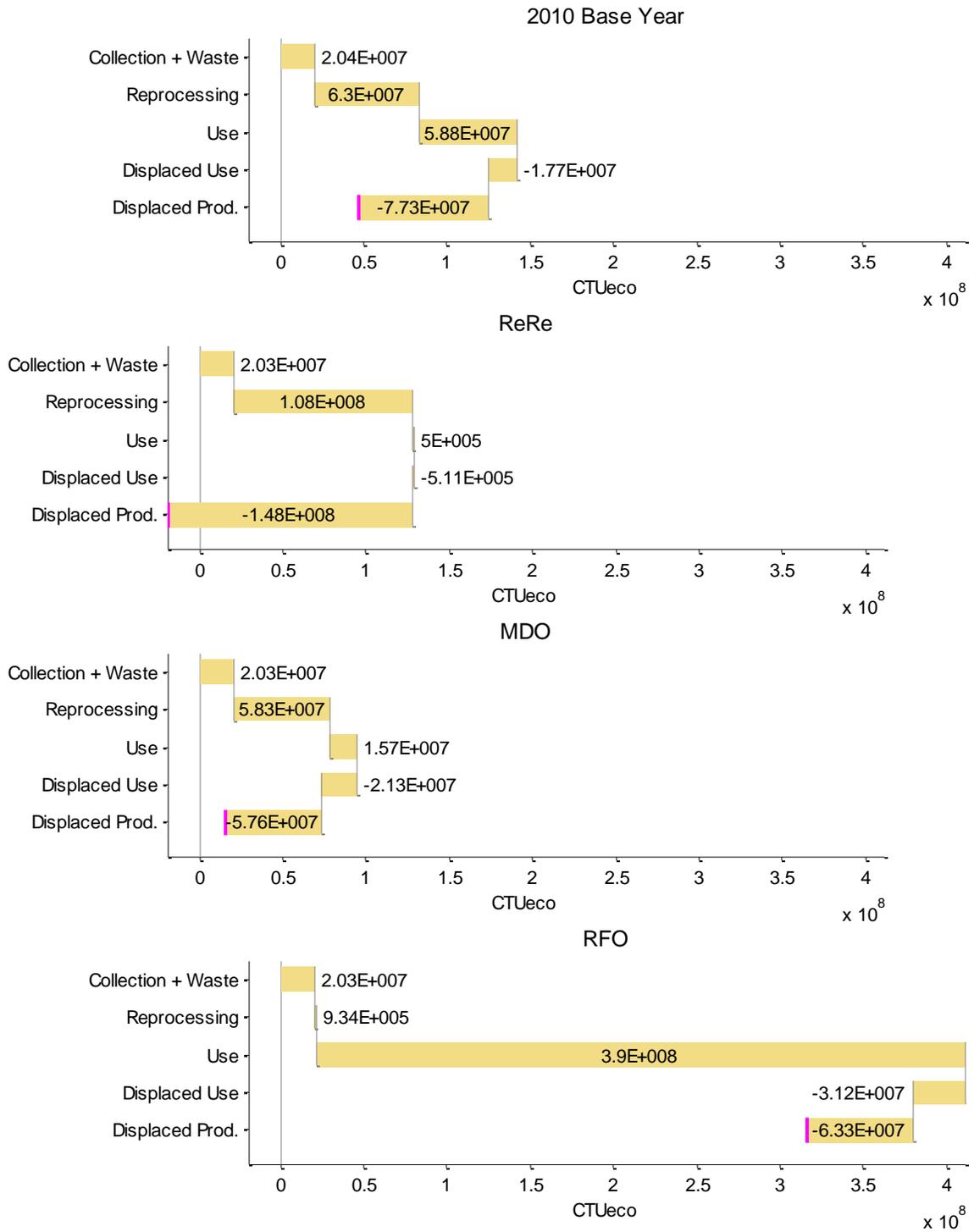


Figure 21: Ecotoxicity Potential in CTUeco for the 2010 base year model and the three extreme reprocessing scenarios.

5.2.5 Human Health Cancer (HHCP)

In TRACI 2.0 human health cancer potential (HHCP) are reported in terms of estimated increase in morbidity in the total human population per unit mass of emitted chemical (cases). Human health cancer potentials resulting from emissions to air, soil, and water are combined in the results presented here. Figure 22 shows the range of human health cancer potential impacts for the base year and three extreme formal management scenarios.

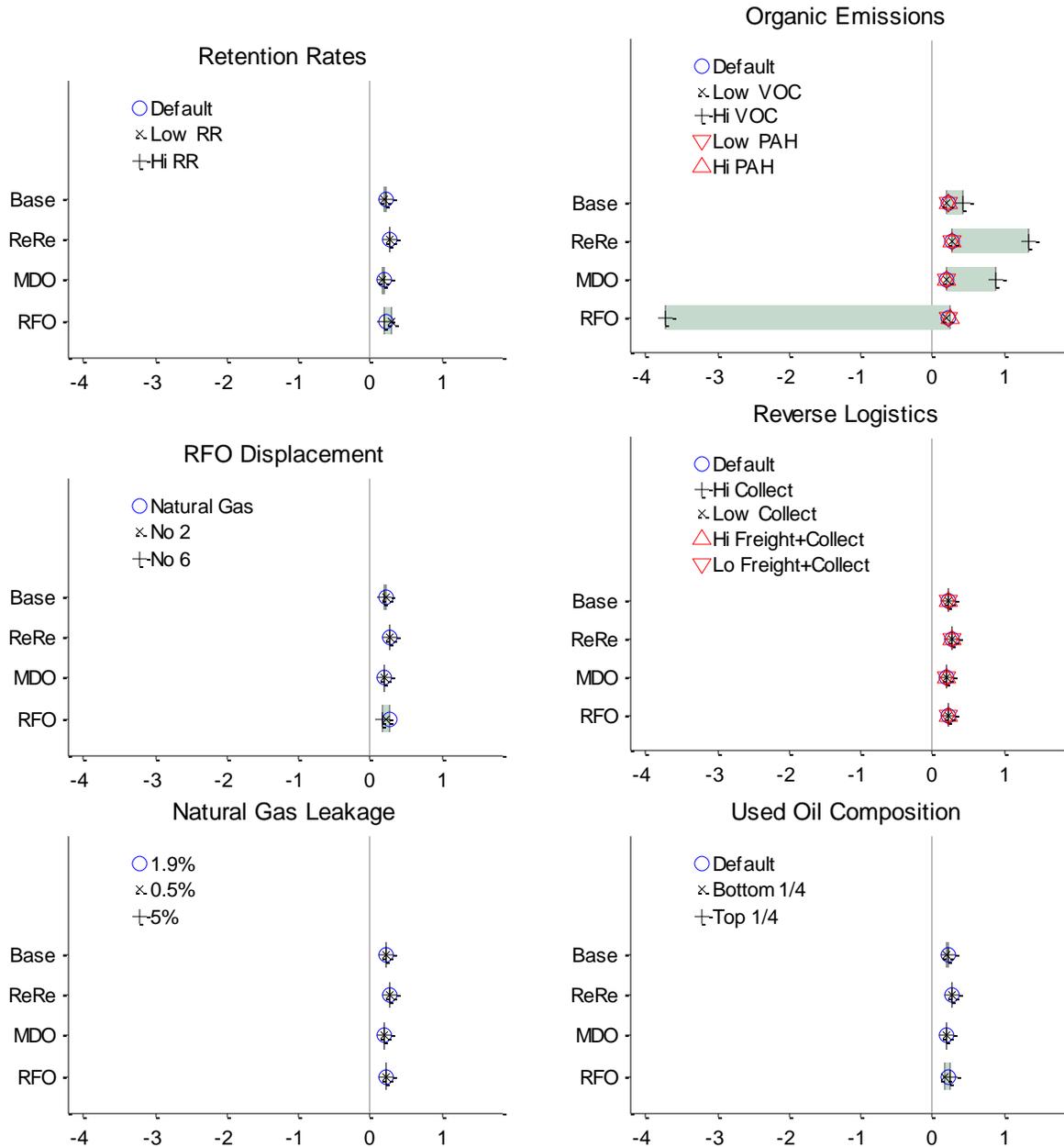


Figure 22: Human Health Cancer Potential ranges for formal management in cases.

In the 2010 base year model the human health cancer potential (HHCP) of collection and hazardous waste disposal is 0.25 cases. In all extreme scenarios, the HHCP of collection and hazardous waste disposal is also 0.25 cases.

In the extreme re-refining scenario, the HHCP of reprocessing is $3.19\text{E}-10$ cases per kg of processed used oil, or 0.11 cases in total. The HHCP of 0.007 cases from the combustion of the 23 million kg of secondary fuels is equal to the avoided HHCP from avoided combustion of the 23 million kg of displaced primary fuels which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided HHCP from displaced production of primary products is $2.6\text{E}-10$ cases per kg of processed used oil, 79 percent of which comes from displaced base oil production. The second largest fraction is 10 percent and comes from displaced asphalt.

The total avoided HHCP from displaced production is 0.09 cases, 0.07 of which are due to displaced base oil production. In the extreme re-refining scenario the net total HHCP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(0.25 + 0.11 + 0.007 - 0.007 - 0.09) \text{ cases} = 0.27 \text{ cases.}$$

In the extreme marine distillate oil scenario, the HHCP of reprocessing is $1.11\text{E}-10$ cases per kg of processed used oil, or 0.04 cases in total. The 0.56 cases from the combustion of the 196 million kg of secondary fuels, mostly marine distillate oil, are slightly less than the avoided 0.50 from avoided combustion of the 196 million kg of displaced primary fuels. The avoided HHCP from displaced production of primary products is $-1.86\text{E}-10$ cases per kg of processed used oil, 57 percent of which comes from displaced production of distillate fuels and 26 percent of which comes from displaced production of asphalt.

The total avoided HHCP from displaced production is 0.06 cases. In the extreme marine distillate oil scenario the net total HHCP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(0.25 + 0.04 + 0.5 - 0.50 - 0.06) \text{ cases} = 0.19 \text{ cases.}$$

In the extreme recycled fuel oil scenario, the HHCP of re-reprocessing is $6.62\text{E}-12$ cases per kg of processed used oil, or 0.002 cases in total. The HHCP from the combustion of the 325 million kg of recycled fuel oil is 0.110 cases. The avoided HHCP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 0.088 cases.

The avoided HHCP from displaced production of these primary fuels is 0.06 cases or $-1.61\text{E}-10$ cases per kg of processed used oil. In the extreme recycled fuel oil scenario the net total HHCP of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(0.251 + 0.002 + 0.110 - 0.088 - 0.057) \text{ cases} = 0.22 \text{ cases.}$$

Both use and avoided use phases are high in the marine distillate oil extreme scenario. Human health cancer impacts in these processes are largely driven by emissions of non-methane VOCs to air, and secondarily by emissions of mercury (+II) to air.

The highest incurred impacts occur in the extreme marine distillate oil scenario. In all four scenarios, the used oil management system has a positive net impact on human health cancer cases. The extreme marine distillate oil and extreme recycled fuel oil scenarios cause the lowest, and roughly equivalent, impacts.

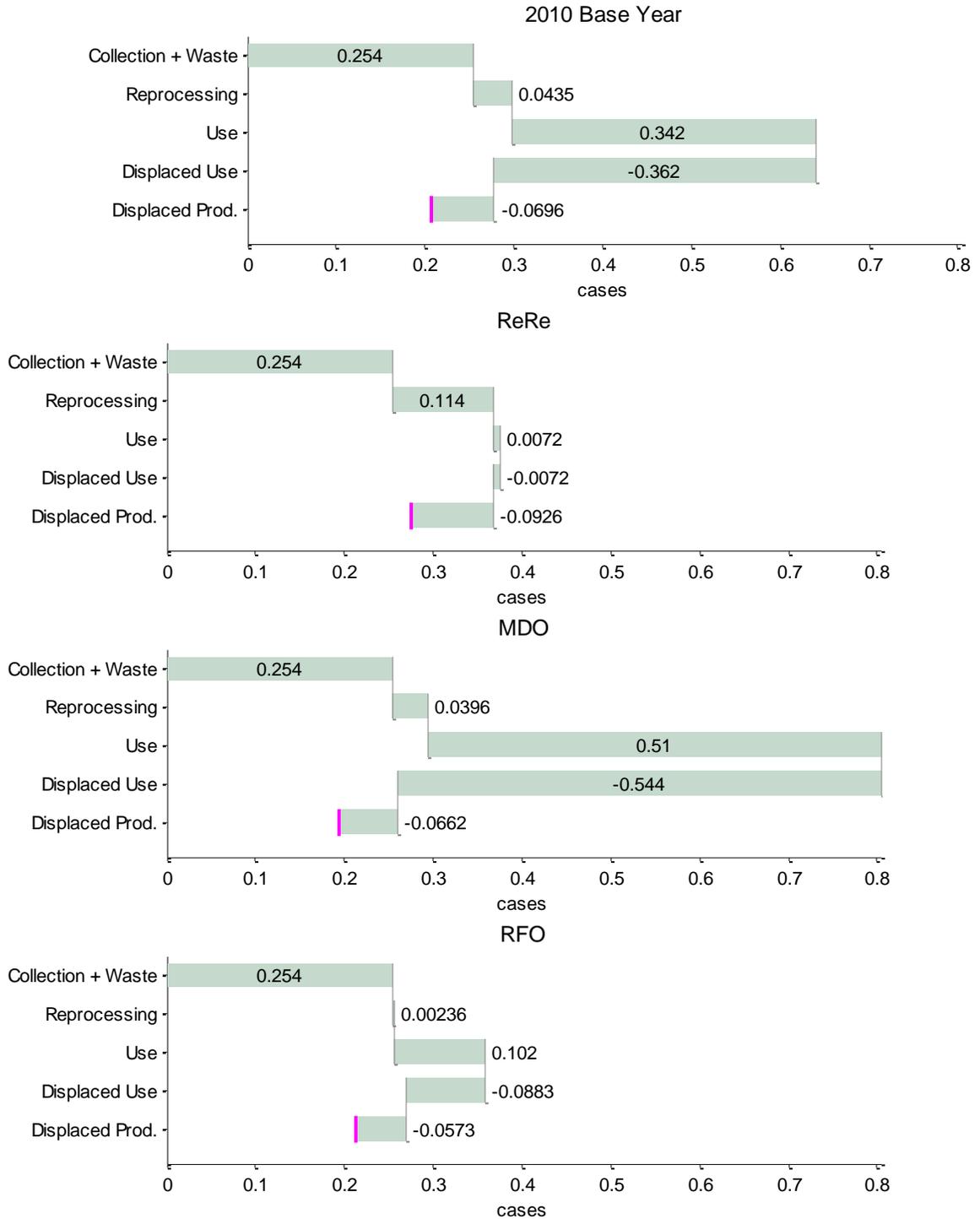


Figure 23: Human Health (Cancer) Potential in cases for the 2010 base year model and the three extreme reprocessing scenarios.

While human health cancer impacts are here reported as the combined impacts of emissions to air, water, and soil, Table 38 shows the percentage of the total impact that was contributed by emissions to each of the three environmental fates.

[all in cases]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	2.54E-01	2.54E-01	2.54E-01	2.54E-01
Reprocessing	4.35E-02	1.14E-01	3.96E-02	2.36E-03
Use of sec. products	3.43E-01	7.20E-03	5.10E-01	1.10E-01
Displaced use	-3.62E-01	-7.20E-03	-5.44E-01	-8.83E-02
Displaced production	-6.96E-02	-9.26E-02	-6.62E-02	-5.73E-02
Net results	2.09E-01	2.75E-01	1.94E-01	2.21E-01

Table 37: Human Health (Cancer) Potential in cases for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

[% Contribution]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Air	108%	47%	577%	101%
Soil	-3%	16%	-216%	-1%
Water	-5%	37%	-261%	-1%

Table 38: Human Health (Cancer) Potential Emission Fate Contribution Analysis.

5.2.6 Human Health Non Cancer (HHNCP)

Human health non-cancer potential (HHNCP) is measured in terms of estimated increase in morbidity in the total human population per unit mass of a chemical emitted (cases). Human health non-cancer potentials resulting from emissions to air, land, and water are combined.

Figure 24 shows the range of global warming potential impacts for the base year and three extreme formal management scenarios.

In the 2010 base year model the human health non-cancer potentials of collection and hazardous waste disposal is 0.91 cases. In all extreme scenarios the human health non-cancer potentials of collection and hazardous waste disposal is 0.90 cases. The lower value is due to the extreme scenario assumption that all collected used oil is processed in-state.

In the extreme re-refining scenario, the human health non-cancer potentials of reprocessing is 1.52E-08 cases per kg of processed used oil, or 5.4 cases in total. The human health non-cancer potentials of 0.46 cases from the combustion of the 23 million kg of secondary fuels is roughly equal to the avoided human health non-cancer potentials from avoided combustion of the 23 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided human health non-cancer potentials from displaced production of primary products is 4.02E-08 cases per kg of processed used oil, 85 percent of which comes

from displaced base oil production. The remainder comes in roughly equal parts from displaced asphalt and distillate fuels production. The total avoided human health non-cancer potentials from displaced production is 14.4 cases. In the extreme re-refining scenario the net total human health non-cancer potentials of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(0.9 + 5.4 + 0.46 - 0.46 - 14.4) \text{ cases} = -8.07 \text{ cases.}$$

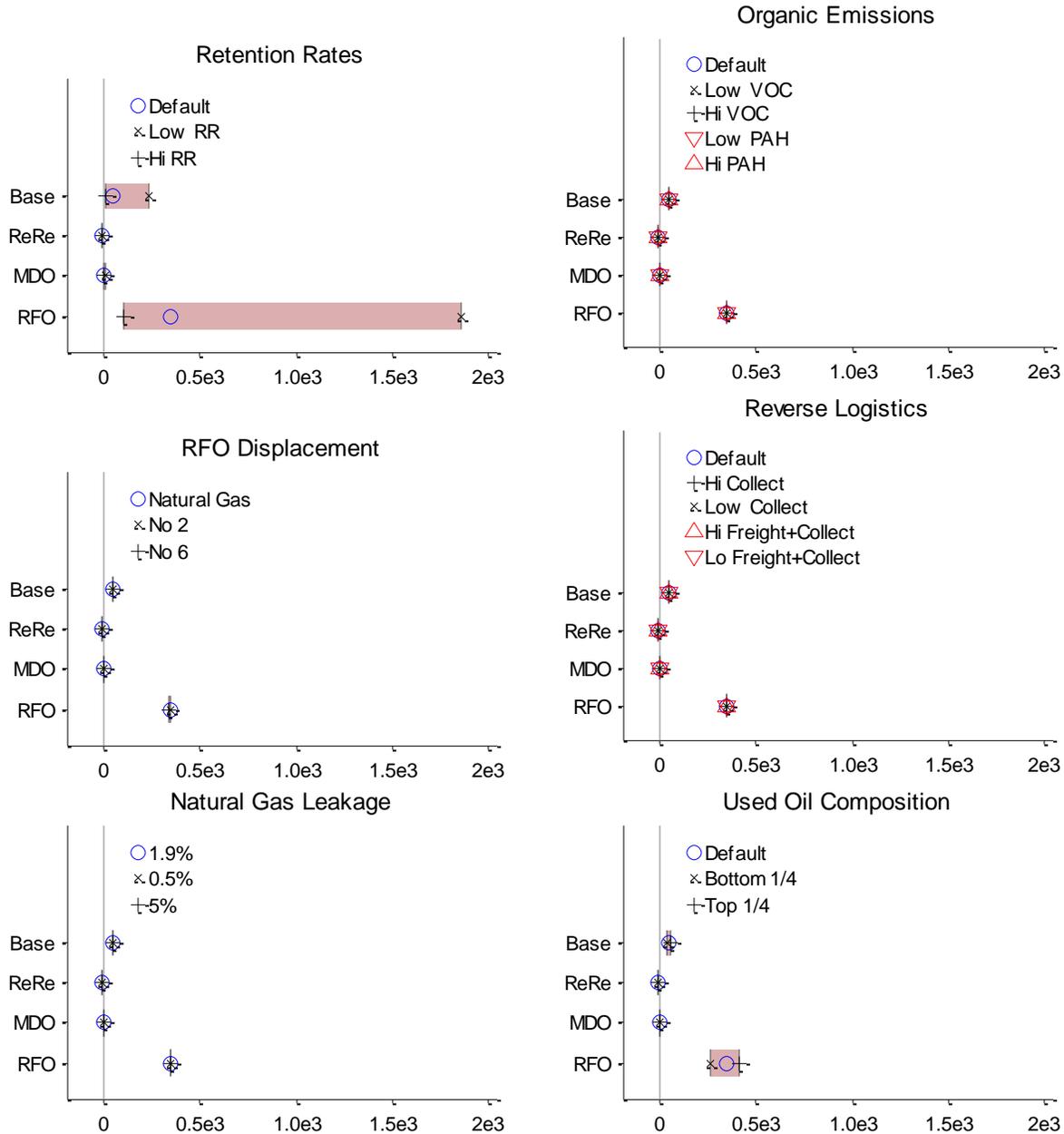


Figure 24: Human Health Non-Cancer Potential ranges for formal management in cases.

In the extreme marine distillate oil scenario, the human health non-cancer potentials of reprocessing is 7.72E-09 cases per kg of processed used oil, or 2.8 case in total. The 22.9 cases from the combustion of the 196 million kg of secondary fuels, mostly marine distillate oil, are slightly more than the avoided 18.6 from avoided combustion of the 196 million kg of displaced primary fuels. The avoided human health non-cancer potentials from displaced production of primary products is 2.09E-08 cases per kg of processed used oil, 67 percent of which comes from displaced production of distillate fuels and 28 percent of which comes from displaced production of asphalt. The total avoided human health non-cancer potentials from displaced production is 7.5 cases. In the extreme MDO scenario the net total human health non-cancer potentials of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(0.9 + 2.8 + 22.9 - 18.6 - 7.5) \text{ cases} = 0.6 \text{ case}.$$

In the extreme recycled fuel oil scenario, the human health non-cancer potentials of reprocessing is 1.55E-10 cases per kg of processed used oil, or 0.055 cases in total. The human health non-cancer potential from the combustion of the 325 million kg of recycled fuel oil is 355.7 cases. The avoided human health non-cancer potential from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 4.3 cases. The avoided human health non-cancer potential from displaced production of these primary fuels is 7.6 cases or 2.12E-08 cases per kg of processed used oil. In the extreme recycled fuel oil scenario, the net total human health non-cancer potentials of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(0.9 + 0.0 + 355.7 - 4.3 - 7.6) \text{ cases} = 345 \text{ cases}.$$

The highest incurred impacts occur during the recycled fuel oil use phase, which are caused almost exclusively by zinc emissions to air from combustion. The extreme re-refining scenario has a net negative impact, while the 2010 base year, extreme marine distillate oil, and extreme recycled fuel oil scenario all have net positive impacts.

Human health cancer and human health non-cancer impacts are both reported in terms of cases, and the scale of the two can thus be compared. In terms of their joint metric, cases, the impacts to human health non-cancer are almost three orders of magnitude higher than impacts to human health cancer.

While human health cancer impacts are here reported as the combined impacts of emissions to air, water, and soil, Table 40 shows the percentage of the total impact that was contributed by emissions to each of the three environmental fates.

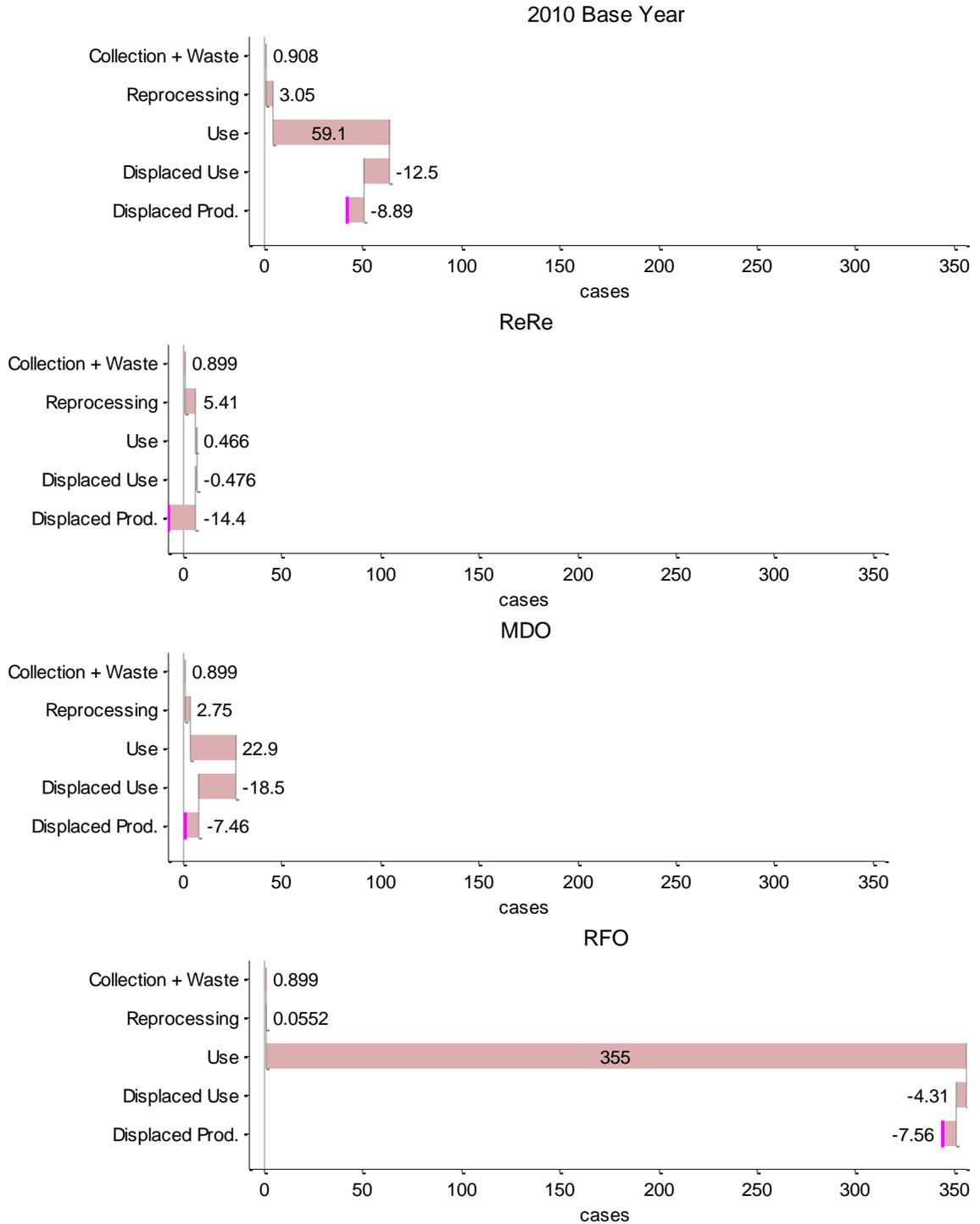


Figure 25: Human Health (Non Cancer) Potential in cases for the 2010 base year model and the three extreme reprocessing scenarios.

[all in cases]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	9.08E-01	8.99E-01	8.99E-01	8.99E-01
Reprocessing	3.05E+00	5.41E+00	2.75E+00	5.52E-02
Use of sec. products	5.92E+01	4.66E-01	2.29E+01	3.56E+02
Displaced use	-1.25E+01	-4.76E-01	-1.85E+01	-4.31E+00
Displaced production	-8.89E+00	-1.44E+01	-7.46E+00	-7.56E+00
Net results	4.18E+01	-8.07E+00	5.95E-01	3.45E+02

Table 39: Human Health (Non Cancer) Potential in cases for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

[% Contribution]	2010 Base Year	Extreme Re-Re	Extreme MDO	Extreme RFO
Air	80%	38%	-48%	113%
Soil	-1%	3%	-4%	0%
Water	21%	59%	153%	-12%

Table 40: Human Health (Non Cancer) Potential Emission Fate Contribution Analysis.

5.2.7 Human Health Criteria Air Potential (HHCAP)

Impacts to the category human health criteria air potential (HHCAP) are measured in terms of kilograms of PM₁₀ equivalents (kg PM₁₀ eq). PM₁₀ is particulate matter with a diameter of 10 micrometers or less. Flows contributing to this impact category are substances like PM₁₀, PM_{2.5}, aluminum dust, silicon dioxide, and other metal particles.

Figure 26 shows the range of human health criteria air potential impacts for the base year and three extreme formal management scenarios.

In the 2010 base year model the HHCAP of collection and hazardous waste disposal is 39,000 kg PM₁₀ eq. In all extreme scenarios the HHCAP of collection and hazardous waste disposal is 36,000 kg PM₁₀ eq. The lower value is due to the extreme scenario assumption that all collected used oil is processed in-state.

In the extreme re-refining scenario, the HHCAP of reprocessing is 3.30E-04 kg PM₁₀ eq per kg of processed used oil, or 118,000 kg PM₁₀ eq in total. The 13,000 kg PM₁₀ eq from the combustion of the 23 million kg of secondary fuels are slightly less than the avoided 14,000 kg PM₁₀ eq from avoided combustion of the 23 million kg of displaced primary fuels. The avoided HHCAP from displaced production of primary products is 1.09E-03 kg PM₁₀ eq per kg of processed used oil, 90 percent of which comes from displaced base oil production. The remainder comes in equal parts from displaced asphalt and distillate fuels production. The total avoided HHCAP from displaced production is 390,000 kg PM₁₀ eq. In the extreme re-refining scenario the net total HHCAP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(36 + 118 + 13 - 14 - 390) \text{ thousand kg PM}_{10}\text{eq} = -237 \text{ thousand kg PM}_{10}\text{eq}.$$



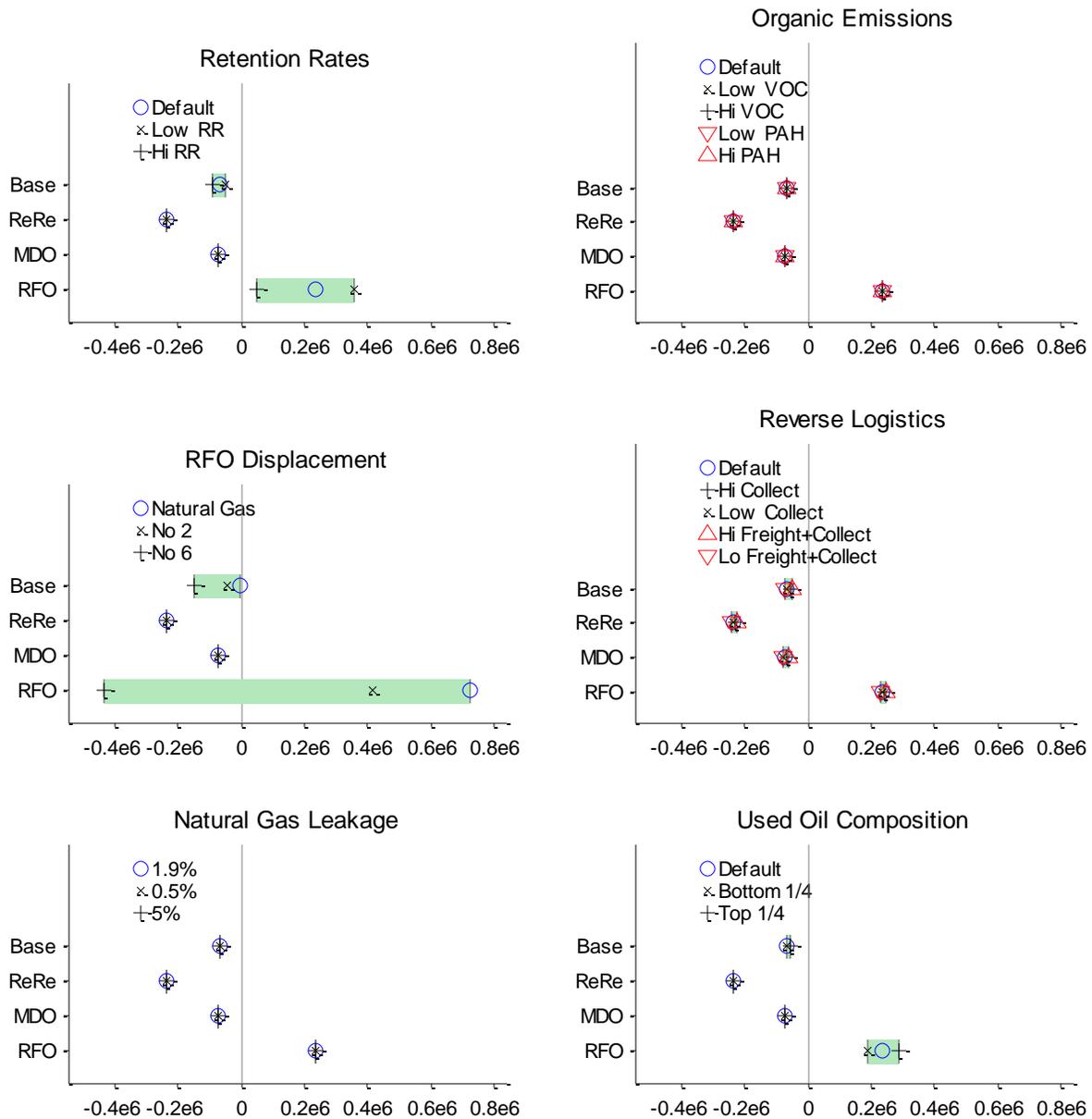


Figure 26: Human Health Criteria Air Potential ranges for formal management in kg PM₁₀ equivalent.

In the extreme marine distillate oil (MDO) scenario, the human health criteria air potential (HHCAP) of reprocessing is 1.79E-04 kg PM₁₀ eq per kg of processed used oil, or 63,000 kg PM₁₀ eq in total. The HHCAP of 961,000 kg PM₁₀ eq from the combustion of the secondary fuels, almost all of which is MDO, is almost the same as the avoided HHCAP from avoided combustion of the 196 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided human health criteria air potential (HHCAP) from

displaced production of primary products is 4.95E-04 kg PM₁₀ eq per kg of processed used oil, 71 percent of which comes from displaced production of distillate fuels and 25 percent of which comes from displaced production of asphalt. The total avoided HHCAP from displaced production is 176,000 kg PM₁₀ eq. In the extreme marine distillate oil scenario the net total HHCAP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(36 + 63 + 961 - 962 - 176) \text{ thousand kg PM}_{10} \text{ eq} = -77 \text{ thousand kg PM}_{10} \text{ eq.}$$

In the extreme RFO scenario, the HHCAP of reprocessing is 4.97E-06 kg PM₁₀ eq per kg of processed used oil, or 1,800 kg PM₁₀ eq in total. The HHCAP from the combustion of the 325 million kg of recycled fuel oil (RFO) is 797,000 kg PM₁₀ eq. The avoided HHCAP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 380,000 kg PM₁₀ eq. The avoided HHCAP from displaced production of these primary fuels is 167,000 kg PM₁₀ eq or 4.68E-04kg PM₁₀ eq per kg of processed used oil. In the extreme RFP scenario the net total HHCAP of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(36 + 2 + 797 - 380 - 167) \text{ thousand kg PM}_{10} \text{ eq} = 289 \text{ thousand kg PM}_{10} \text{ eq.}$$

HHCAP impacts are large in both marine distillate oil use and avoided use, and result from a combination of particulate matter, NO_x, and SO₂ emissions. Recycled fuel oil combustion also causes significant impacts during its combustion primarily due to particulate matter emissions and secondarily due to SO₂ emissions to air.

The highest incurred burden occurs in the extreme marine distillate oil scenario use phase. The net impacts are negative in all scenarios except for extreme RFO. Extreme re-refining has the lowest net impacts of the four scenarios.

[all in kg PM ₁₀ eq]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	3.90E+04	3.62E+04	3.62E+04	3.62E+04
Reprocessing	7.07E+04	1.18E+05	6.39E+04	1.78E+03
Use of sec. products	7.13E+05	1.26E+04	9.62E+05	7.43E+05
Displaced use	-6.69E+05	-1.40E+04	-9.62E+05	-3.79E+05
Displaced production	-2.20E+05	-3.90E+05	-1.77E+05	-1.67E+05
Net results	-5.91E+04	-2.37E+05	-7.71E+04	2.35E+05

Table 41: Human Health (Criteria Air) Potential in kg PM₁₀ equivalent for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

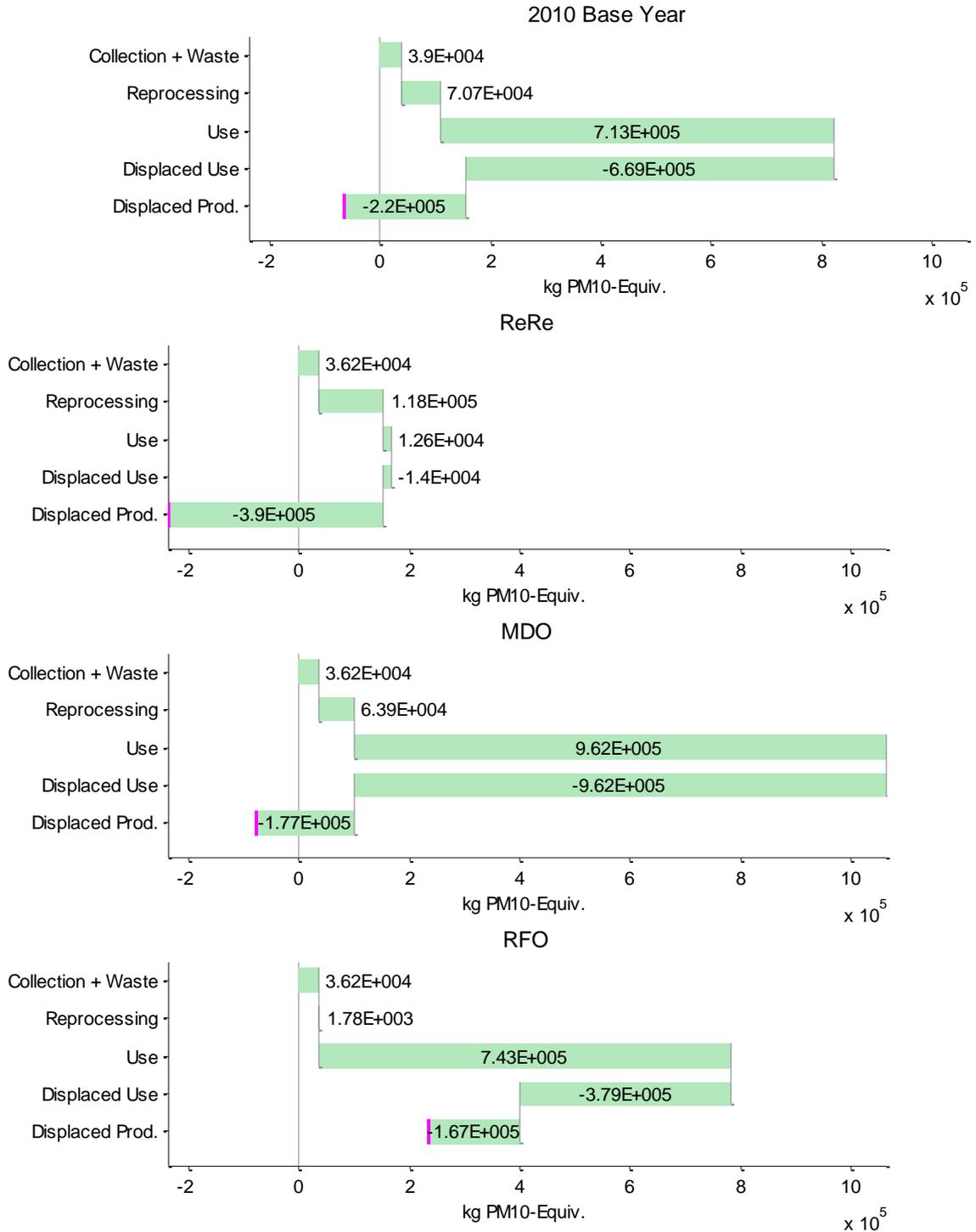


Figure 27: Human Health (Criteria Air) Potential in kg PM₁₀ equivalent for the 2010 base year model and the three extreme reprocessing scenarios.

5.2.8 Smog Creation (SCP)

Smog creation potential (SCP) is reported in terms of kilograms of ground-level ozone equivalent (kg O₃ eq). Smog is created when nitrogen oxides and various VOCs react in the presence of sunlight to create airborne particles and ground-level ozone.

Figure 28 shows the range of smog creation potential impacts for the base year and three extreme formal management scenarios.

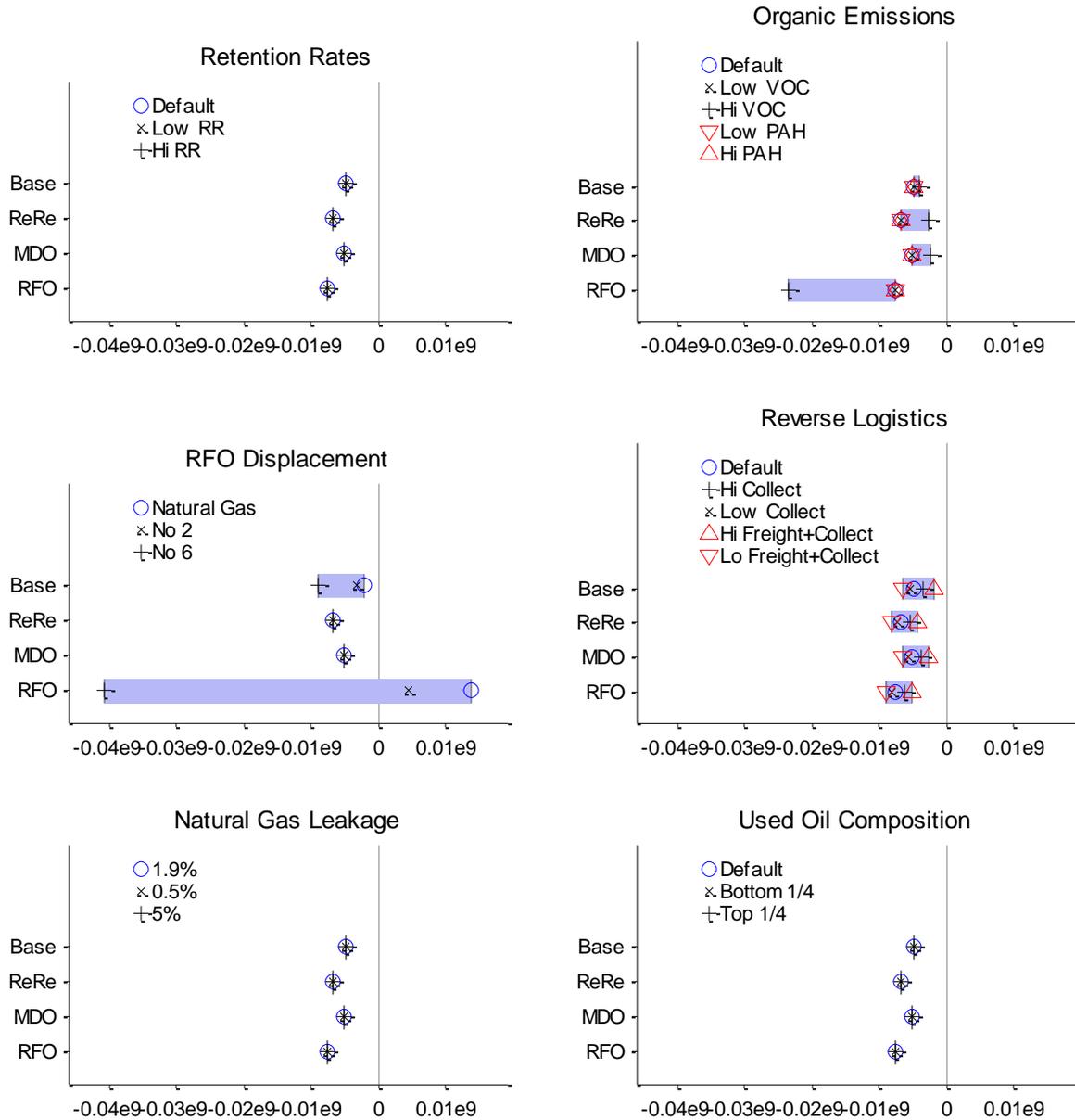


Figure 28: Smog Creation Potential ranges for formal management in kg O₃ equivalent.

In the 2010 base year model the smog creation potential (SCP) of collection and hazardous waste disposal is 4.4 million kg O₃ eq. In all extreme scenarios, the SCP of collection and hazardous waste disposal is 3.6 million kg O₃ eq. The lower value is due to the extreme scenario assumption that all collected used oil is processed in-state.

In the extreme re-refining scenario, the SCP of reprocessing is 5.75E-03 kg O₃ eq per kg of processed used oil, or 2.0 million kg O₃ eq in total. The 1.1 million kg O₃ eq from the combustion of the 23 million kg of secondary fuels are slightly more than the avoided 960,000 kg O₃ eq from avoided combustion of the 23 million kg of displaced primary fuels. The avoided SCP from displaced production of primary products is 3.52E-02 kg O₃ eq per kg of processed used oil, 82 percent of which comes from displaced base oil production. The second largest fraction is 11 percent and comes from displaced asphalt. The total avoided SCP from displaced production is 12.6 million kg O₃ eq. In the extreme re-refining scenario the net total SCP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(3.6 + 2.0 + 1.1 - 0.96 - 12.6) \text{ million kg } O_3 \text{ eq} = -6.8 \text{ million kg } O_3 \text{ eq}.$$

In the extreme marine distillate oil scenario, the SCP of reprocessing is 2.24E-03 kg O₃ eq per kg of processed used oil, or 0.8 million kg O₃ eq in total. The SCP of 177 million kg O₃ eq from the combustion of the secondary fuels, almost all of which is marine distillate oil, is identical to the avoided SCP from avoided combustion of the 196 million kg of displaced primary fuels, which are assumed to have combustion profiles similar to No. 2 distillate fuel. The avoided SCP from displaced production of primary products is 2.67E-02 kg O₃ eq per kg of processed used oil, 65 percent of which comes from displaced production of distillate fuels and 30 percent of which comes from displaced production of asphalt. The total avoided SCP from displaced production is 9.5 million kg O₃ eq. In the extreme marine distillate oil scenario the net total SCP of California's formal used oil management system, i.e. the sum of collection, processing, and use minus avoided production and use, is

$$(3.6 + 0.8 + 177 - 177 - 9.5) \text{ million kg } O_3 \text{ eq} = -5.13 \text{ million kg } O_3 \text{ eq}.$$

In the extreme recycled fuel oil scenario, the SCP of reprocessing is 2.09E-04 kg O₃ eq per kg of processed used oil, or 0.07 million kg O₃ eq in total. The SCP from the combustion of the 325 million kg of recycled fuel oil is 24 million kg O₃ eq. The avoided SCP from avoided combustion of the assumed 104 million kg of displaced No. 2 distillate fuel, 111 million kg of No. 6 residual fuel, and 92 million kg of natural gas is 25 million kg O₃ eq. The avoided SCP from displaced production of these primary fuels is 10 million kg O₃ eq or 2.83E-02 kg CO₂ eq per kg of processed used oil. In the extreme recycled fuel oil scenario the net total SCP of California's formal used oil management system, i.e. the sum of used oil collection, re-processing and recycled fuel oil combustion minus avoided production and combustion of No. 2, No. 6, and natural gas, is

$$(3.6 + 0.1 + 24.4 - 25.4 - 10) \text{ million kg } O_3 \text{ eq} = -7.5 \text{ million kg } O_3 \text{ eq}.$$

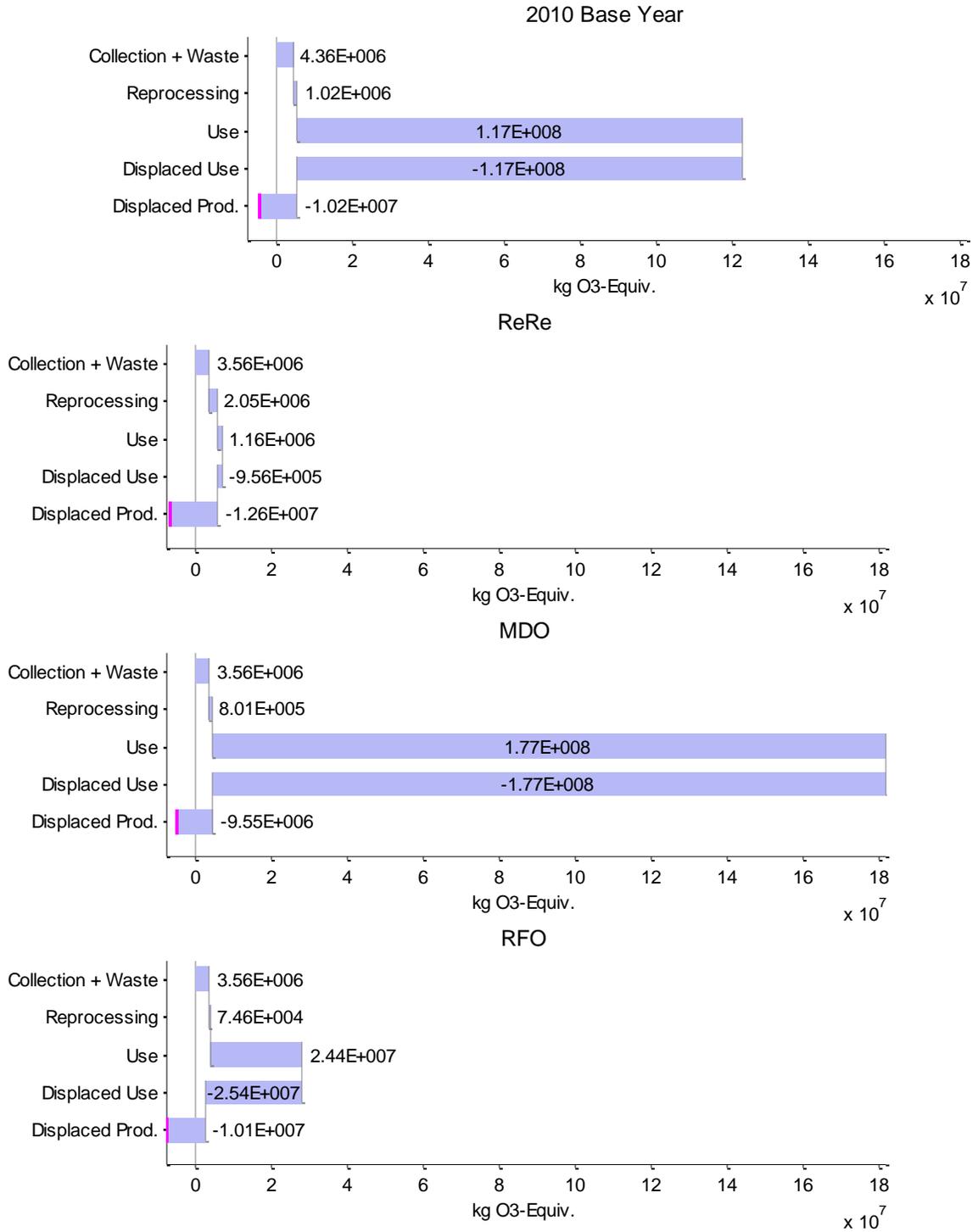


Figure 29: Smog Potential in kg O₃ equivalent for the 2010 base year model and the three extreme reprocessing scenarios.

[all in kg O ₃ eq]	2010 Base Year	Extreme Re-re	Extreme MDO	Extreme RFO
Collection & haz. disp.	4.36E+06	3.56E+06	3.56E+06	3.56E+06
Reprocessing	1.02E+06	2.05E+06	8.01E+05	7.46E+04
Use of sec. products	1.17E+08	1.16E+06	1.77E+08	2.44E+07
Displaced use	-1.17E+08	-9.56E+05	-1.77E+08	-2.54E+07
Displaced production	-1.02E+07	-1.26E+07	-9.55E+06	-1.01E+07
Net results	-4.79E+06	-6.75E+06	-5.13E+06	-7.52E+06

Table 42: Smog Potential in kg O₃ equivalent for the formal used oil management in the 2010 base year model and the three extreme reprocessing scenarios.

Smog impacts from marine distillate oil use are almost exclusively the result of NO_x emissions from combustion. These are equally balanced by the avoided use phase in this scenario. These emissions also drive the impacts of the 2010 Base Year use phase.

The highest incurred impacts occur in the use phase of the extreme marine distillate oil scenario. All four scenarios result in net negative emissions of roughly equivalent values.

5.3 Direct Impact Model Scenarios

This section reports and discusses the impact assessment results of 10 economically driven scenarios. The material flow inputs to the life cycle assessment model in these scenarios was derived from the work of the economic contractor's Direct Impacts Model.

Results are reported by impact category in order to compare the relative impacts of the different hypothetical scenarios. Each scenario is described briefly below, but additional information can be found in the ICF report *Direct Impact Model (DIM) Analysis of the California Used Oil Market*. All scenario descriptions are summaries extracted from the aforementioned report. A table is included for each scenario that reports mass flow inputs to the scenario parameters and life cycle impact assessment results are listed in the tables below for each life cycle impact category assessed: Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Ecotoxicity (Air + Soil + Water) Potential (ETP), Human Health Cancer (Air + Water + Soil) Potential (HHCP), Human Health Non-Cancer (Air + Water + Soil) Potential (HHNCP), Human Health Criteria Air Potential (HHCAP), and Smog Creation Potential (SCP).

5.3.1 Baseline

Material flow analysis flows for the baseline are included in Table 43. Flows for all model scenarios are a variation of the baseline material flow quantities. The percent change from baseline is presented in all scenario tables. Results for the life cycle impact assessment of the baseline are shown in Table 44 through Table 51.

Baseline [all in million kg]	2015	2020	2030
<i>Used Oil generation</i>			
Collectable used oil	446	446	452
<i>Informal Management</i>			
Onsite combustion	11	11	12
Dumped or landfilled	103	107	115
<i>Formal Management</i>			
Used oil collected	378	64	69
Used oil reprocessed	347.1	345.5	348.5
<i>Secondary Products</i>			
Re-refined	63	64	69
Light fuels	141	141	141
RFO	13	11	7
Asphalt flux	95	95	96
Ethylene glycol	0.7	0.6	0.6

Table 43: Used oil and secondary product flows for Baseline Scenario.

LIFE CYCLE IMPACT ASSESSMENT OF BASELINE:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015	2020	2030
Dumping & net landfill	3.10E+06	2.86E+06	2.68E+06
Net onsite combustion	-4.64E+06	-4.81E+06	-5.20E+06
Net formal management	-9.53E+07	-9.59E+07	-9.95E+07
Net informal & formal UO management	-9.69E+07	-9.79E+07	-1.02E+08

Table 44: Global Warming Potential in kg CO₂ equivalent for Baseline Scenario.

[H+ moles-Equiv.]	2015	2020	2030
Dumping & net landfill	7.99E+04	8.25E+04	8.87E+04
Net onsite combustion	7.41E+05	7.71E+05	8.35E+05
Net formal management	-2.53E+07	-2.64E+07	-2.79E+07
Net informal & formal UO management	-2.45E+07	-2.56E+07	-2.70E+07

Table 45: Acidification Potential in H+ moles equivalent for Baseline Scenario.

[kg N-Equiv.]	2015	2020	2030
Dumping & net landfill	2.68E+05	2.78E+05	3.01E+05
Net onsite combustion	4.72E+03	4.90E+03	5.30E+03
Net formal management	-1.92E+01	-2.69E+03	-5.62E+03
Net informal & formal UO management	2.72E+05	2.80E+05	3.00E+05

Table 46: Eutrophication Potential in kg N equivalent for Baseline Scenario.

[CTUeco]	2015	2020	2030
Dumping & net landfill	1.58E+09	1.64E+09	1.77E+09
Net onsite combustion	7.39E+07	7.67E+07	8.30E+07
Net formal management	1.97E+07	1.69E+07	1.32E+07
Net informal & formal UO management	1.67E+09	1.73E+09	1.87E+09

Table 47: Ecotoxicity Potential in CTUeco for Baseline Scenario.

[cases]	2015	2020	2030
Dumping & net landfill	8.16E-01	8.47E-01	9.16E-01
Net onsite combustion	4.70E-03	4.88E-03	5.28E-03
Net formal management	2.01E-01	2.00E-01	2.02E-01
Net informal & formal UO management	1.02E+00	1.05E+00	1.12E+00

Table 48: Human Health (Cancer) Potential in cases for Baseline Scenario.

[cases]	2015	2020	2030
Dumping & net landfill	1.37E+03	1.42E+03	1.53E+03
Net onsite combustion	6.76E+01	7.02E+01	7.59E+01
Net formal management	1.24E+01	9.46E+00	5.88E+00
Net informal & formal UO management	1.45E+03	1.50E+03	1.62E+03

Table 49: Human Health (Non Cancer) Potential in cases for Baseline Scenario.



[kg PM10-Equiv.]	2015	2020	2030
Dumping & net landfill	3.44E+02	3.55E+02	3.81E+02
Net onsite combustion	4.34E+04	4.50E+04	4.87E+04
Net formal management	-1.11E+05	-1.17E+05	-1.25E+05
Net informal & formal UO management	-6.76E+04	-7.12E+04	-7.62E+04

Table 50: Human Health (Criteria Air) Potential in kg PM10 equivalent for Baseline Scenario.

[kg O3-Equiv.]	2015	2020	2030
Dumping & net landfill	-2.26E+04	-2.35E+04	-2.53E+04
Net onsite combustion	-9.56E+04	-9.95E+04	-1.07E+05
Net formal management	-6.18E+06	-6.94E+06	-7.67E+06
Net informal & formal UO management	-6.30E+06	-7.06E+06	-7.80E+06

Table 51: Smog Potential in kg O3 equivalent for Baseline Scenario.

5.3.2 DIM Scenario 1

Scenario 1 examines the impacts of increasing the do it yourself (DIY) oil change incentive payment from \$0.40 in 2013 to \$0.80 in 2014-2030, an increase of \$0.40. This has the effect of increasing used oil collection by 1.6 million gallons and recycled fuel oil production by 1.4 million gallons by 2030. Results for all flows (in kg) shown in Percent change *from baseline shown to the right of flow quantity*.

Table 52. Results for the life cycle impact assessment of the baseline are shown in Table 53 through Table 60.

Scenario 1 [all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	10	(-5%)	11	(-5%)	12	(-4%)
Dumped or landfilled	98	(-5%)	102	(-4%)	111	(-4%)
<i>Formal Management</i>						
Used oil collected	384	(+2%)	383	(+2%)	386	(+1%)
Used oil reprocessed	355	(+2%)	353	(+2%)	356	(+1%)
<i>Secondary Products</i>						
Re-refined	63	(+1%)	65	(+1%)	69	(+0%)
Light fuels	141	(+0%)	141	(+0%)	141	(+0%)
RFO	18	(+34%)	15	(+40%)	12	(+61%)
Asphalt flux	95	(+0%)	95	(+0%)	96	(+0%)
Ethylene glycol	0.7	(+2%)	0.7	(+2%)	0.6	(+0%)

Percent change from baseline shown to the right of flow quantity.

Table 52: Used oil and secondary product flows for Scenario 1.

LIFE CYCLE IMPACT ASSESSMENT OF SCENARIO 1:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 53: Global Warming Potential in kg CO₂ equivalent for Scenario 1.

[H ⁺ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 54: Acidification Potential in H⁺ moles equivalent for Scenario 1.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 55: Eutrophication Potential in kg N equivalent for Scenario 1.

[CTUeco]	2015		2020		2030	
Dumping & net	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 56: Ecotoxicity Potential in CTUeco for Scenario 1.

[cases]	2015		2020		2030	
Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 57: Human Health (Cancer) Potential in cases for Scenario 1.

[cases]	2015	2020	2030
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Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 58: Human Health (Non Cancer) Potential in cases for Scenario 1.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 59: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 1.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.98E+06	(-4%)	2.76E+06	(-3%)	2.60E+06	(-3%)
Net onsite combustion	-4.41E+06	(+5%)	-4.59E+06	(+5%)	-5.00E+06	(+4%)
Net formal management	-9.74E+07	(-2%)	-9.79E+07	(-2%)	-1.01E+08	(-2%)
Net Total	-9.88E+07	(-2%)	-9.97E+07	(-2%)	-1.04E+08	(-2%)

Percent change from baseline shown to the right of flow quantity

Table 60: Smog Potential in kg O3 equivalent for Scenario 1.

5.3.3 DIM Scenario 2

Scenario 2 examines the impacts of increasing the non-DIY used lube oil incentive payment from \$0.16 in 2013 to \$0.56 in 2014-2030, an increase of \$0.40. This increases used lube oil collected by 12.1 million gallons to 89.8 million gallons and increased recycled fuel oil production by 10 million gallons by 2030. Results for all flows (in kg) shown in *Percent change from baseline shown to the right of flow quantity*.

Table 61. Results for the life cycle impact assessment of DIM scenario 2 are shown in *Percent change from baseline shown to the right of flow quantity*.

Table 61 through Table 69.

Scenario 2						
[all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	7	(-36%)	8	(-33%)	9	(-28%)
Dumped or landfilled	67	(-35%)	72	(-32%)	84	(-27%)
<i>Formal Management</i>						
Used oil collected	423	(+12%)	421	(+12%)	421	(+11%)
Used oil reprocessed	391	(+12%)	388	(+12%)	389	(+11%)
<i>Secondary Products</i>						
Re-refined	66	(+5%)	68	(+5%)	72	(+4%)
Light fuels	141	(+0%)	141	(+0%)	141	(+0%)
RFO	47	(+248%)	43	(+302%)	38	(+414%)
Asphalt flux	96	(+1%)	96	(+1%)	96	(+1%)
Ethylene glycol	0.7	(+12%)	0.7	(+12%)	0.7	(+10%)

Percent change from baseline shown to the right of flow quantity.

Table 61: Used oil and secondary product flows for Scenario 2.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 2:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	2.24E+06	(-28%)	2.14E+06	(-25%)	2.12E+06	(-21%)
Net onsite combustion	-2.96E+06	(+36%)	-3.20E+06	(+33%)	-3.72E+06	(+28%)
Net formal management	-1.10E+08	(-16%)	-1.10E+08	(-15%)	-1.13E+08	(-14%)
Net Total	-1.11E+08	(-14%)	-1.11E+08	(-14%)	-1.15E+08	(-12%)

Percent change from baseline shown to the right of flow quantity

Table 62: Global Warming Potential in kg CO₂ equivalent for Scenario 2.

[H+ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	5.35E+04	(-33%)	5.72E+04	(-31%)	6.54E+04	(-26%)
Net onsite combustion	4.73E+05	(-36%)	5.13E+05	(-33%)	5.98E+05	(-28%)
Net formal management	-2.98E+07	(-18%)	-3.09E+07	(-17%)	-3.22E+07	(-15%)
Net Total	-2.92E+07	(-19%)	-3.03E+07	(-19%)	-3.16E+07	(-17%)

Percent change from baseline shown to the right of flow quantity

Table 63: Acidification Potential in H+ moles equivalent for Scenario 2.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	1.71E+05	(-36%)	1.85E+05	(-33%)	2.15E+05	(-28%)
Net onsite combustion	3.01E+03	(-36%)	3.26E+03	(-33%)	3.79E+03	(-28%)
Net formal management	1.39E+04	(+72343%)	1.06E+04	(+493%)	6.88E+03	(+222%)
Net Total	1.88E+05	(-31%)	1.99E+05	(-29%)	2.26E+05	(-25%)

Percent change from baseline shown to the right of flow quantity

Table 64: Eutrophication Potential in kg N equivalent for Scenario 2.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.01E+09	(-36%)	1.09E+09	(-33%)	1.27E+09	(-28%)
Net onsite combustion	4.72E+07	(-36%)	5.11E+07	(-33%)	5.94E+07	(-28%)
Net formal management	5.32E+07	(+170%)	4.92E+07	(+191%)	4.41E+07	(+233%)
Net Total	1.11E+09	(-34%)	1.19E+09	(-31%)	1.37E+09	(-27%)

Percent change from baseline shown to the right of flow quantity

Table 65: Ecotoxicity Potential in CTUeco for Scenario 2.

[cases]	2015		2020		2030	
Dumping & net landfill	5.21E-01	(-36%)	5.63E-01	(-33%)	6.55E-01	(-28%)
Net onsite combustion	3.00E-03	(-36%)	3.25E-03	(-33%)	3.78E-03	(-28%)
Net formal management	2.28E-01	(+13%)	2.26E-01	(+13%)	2.27E-01	(+12%)
Net Total	7.52E-01	(-26%)	7.93E-01	(-25%)	8.86E-01	(-21%)

Percent change from baseline shown to the right of flow quantity

Table 66: Human Health (Cancer) Potential in cases for Scenario 2.

[cases]	2015		2020		2030	
Dumping & net landfill	8.73E+02	(-36%)	9.44E+02	(-33%)	1.10E+03	(-28%)
Net onsite combustion	4.32E+01	(-36%)	4.67E+01	(-33%)	5.43E+01	(-28%)
Net formal management	4.76E+01	(+282%)	4.34E+01	(+358%)	3.82E+01	(+550%)
Net Total	9.63E+02	(-33%)	1.03E+03	(-31%)	1.19E+03	(-26%)

Percent change from baseline shown to the right of flow quantity

Table 67: Human Health (Non Cancer) Potential in cases for Scenario 2.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.33E+02	(-32%)	2.49E+02	(-30%)	2.83E+02	(-26%)
Net onsite combustion	2.77E+04	(-36%)	3.00E+04	(-33%)	3.48E+04	(-28%)
Net formal management	-8.52E+04	(+23%)	-9.17E+04	(+21%)	-1.01E+05	(+19%)
Net Total	-5.72E+04	(+15%)	-6.14E+04	(+14%)	-6.61E+04	(+13%)

Percent change from baseline shown to the right of flow quantity

Table 68: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 2.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-1.60E+04	(+29%)	-1.71E+04	(+27%)	-1.93E+04	(+24%)
Net onsite combustion	-6.10E+04	(+36%)	-6.62E+04	(+33%)	-7.69E+04	(+28%)
Net formal management	-7.01E+06	(-13%)	-7.84E+06	(-13%)	-8.61E+06	(-12%)
Net Total	-7.09E+06	(-13%)	-7.93E+06	(-12%)	-8.70E+06	(-12%)

Percent change from baseline shown to the right of flow quantity

Table 69: Smog Potential in kg O3 equivalent for Scenario 2.

5.3.4 DIM Scenario 3

Scenario 3 examines the impacts of creating a used industrial oil incentive of \$0.40 in 2014-2030.

This increases used industrial oil collected by 9.1 million gallons to 43.1 million gallons and increases recycled fuel oil by 7.6 million gallons by 2030. Results for all flows (in kg) shown in

Table 70 *Percent change from baseline shown to the right of flow quantity.*

Table 70. Results for the life cycle impact assessment of the baseline are shown in Table 71 through Table 78.

Scenario 3						
[all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	9	(-18%)	9	(-19%)	10	(-21%)
Dumped or landfilled	85	(-17%)	87	(-18%)	92	(-21%)
<i>Formal Management</i>						
Used oil collected	401	(+6%)	402	(+7%)	411	(+8%)
Used oil reprocessed	370	(+6%)	371	(+7%)	379	(+8%)
<i>Secondary Products</i>						
Re-refined	65	(+3%)	66	(+3%)	71	(+3%)
Light fuels	141	(+0%)	141	(+0%)	141	(+0%)
RFO	30	(+124%)	29	(+171%)	30	(+310%)
Asphalt flux	95	(+0%)	96	(+0%)	96	(+0%)
Ethylene glycol	0.7	(+6%)	0.7	(+7%)	0.7	(+7%)

Percent change from baseline shown to the right of flow quantity.

Table 70: Used oil and secondary product flows for Scenario 3.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 3:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	2.67E+06	(-14%)	2.45E+06	(-14%)	2.26E+06	(-16%)
Net onsite combustion	-3.80E+06	(+18%)	-3.89E+06	(+19%)	-4.09E+06	(+21%)
Net formal management	-1.03E+08	(-8%)	-1.04E+08	(-9%)	-1.10E+08	(-10%)
Net Total	-1.04E+08	(-7%)	-1.06E+08	(-8%)	-1.11E+08	(-9%)

Percent change from baseline shown to the right of flow quantity

Table 71: Global Warming Potential in kg CO₂ equivalent for Scenario 3.

[H ⁺ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	6.66E+04	(-17%)	6.81E+04	(-17%)	7.12E+04	(-20%)
Net onsite combustion	6.06E+05	(-18%)	6.24E+05	(-19%)	6.57E+05	(-21%)
Net formal management	-2.76E+07	(-9%)	-2.90E+07	(-10%)	-3.12E+07	(-12%)
Net Total	-2.69E+07	(-10%)	-2.83E+07	(-11%)	-3.04E+07	(-13%)

Percent change from baseline shown to the right of flow quantity

Table 72: Acidification Potential in H⁺ moles equivalent for Scenario 3.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.19E+05	(-18%)	2.25E+05	(-19%)	2.37E+05	(-21%)
Net onsite combustion	3.86E+03	(-18%)	3.96E+03	(-19%)	4.17E+03	(-21%)
Net formal management	6.91E+03	(+36018%)	4.80E+03	(+279%)	3.76E+03	(+167%)
Net Total	2.30E+05	(-16%)	2.34E+05	(-17%)	2.44E+05	(-19%)

Percent change from baseline shown to the right of flow quantity

Table 73: Eutrophication Potential in kg N equivalent for Scenario 3.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.29E+09	(-18%)	1.32E+09	(-19%)	1.39E+09	(-21%)
Net onsite combustion	6.05E+07	(-18%)	6.21E+07	(-19%)	6.53E+07	(-21%)
Net formal management	3.64E+07	(+84%)	3.51E+07	(+108%)	3.64E+07	(+175%)
Net Total	1.39E+09	(-17%)	1.42E+09	(-18%)	1.49E+09	(-20%)

Percent change from baseline shown to the right of flow quantity

Table 74: Ecotoxicity Potential in CTUeco for Scenario 3.

[cases]	2015		2020		2030	
Dumping & net landfill	6.68E-01	(-18%)	6.85E-01	(-19%)	7.21E-01	(-21%)
Net onsite combustion	3.85E-03	(-18%)	3.95E-03	(-19%)	4.16E-03	(-21%)
Net formal management	2.15E-01	(+7%)	2.15E-01	(+7%)	2.21E-01	(+9%)
Net Total	8.86E-01	(-13%)	9.04E-01	(-14%)	9.45E-01	(-16%)

Percent change from baseline shown to the right of flow quantity

Table 75: Human Health (Cancer) Potential in cases for Scenario 3.

[cases]	2015		2020		2030	
Dumping & net landfill	1.12E+03	(-18%)	1.15E+03	(-19%)	1.21E+03	(-21%)
Net onsite combustion	5.53E+01	(-18%)	5.68E+01	(-19%)	5.97E+01	(-21%)
Net formal management	2.99E+01	(+140%)	2.86E+01	(+203%)	3.01E+01	(+412%)
Net Total	1.20E+03	(-17%)	1.23E+03	(-18%)	1.30E+03	(-20%)

Percent change from baseline shown to the right of flow quantity

Table 76: Human Health (Non Cancer) Potential in cases for Scenario 3.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.88E+02	(-16%)	2.95E+02	(-17%)	3.08E+02	(-19%)
Net onsite combustion	3.55E+04	(-18%)	3.64E+04	(-19%)	3.83E+04	(-21%)
Net formal management	-9.84E+04	(+12%)	-1.03E+05	(+12%)	-1.07E+05	(+14%)
Net Total	-6.26E+04	(+7%)	-6.59E+04	(+8%)	-6.86E+04	(+10%)

Percent change from baseline shown to the right of flow quantity

Table 77: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 3.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-1.93E+04	(+15%)	-1.98E+04	(+16%)	-2.08E+04	(+18%)
Net onsite combustion	-7.83E+04	(+18%)	-8.05E+04	(+19%)	-8.46E+04	(+21%)
Net formal management	-6.60E+06	(-7%)	-7.45E+06	(-7%)	-8.37E+06	(-9%)
Net Total	-6.70E+06	(-6%)	-7.55E+06	(-7%)	-8.48E+06	(-9%)

Percent change from baseline shown to the right of flow quantity

Table 78: Smog Potential in kg O3 equivalent for Scenario 3.

5.3.5 DIM Scenario 4

Scenario 4 examines the impacts of an increase of \$0.40 in the market value of California used oil, from \$0.30 in 2013 to \$0.70 in 2014-2030. This increases 2030 used lube oil collected by 12.1 million gallons and increases industrial oil collected by 9.1 million gallons. It also increases recycled fuel oil production by 17.6 million gallons. Results for all flows (in kg) shown in *Percent change from baseline shown to the right of flow quantity*.

Table 79 Table 79. Results for the life cycle impact assessment of the baseline are shown in Table 80 through Table 87.

Scenario 4						
[all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	5	(-54%)	5	(-53%)	6	(-50%)
Dumped or landfilled	49	(-52%)	53	(-51%)	60	(-48%)
<i>Formal Management</i>						
Used oil collected	446	(+18%)	446	(+18%)	452	(+19%)
Used oil reprocessed	412	(+18%)	411	(+18%)	417	(+19%)
<i>Secondary Products</i>						
Re-refined	68	(+8%)	69	(+8%)	74	(+7%)
Light fuels	141	(+0%)	141	(+0%)	141	(+0%)
RFO	64	(+376%)	61	(+479%)	61	(+725%)
Asphalt flux	96	(+1%)	96	(+1%)	97	(+1%)
Ethylene glycol	0.8	(+17%)	0.8	(+17%)	0.7	(+17%)

Percent change from baseline shown to the right of flow quantity.

Table 79: Used oil and secondary product flows for Scenario 4.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 4:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	1.80E+06	(-42%)	1.73E+06	(-40%)	1.70E+06	(-37%)
Net onsite combustion	-2.12E+06	(+54%)	-2.28E+06	(+53%)	-2.61E+06	(+50%)
Net formal management	-1.18E+08	(-23%)	-1.19E+08	(-24%)	-1.23E+08	(-24%)
Net Total	-1.18E+08	(-22%)	-1.19E+08	(-22%)	-1.24E+08	(-22%)

Percent change from baseline shown to the right of flow quantity

Table 80: Global Warming Potential in kg CO₂ equivalent for Scenario 4.

[H ⁺ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	4.02E+04	(-50%)	4.28E+04	(-48%)	4.79E+04	(-46%)
Net onsite combustion	3.38E+05	(-54%)	3.66E+05	(-53%)	4.20E+05	(-50%)
Net formal management	-3.20E+07	(-26%)	-3.35E+07	(-27%)	-3.55E+07	(-27%)
Net Total	-3.16E+07	(-29%)	-3.31E+07	(-29%)	-3.50E+07	(-30%)

Percent change from baseline shown to the right of flow quantity

Table 81: Acidification Potential in H⁺ moles equivalent for Scenario 4.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	1.22E+05	(-54%)	1.32E+05	(-53%)	1.51E+05	(-50%)
Net onsite combustion	2.16E+03	(-54%)	2.33E+03	(-53%)	2.66E+03	(-50%)
Net formal management	2.11E+04	(+109521%)	1.83E+04	(+780%)	1.63E+04	(+390%)
Net Total	1.45E+05	(-47%)	1.53E+05	(-46%)	1.70E+05	(-43%)

Percent change from baseline shown to the right of flow quantity

Table 82: Eutrophication Potential in kg N equivalent for Scenario 4.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	7.20E+08	(-54%)	7.77E+08	(-53%)	8.89E+08	(-50%)
Net onsite combustion	3.38E+07	(-54%)	3.64E+07	(-53%)	4.17E+07	(-50%)
Net formal management	7.04E+07	(+257%)	6.80E+07	(+303%)	6.73E+07	(+408%)
Net Total	8.24E+08	(-51%)	8.82E+08	(-49%)	9.98E+08	(-47%)

Percent change from baseline shown to the right of flow quantity

Table 83: Ecotoxicity Potential in CTUeco for Scenario 4.

[cases]	2015		2020		2030	
Dumping & net landfill	3.73E-01	(-54%)	4.02E-01	(-53%)	4.60E-01	(-50%)
Net onsite combustion	2.15E-03	(-54%)	2.32E-03	(-53%)	2.65E-03	(-50%)
Net formal management	2.42E-01	(+20%)	2.41E-01	(+20%)	2.45E-01	(+21%)
Net Total	6.16E-01	(-40%)	6.45E-01	(-39%)	7.07E-01	(-37%)

Percent change from baseline shown to the right of flow quantity

Table 84: Human Health (Cancer) Potential in cases for Scenario 4.

[cases]	2015		2020		2030	
Dumping & net landfill	6.24E+02	(-54%)	6.74E+02	(-53%)	7.71E+02	(-50%)
Net onsite combustion	3.09E+01	(-54%)	3.33E+01	(-53%)	3.81E+01	(-50%)
Net formal management	6.56E+01	(+427%)	6.31E+01	(+567%)	6.26E+01	(+964%)
Net Total	7.21E+02	(-50%)	7.70E+02	(-49%)	8.71E+02	(-46%)

Percent change from baseline shown to the right of flow quantity

Table 85: Human Health (Non Cancer) Potential in cases for Scenario 4.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	1.77E+02	(-49%)	1.88E+02	(-47%)	2.10E+02	(-45%)
Net onsite combustion	1.98E+04	(-54%)	2.14E+04	(-53%)	2.45E+04	(-50%)
Net formal management	-7.15E+04	(+36%)	-7.68E+04	(+34%)	-8.31E+04	(+34%)
Net Total	-5.15E+04	(+24%)	-5.52E+04	(+22%)	-5.84E+04	(+23%)

Percent change from baseline shown to the right of flow quantity

Table 86: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 4.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-1.27E+04	(+44%)	-1.34E+04	(+43%)	-1.48E+04	(+41%)
Net onsite combustion	-4.37E+04	(+54%)	-4.72E+04	(+53%)	-5.40E+04	(+50%)
Net formal management	-7.44E+06	(-20%)	-8.37E+06	(-21%)	-9.31E+06	(-21%)
Net Total	-7.50E+06	(-19%)	-8.43E+06	(-19%)	-9.38E+06	(-20%)

Percent change from baseline shown to the right of flow quantity

Table 87: Smog Potential in kg O3 equivalent for Scenario 4.

5.3.6 DIM Scenario 5

Scenario 5 examines the impacts of \$0.10 decrease in the fee for lube oil from re-refined, from \$0.12 in 2013 to \$0.02 in 2014-2030, with no change in the \$0.24 fee for lube oil from virgin base oil. Has no impact on the amount of collected or uncollected used oil, but increases 2030 re-refined base oil by 1.2 million gallons, decreases 2030 marine distillate oil/light fuels recovered by 200,000 gallons, increases 2030 asphalt flux recovered by 100,000 gallons, and decreases 2030 recycled fuel oil by 1.1 million gallons. Results for all flows (in kg) shown in Table

88Percent change from baseline shown to the right of flow quantity

Table 88. Results for the life cycle impact assessment of the baseline are shown in Table 89 through Table 96.

Scenario 5						
[all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	11	(+0%)	11	(+0%)	12	(+0%)
Dumped or landfilled	103	(+0%)	107	(+0%)	115	(+0%)
<i>Formal Management</i>						
Used oil collected	378	(+0%)	377	(+0%)	380	(+0%)
Used oil reprocessed	349	(+0%)	348	(+0%)	351	(+0%)
<i>Secondary Products</i>						
Re-refined	66	(+4%)	68	(+5%)	73	(+5%)
Light fuels	141	(-0%)	141	(-0%)	140	(-0%)
RFO	10	(-25%)	6	(-39%)	3.9	(-48%)
Asphalt flux	95	(+0%)	96	(+0%)	96	(+0%)
Ethylene glycol	0.6	(-2%)	0.6	(-0%)	0.6	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 88: Used oil and secondary product flows for Scenario 5.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 5:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	3.10E+06	(+0%)	2.86E+06	(+0%)	2.68E+06	(+0%)
Net onsite combustion	-4.64E+06	(+0%)	-4.81E+06	(+0%)	-5.20E+06	(+0%)
Net formal management	-9.58E+07	(-1%)	-9.66E+07	(-1%)	-1.00E+08	(-1%)
Net Total	-9.74E+07	(-1%)	-9.86E+07	(-1%)	-1.03E+08	(-1%)

Percent change from baseline shown to the right of flow quantity

Table 89: Global Warming Potential in kg CO₂ equivalent for Scenario 5.

[H ⁺ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	7.99E+04	(+0%)	8.25E+04	(+0%)	8.87E+04	(+0%)
Net onsite combustion	7.41E+05	(+0%)	7.71E+05	(+0%)	8.35E+05	(+0%)
Net formal management	-2.53E+07	(+0%)	-2.64E+07	(+0%)	-2.79E+07	(-0%)
Net Total	-2.45E+07	(+0%)	-2.56E+07	(+0%)	-2.70E+07	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 90: Acidification Potential in H⁺ moles equivalent for Scenario 5.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.68E+05	(+0%)	2.78E+05	(+0%)	3.01E+05	(+0%)
Net onsite combustion	4.72E+03	(+0%)	4.90E+03	(+0%)	5.30E+03	(+0%)
Net formal management	-1.65E+03	(-8468%)	-4.65E+03	(-73%)	-7.32E+03	(-30%)
Net Total	2.71E+05	(-1%)	2.78E+05	(-1%)	2.99E+05	(-1%)

Percent change from baseline shown to the right of flow quantity

Table 91: Eutrophication Potential in kg N equivalent for Scenario 5.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.58E+09	(+0%)	1.64E+09	(+0%)	1.77E+09	(+0%)
Net onsite combustion	7.39E+07	(+0%)	7.67E+07	(+0%)	8.30E+07	(+0%)
Net formal management	1.62E+07	(-18%)	1.25E+07	(-26%)	9.48E+06	(-28%)
Net Total	1.67E+09	(-0%)	1.73E+09	(-0%)	1.86E+09	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 92: Ecotoxicity Potential in CTUeco for Scenario 5.

[cases]	2015		2020		2030	
Dumping & net landfill	8.16E-01	(+0%)	8.47E-01	(+0%)	9.16E-01	(+0%)
Net onsite combustion	4.70E-03	(+0%)	4.88E-03	(+0%)	5.28E-03	(+0%)
Net formal management	2.01E-01	(+0%)	2.00E-01	(+0%)	2.03E-01	(+0%)
Net Total	1.02E+00	(+0%)	1.05E+00	(+0%)	1.12E+00	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 93: Human Health (Cancer) Potential in cases for Scenario 5.

[cases]	2015		2020		2030	
Dumping & net landfill	1.37E+03	(+0%)	1.42E+03	(+0%)	1.53E+03	(+0%)
Net onsite combustion	6.76E+01	(+0%)	7.02E+01	(+0%)	7.59E+01	(+0%)
Net formal management	8.75E+00	(-30%)	4.97E+00	(-47%)	2.03E+00	(-65%)
Net Total	1.44E+03	(-0%)	1.49E+03	(-0%)	1.61E+03	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 94: Human Health (Non Cancer) Potential in cases for Scenario 5.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	3.44E+02	(+0%)	3.55E+02	(+0%)	3.81E+02	(+0%)
Net onsite combustion	4.34E+04	(+0%)	4.50E+04	(+0%)	4.87E+04	(+0%)
Net formal management	-1.17E+05	(-5%)	-1.23E+05	(-6%)	-1.31E+05	(-5%)
Net Total	-7.31E+04	(-8%)	-7.79E+04	(-9%)	-8.23E+04	(-8%)

Percent change from baseline shown to the right of flow quantity

Table 95: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 5.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-2.26E+04	(+0%)	-2.35E+04	(+0%)	-2.53E+04	(+0%)
Net onsite combustion	-9.56E+04	(+0%)	-9.95E+04	(+0%)	-1.07E+05	(+0%)
Net formal management	-6.19E+06	(-0%)	-6.94E+06	(+0%)	-7.67E+06	(+0%)
Net Total	-6.31E+06	(-0%)	-7.06E+06	(+0%)	-7.80E+06	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 96: Smog Potential in kg O3 equivalent for Scenario 5.

5.3.7 DIM Scenario 6

Scenario 6 examines the impacts of \$0.10 increase in the incentive for re-refined base oil, from \$0.12 in 2013 to \$0.04 in 2014-2030. This has no impact on the amount of collected or uncollected used oil, increases 2030 re-refined base oil by 900,000 gallons, increases 2030 asphalt flux recovered by 100,000 gallons, and decreases 2030 recycled fuel oil by 1.1 million gallons. Results for all flows (in kg) shown in Table 97. Results for the life cycle impact assessment of the baseline are shown in Table 98 through Table 105.

Scenario 6						
[all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	11	(+0%)	11	(+0%)	12	(+0%)
Dumped or landfilled	103	(+0%)	107	(+0%)	115	(+0%)
<i>Formal Management</i>						
Used oil collected	378	(+0%)	377	(+0%)	380	(+0%)
Used oil reprocessed	349	(+0%)	348	(+0%)	351	(+0%)
<i>Secondary Products</i>						
Re-refined	65	(+4%)	67	(+4%)	72	(+4%)
Light fuels	141	(-0%)	141	(-0%)	141	(-0%)
RFO	11	(-20%)	7	(-31%)	3.9	(-47%)
Asphalt flux	95	(+0%)	96	(+0%)	96	(+0%)
Ethylene glycol	0.6	(-1%)	0.6	(-0%)	0.6	(-0%)

Percent change from baseline shown to the right of flow quantity
Table 97: Used oil and secondary product flows for Scenario 6.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 6:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	3.10E+06	(+0%)	2.86E+06	(+0%)	2.68E+06	(+0%)
Net onsite combustion	-4.64E+06	(+0%)	-4.81E+06	(+0%)	-5.20E+06	(+0%)
Net formal management	-9.57E+07	(-0%)	-9.65E+07	(-1%)	-1.00E+08	(-1%)
Net Total	-9.73E+07	(-0%)	-9.84E+07	(-1%)	-1.03E+08	(-1%)

Percent change from baseline shown to the right of flow quantity
Table 98: Global Warming Potential in kg CO₂ equivalent for Scenario 6.

[H ⁺ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	7.99E+04	(+0%)	8.25E+04	(+0%)	8.87E+04	(+0%)
Net onsite combustion	7.41E+05	(+0%)	7.71E+05	(+0%)	8.35E+05	(+0%)
Net formal management	-2.53E+07	(+0%)	-2.64E+07	(+0%)	-2.79E+07	(+0%)
Net Total	-2.45E+07	(+0%)	-2.56E+07	(+0%)	-2.70E+07	(+0%)

Percent change from baseline shown to the right of flow quantity
Table 99: Acidification Potential in H⁺ moles equivalent for Scenario 6.



[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.68E+05	(+0%)	2.78E+05	(+0%)	3.01E+05	(+0%)
Net onsite combustion	4.72E+03	(+0%)	4.90E+03	(+0%)	5.30E+03	(+0%)
Net formal management	-1.31E+03	(-6701%)	-4.24E+03	(-58%)	-7.27E+03	(-29%)
Net Total	2.71E+05	(-0%)	2.79E+05	(-1%)	2.99E+05	(-1%)

Percent change from baseline shown to the right of flow quantity

Table 100: Eutrophication Potential in kg N equivalent for Scenario 6.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.58E+09	(+0%)	1.64E+09	(+0%)	1.77E+09	(+0%)
Net onsite combustion	7.39E+07	(+0%)	7.67E+07	(+0%)	8.30E+07	(+0%)
Net formal management	1.69E+07	(-14%)	1.35E+07	(-20%)	9.57E+06	(-28%)
Net Total	1.67E+09	(-0%)	1.73E+09	(-0%)	1.86E+09	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 101: Ecotoxicity Potential in CTUeco for Scenario 6.

[cases]	2015		2020		2030	
Dumping & net landfill	8.16E-01	(+0%)	8.47E-01	(+0%)	9.16E-01	(+0%)
Net onsite combustion	4.70E-03	(+0%)	4.88E-03	(+0%)	5.28E-03	(+0%)
Net formal management	2.01E-01	(+0%)	2.00E-01	(+0%)	2.02E-01	(+0%)
Net Total	1.02E+00	(+0%)	1.05E+00	(+0%)	1.12E+00	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 102: Human Health (Cancer) Potential in cases for Scenario 6.

[cases]	2015		2020		2030	
Dumping & net landfill	1.37E+03	(+0%)	1.42E+03	(+0%)	1.53E+03	(+0%)
Net onsite combustion	6.76E+01	(+0%)	7.02E+01	(+0%)	7.59E+01	(+0%)
Net formal management	9.52E+00	(-24%)	5.93E+00	(-37%)	2.08E+00	(-65%)
Net Total	1.44E+03	(-0%)	1.49E+03	(-0%)	1.61E+03	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 103: Human Health (Non Cancer) Potential in cases for Scenario 6.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	3.44E+02	(+0%)	3.55E+02	(+0%)	3.81E+02	(+0%)
Net onsite combustion	4.34E+04	(+0%)	4.50E+04	(+0%)	4.87E+04	(+0%)
Net formal management	-1.16E+05	(-4%)	-1.22E+05	(-5%)	-1.31E+05	(-5%)
Net Total	-7.19E+04	(-6%)	-7.65E+04	(-7%)	-8.19E+04	(-7%)

Percent change from baseline shown to the right of flow quantity

Table 104: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 6.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-2.26E+04	(+0%)	-2.35E+04	(+0%)	-2.53E+04	(+0%)
Net onsite combustion	-9.56E+04	(+0%)	-9.95E+04	(+0%)	-1.07E+05	(+0%)
Net formal management	-6.19E+06	(-0%)	-6.94E+06	(+0%)	-7.67E+06	(+0%)
Net Total	-6.30E+06	(-0%)	-7.06E+06	(+0%)	-7.80E+06	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 105: Smog Potential in kg O3 equivalent for Scenario 6.

5.3.8 DIM Scenario 7

Scenario 7 examines impacts of creating \$0.10 recovered light fuel/marine distillate oil incentive in 2014-2030. This has no impact on the amount of collected or uncollected used oil, increases 2030 marine distillate oil/light fuels recovered by 400,000 gallons, increases 2030 asphalt flux recovered by 200,000 gallons, and decreases 2030 recycled fuel oil by 700,000 gallons (rounded). Results for all flows (in kg) shown in Table 106. Results for the life cycle impact assessment of the baseline are shown in Table 107 through Table 114.

Scenario 7 [all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	11	(+0%)	11	(+0%)	12	(+0%)
Dumped or landfilled	103	(+0%)	107	(+0%)	115	(+0%)
<i>Formal Management</i>						
Used oil collected	378	(+0%)	377	(+0%)	380	(+0%)
Used oil reprocessed	349	(+0%)	348	(+0%)	351	(+0%)
<i>Secondary Products</i>						
Re-refined	63	(-0%)	64	(-0%)	69	(+0%)
Light fuels	141	(+0%)	142	(+1%)	142	(+1%)
RFO	13	(-6%)	9	(-11%)	5	(-31%)
Asphalt flux	95	(+0%)	96	(+0%)	97	(+1%)
Ethylene glycol	0.6	(-0%)	0.6	(-0%)	0.6	(+0%)

Percent change from baseline shown to the right of flow quantity
Table 106: Used oil and secondary product flows for Scenario 7.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 7:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	3.10E+06	(+0%)	2.86E+06	(+0%)	2.68E+06	(+0%)
Net onsite combustion	-4.64E+06	(+0%)	-4.81E+06	(+0%)	-5.20E+06	(+0%)
Net formal management	-9.52E+07	(+0%)	-9.58E+07	(+0%)	-9.93E+07	(+0%)
Net Total	-9.67E+07	(+0%)	-9.77E+07	(+0%)	-1.02E+08	(+0%)

Percent change from baseline shown to the right of flow quantity
Table 107: Global Warming Potential in kg CO₂ equivalent for Scenario 7.

[H ⁺ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	7.99E+04	(+0%)	8.25E+04	(+0%)	8.87E+04	(+0%)
Net onsite combustion	7.41E+05	(+0%)	7.71E+05	(+0%)	8.35E+05	(+0%)
Net formal management	-2.53E+07	(+0%)	-2.64E+07	(+0%)	-2.78E+07	(+0%)
Net Total	-2.45E+07	(+0%)	-2.55E+07	(+0%)	-2.69E+07	(+0%)

Percent change from baseline shown to the right of flow quantity
Table 108: Acidification Potential in H⁺ moles equivalent for Scenario 7.



[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.68E+05	(+0%)	2.78E+05	(+0%)	3.01E+05	(+0%)
Net onsite combustion	4.72E+03	(+0%)	4.90E+03	(+0%)	5.30E+03	(+0%)
Net formal management	-3.52E+02	(-1732%)	-3.18E+03	(-18%)	-6.62E+03	(-18%)
Net Total	2.72E+05	(-0%)	2.80E+05	(-0%)	2.99E+05	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 109: Eutrophication Potential in kg N equivalent for Scenario 7.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.58E+09	(+0%)	1.64E+09	(+0%)	1.77E+09	(+0%)
Net onsite combustion	7.39E+07	(+0%)	7.67E+07	(+0%)	8.30E+07	(+0%)
Net formal management	1.90E+07	(-4%)	1.58E+07	(-6%)	1.10E+07	(-17%)
Net Total	1.67E+09	(-0%)	1.73E+09	(-0%)	1.86E+09	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 110: Ecotoxicity Potential in CTUeco for Scenario 7.

[cases]	2015		2020		2030	
Dumping & net landfill	8.16E-01	(+0%)	8.47E-01	(+0%)	9.16E-01	(+0%)
Net onsite combustion	4.70E-03	(+0%)	4.88E-03	(+0%)	5.28E-03	(+0%)
Net formal management	2.01E-01	(-0%)	2.00E-01	(-0%)	2.02E-01	(-0%)
Net Total	1.02E+00	(-0%)	1.05E+00	(-0%)	1.12E+00	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 111: Human Health (Cancer) Potential in cases for Scenario 7.

[cases]	2015		2020		2030	
Dumping & net landfill	1.37E+03	(+0%)	1.42E+03	(+0%)	1.53E+03	(+0%)
Net onsite combustion	6.76E+01	(+0%)	7.02E+01	(+0%)	7.59E+01	(+0%)
Net formal management	1.16E+01	(-6%)	8.28E+00	(-13%)	3.46E+00	(-41%)
Net Total	1.45E+03	(-0%)	1.50E+03	(-0%)	1.61E+03	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 112: Human Health (Non Cancer) Potential in cases for Scenario 7.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	3.44E+02	(+0%)	3.55E+02	(+0%)	3.81E+02	(+0%)
Net onsite combustion	4.34E+04	(+0%)	4.50E+04	(+0%)	4.87E+04	(+0%)
Net formal management	-1.12E+05	(-1%)	-1.18E+05	(-1%)	-1.28E+05	(-2%)
Net Total	-6.84E+04	(-1%)	-7.25E+04	(-2%)	-7.90E+04	(-4%)

Percent change from baseline shown to the right of flow quantity

Table 113: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 7.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-2.26E+04	(+0%)	-2.35E+04	(+0%)	-2.53E+04	(+0%)
Net onsite combustion	-9.56E+04	(+0%)	-9.95E+04	(+0%)	-1.07E+05	(+0%)
Net formal management	-6.19E+06	(-0%)	-6.94E+06	(-0%)	-7.67E+06	(+0%)
Net Total	-6.30E+06	(-0%)	-7.07E+06	(-0%)	-7.80E+06	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 114: Smog Potential in kg O3 equivalent for Scenario 7.

5.3.9 DIM Scenario 8

Scenario 8 shows model outputs for creating a \$0.10 incentive for recycled fuel oil production. This scenario does not change any outputs because this incentive does not affect the market equilibrium for re-refined versus virgin base oil or recovered light fuel/marine distillate oil versus ultra low-sulfur diesel. Graphs and tables for this scenario are therefore not shown, since quantities are the same as the baseline.

5.3.10 DIM Scenario 9

Scenario 9 addresses the statutory requirement to evaluate the impacts of the tiered fee structure for lube oil sales. The fee on virgin base lube oil is reduced to \$0.16 and the fee on re-refined base lube is increased to \$0.16 (in 2014-2030). This has no impact on the amount of collected or uncollected used oil, but decreases 2030 re-refined base oil by 1.1 million gallons (rounded), decreases 2030 asphalt flux recovered by 100,000 gallons, and increases 2030 recycled fuel oil by 1.3 million gallons (rounded). Results for all flows (in kg) shown in Table 115. Results for the life cycle impact assessment of the baseline are shown in 116 through Table 123.

Scenario 9 [all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	11	(+0%)	11	(+0%)	12	(+0%)
Dumped or landfilled	103	(+0%)	107	(+0%)	115	(+0%)
<i>Formal Management</i>						
Used oil collected	378	(+0%)	377	(+0%)	380	(+0%)
Used oil reprocessed	349	(+0%)	348	(+0%)	351	(+0%)
<i>Secondary Products</i>						
Re-refined	60	(-4%)	62	(-4%)	66	(-5%)
Light fuels	141	(+0%)	141	(+0%)	141	(+0%)
RFO	17	(+24%)	14	(+31%)	12	(+56%)
Asphalt flux	95	(-0%)	95	(-0%)	95	(-0%)
Ethylene glycol	0.7	(+2%)	0.7	(+2%)	0.6	(+0%)

Percent change from baseline shown to the right of flow quantity
Table 115: Used oil and secondary product flows for Scenario 9.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 9:

Note: Table headings are shaded to match the colors in the corresponding bar charts.



[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	3.10E+06	(+0%)	2.86E+06	(+0%)	2.68E+06	(+0%)
Net onsite combustion	-4.64E+06	(+0%)	-4.81E+06	(+0%)	-5.20E+06	(+0%)
Net formal management	-9.48E+07	(+1%)	-9.54E+07	(+1%)	-9.89E+07	(+1%)
Net Total	-9.64E+07	(+0%)	-9.74E+07	(+1%)	-1.01E+08	(+1%)

Percent change from baseline shown to the right of flow quantity

Table 116: Global Warming Potential in kg CO₂ equivalent for Scenario 9.

[H+ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	7.99E+04	(+0%)	8.25E+04	(+0%)	8.87E+04	(+0%)
Net onsite combustion	7.41E+05	(+0%)	7.71E+05	(+0%)	8.35E+05	(+0%)
Net formal management	-2.54E+07	(-0%)	-2.65E+07	(-0%)	-2.80E+07	(-0%)
Net Total	-2.45E+07	(-0%)	-2.56E+07	(-0%)	-2.70E+07	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 117: Acidification Potential in H+ moles equivalent for Scenario 9.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.68E+05	(+0%)	2.78E+05	(+0%)	3.01E+05	(+0%)
Net onsite combustion	4.72E+03	(+0%)	4.90E+03	(+0%)	5.30E+03	(+0%)
Net formal management	-3.52E+02	(-1732%)	-3.18E+03	(-18%)	-6.62E+03	(-18%)
Net Total	2.72E+05	(-0%)	2.80E+05	(-0%)	2.99E+05	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 118: Eutrophication Potential in kg N equivalent for Scenario 9.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.58E+09	(+0%)	1.64E+09	(+0%)	1.77E+09	(+0%)
Net onsite combustion	7.39E+07	(+0%)	7.67E+07	(+0%)	8.30E+07	(+0%)
Net formal management	2.31E+07	(+17%)	2.03E+07	(+21%)	1.76E+07	(+33%)
Net Total	1.67E+09	(+0%)	1.73E+09	(+0%)	1.87E+09	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 119: Ecotoxicity Potential in CTUeco for Scenario 9.

[cases]	2015		2020		2030	
Dumping & net landfill	8.16E-01	(+0%)	8.47E-01	(+0%)	9.16E-01	(+0%)
Net onsite combustion	4.70E-03	(+0%)	4.88E-03	(+0%)	5.28E-03	(+0%)
Net formal management	2.01E-01	(-0%)	2.00E-01	(-0%)	2.02E-01	(-0%)
Net Total	1.02E+00	(-0%)	1.05E+00	(-0%)	1.12E+00	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 120: Human Health (Cancer) Potential in cases for Scenario 9.

[cases]	2015		2020		2030	
Dumping & net landfill	1.37E+03	(+0%)	1.42E+03	(+0%)	1.53E+03	(+0%)
Net onsite combustion	6.76E+01	(+0%)	7.02E+01	(+0%)	7.59E+01	(+0%)
Net formal management	1.60E+01	(+28%)	1.31E+01	(+38%)	1.04E+01	(+77%)
Net Total	1.45E+03	(+0%)	1.50E+03	(+0%)	1.62E+03	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 121: Human Health (Non Cancer) Potential in cases for Scenario 9.



[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	3.44E+02	(+0%)	3.55E+02	(+0%)	3.81E+02	(+0%)
Net onsite combustion	4.34E+04	(+0%)	4.50E+04	(+0%)	4.87E+04	(+0%)
Net formal management	-1.06E+05	(+5%)	-1.11E+05	(+5%)	-1.19E+05	(+5%)
Net Total	-6.23E+04	(+8%)	-6.58E+04	(+8%)	-6.95E+04	(+9%)

Percent change from baseline shown to the right of flow quantity

Table 122: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 9.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-2.26E+04	(+0%)	-2.35E+04	(+0%)	-2.53E+04	(+0%)
Net onsite combustion	-9.56E+04	(+0%)	-9.95E+04	(+0%)	-1.07E+05	(+0%)
Net formal management	-6.18E+06	(+0%)	-6.94E+06	(+0%)	-7.68E+06	(-0%)
Net Total	-6.30E+06	(+0%)	-7.06E+06	(+0%)	-7.81E+06	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 123: Smog Potential in kg O3 equivalent for Scenario 9.

5.3.11 DIM Scenario 10

Scenario 10 addresses the statutory requirement to evaluate impacts of the tiered incentive structure for lube oil collection and re-refined base oil recovery. The do-it-yourself used lube oil incentive is reduced to \$0.16 and the \$0.2 incentive for re-refined base oil recovery is eliminated. This decreases 2030 lube oil collected by 1 million gallons, increases 2030 uncollected collectible do-it-yourself lube oil by 1 million gallons, decreases 2030 re-refined by 100,000 gallons, and decreases 2030 recycled fuel oil production by 700,000 gallons. Results for all flows (in kg) shown in Table 124. Percent change from baseline shown to the right of flow quantity

Table 124. Results for the life cycle impact assessment of the baseline are shown in Table 125 through Table 132.

Scenario 10 [all in million kg]	2015		2020		2030	
<i>Used Oil generation</i>						
Collectable used oil	446	(+0%)	446	(+0%)	452	(+0%)
<i>Informal Management</i>						
Onsite combustion	11	(+3%)	12	(+3%)	13	(+2%)
Dumped or landfilled	106	(+3%)	110	(+3%)	118	(+2%)
<i>Formal Management</i>						
Used oil collected	374	(-1%)	373	(-1%)	377	(-1%)
Used oil reprocessed	346	(-1%)	344	(-1%)	348	(-1%)
<i>Secondary Products</i>						
Re-refined	62	(-1%)	64	(-1%)	69	(-1%)
Light fuels	141	(-0%)	141	(-0%)	141	(+0%)
RFO	11	(-16%)	8	(-21%)	5	(-28%)
Asphalt flux	95	(-0%)	95	(-0%)	96	(-0%)
Ethylene glycol	0.6	(-1%)	0.6	(-0%)	0.6	(+0%)

Percent change from baseline shown to the right of flow quantity

Table 124: Used oil and secondary product flows for Scenario 10.

LIFE CYCLE IMPACT ASSESSMENT OF DIM SCENARIO 10:

Note: Table headings are shaded to match the colors in the corresponding bar charts.

[kg CO ₂ -Equiv.]	2015		2020		2030	
Dumping & net landfill	3.17E+06	(+2%)	2.92E+06	(+2%)	2.72E+06	(+2%)
Net onsite combustion	-4.78E+06	(-3%)	-4.94E+06	(-3%)	-5.32E+06	(-2%)
Net formal management	-9.40E+07	(+1%)	-9.47E+07	(+1%)	-9.84E+07	(+1%)
Net Total	-9.56E+07	(+1%)	-9.68E+07	(+1%)	-1.01E+08	(+1%)

Percent change from baseline shown to the right of flow quantity

Table 125: Global Warming Potential in kg CO₂ equivalent for Scenario 10.

[H+ moles-Equiv.]	2015		2020		2030	
Dumping & net landfill	8.20E+04	(+3%)	8.46E+04	(+2%)	9.05E+04	(+2%)
Net onsite combustion	7.63E+05	(+3%)	7.92E+05	(+3%)	8.54E+05	(+2%)
Net formal management	-2.50E+07	(+1%)	-2.61E+07	(+1%)	-2.76E+07	(+1%)
Net Total	-2.41E+07	(+2%)	-2.52E+07	(+1%)	-2.66E+07	(+1%)

Percent change from baseline shown to the right of flow quantity

Table 126: Acidification Potential in H+ moles equivalent for Scenario 10.

[kg N-Equiv.]	2015		2020		2030	
Dumping & net landfill	2.76E+05	(+3%)	2.85E+05	(+3%)	3.07E+05	(+2%)
Net onsite combustion	4.86E+03	(+3%)	5.03E+03	(+3%)	5.42E+03	(+2%)
Net formal management	-8.90E+02	(-4523%)	-3.59E+03	(-33%)	-6.44E+03	(-15%)
Net Total	2.80E+05	(+3%)	2.87E+05	(+2%)	3.06E+05	(+2%)

Percent change from baseline shown to the right of flow quantity

Table 127: Eutrophication Potential in kg N equivalent for Scenario 10.

[CTUeco]	2015		2020		2030	
Dumping & net landfill	1.62E+09	(+3%)	1.68E+09	(+3%)	1.81E+09	(+2%)
Net onsite combustion	7.61E+07	(+3%)	7.88E+07	(+3%)	8.49E+07	(+2%)
Net formal management	1.76E+07	(-11%)	1.46E+07	(-13%)	1.11E+07	(-16%)
Net Total	1.72E+09	(+3%)	1.77E+09	(+3%)	1.91E+09	(+2%)

Percent change from baseline shown to the right of flow quantity

Table 128: Ecotoxicity Potential in CTUeco for Scenario 10.

[cases]	2015		2020		2030	
Dumping & net landfill	8.40E-01	(+3%)	8.70E-01	(+3%)	9.37E-01	(+2%)
Net onsite combustion	4.84E-03	(+3%)	5.02E-03	(+3%)	5.40E-03	(+2%)
Net formal management	1.99E-01	(-1%)	1.98E-01	(-1%)	2.00E-01	(-1%)
Net Total	1.04E+00	(+2%)	1.07E+00	(+2%)	1.14E+00	(+2%)

Percent change from baseline shown to the right of flow quantity

Table 129: Human Health (Cancer) Potential in cases for Scenario 10.

[cases]	2015		2020		2030	
Dumping & net landfill	1.41E+03	(+3%)	1.46E+03	(+3%)	1.57E+03	(+2%)
Net onsite combustion	6.96E+01	(+3%)	7.21E+01	(+3%)	7.76E+01	(+2%)
Net formal management	1.02E+01	(-18%)	7.11E+00	(-25%)	3.68E+00	(-37%)
Net Total	1.49E+03	(+3%)	1.54E+03	(+3%)	1.65E+03	(+2%)

Percent change from baseline shown to the right of flow quantity

Table 130: Human Health (Non Cancer) Potential in cases for Scenario 10.

[kg PM10-Equiv.]	2015		2020		2030	
Dumping & net landfill	3.53E+02	(+3%)	3.64E+02	(+2%)	3.89E+02	(+2%)
Net onsite combustion	4.47E+04	(+3%)	4.62E+04	(+3%)	4.98E+04	(+2%)
Net formal management	-1.12E+05	(-1%)	-1.18E+05	(-1%)	-1.27E+05	(-1%)
Net Total	-6.75E+04	(+0%)	-7.14E+04	(-0%)	-7.65E+04	(-0%)

Percent change from baseline shown to the right of flow quantity

Table 131: Human Health (Criteria Air) Potential in kg PM10 equivalent for Scenario 10.

[kg O3-Equiv.]	2015		2020		2030	
Dumping & net landfill	-2.32E+04	(-2%)	-2.40E+04	(-2%)	-2.57E+04	(-2%)
Net onsite combustion	-9.85E+04	(-3%)	-1.02E+05	(-3%)	-1.10E+05	(-2%)
Net formal management	-6.12E+06	(+1%)	-6.87E+06	(+1%)	-7.59E+06	(+1%)
Net Total	-6.24E+06	(+1%)	-6.99E+06	(+1%)	-7.73E+06	(+1%)

Percent change from baseline shown to the right of flow quantity

Table 132: Smog Potential in kg O3 equivalent for Scenario 10.

5.4 DIM Scenario LCIA Graphs

Two types of graphical representations of the life cycle impact assessment (LCIA) results of the Direct Impacts Model scenarios are presented for each life cycle impact category. The first graph is a bar chart that shows the net impacts for each scenario for the years X and Y. The second is a waterfall graph of the impacts of the baseline that shows the contribution to the net impact made by each of the following life stage categories: dumping and net landfill; net onsite combustion; and net formal management. The first allows for a high-level analysis of the overall impacts across scenarios. The second provides insight into the relative contribution of each life stage group to the net impact for that category.

5.4.1 Global Warming Potential

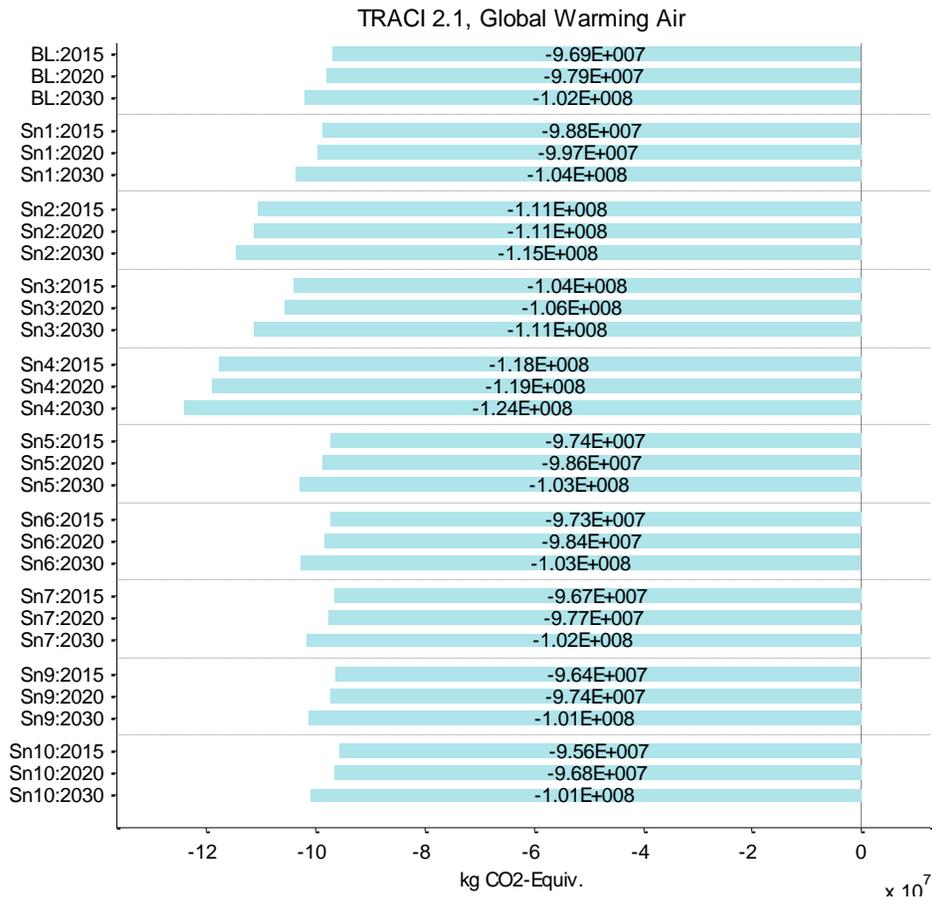


Figure 30: Net Global Warming Potential for all scenarios in kg CO₂ equivalent.

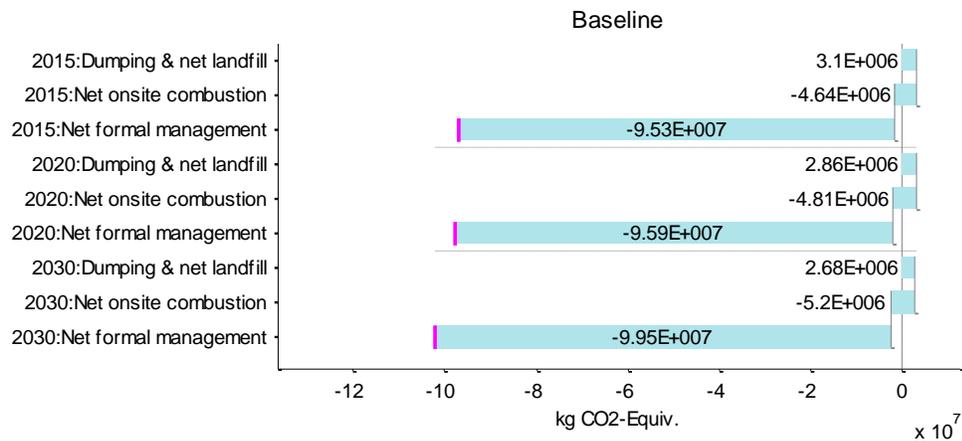


Figure 31: Global Warming Potential of Baseline life stages in kg CO₂ equivalent.

5.4.2 Acidification Potential

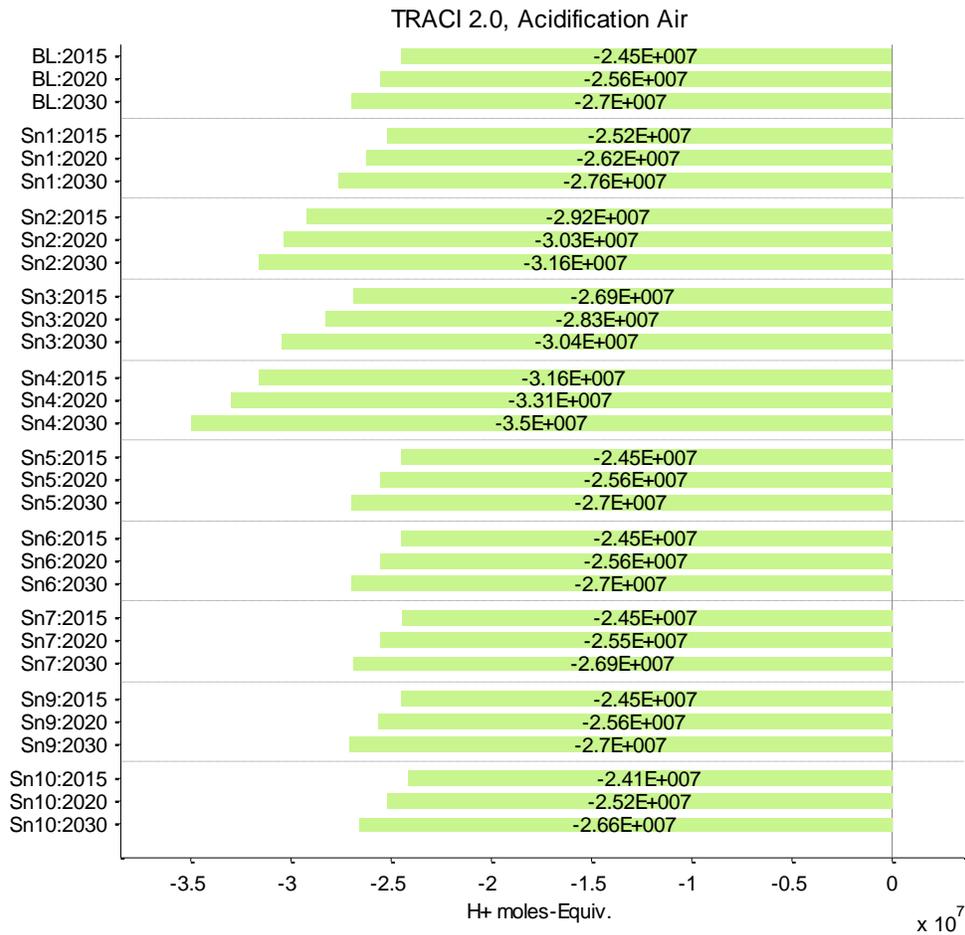


Figure 32: Net Acidification Potential for all scenarios in H+ moles equivalent.

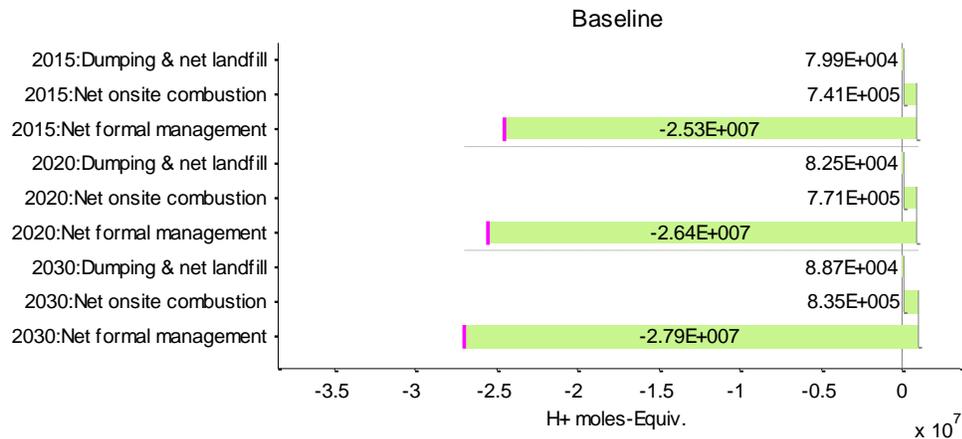


Figure 33: Acidification Potential of Baseline life stages in H+ moles equivalent.

5.4.3 Eutrophication Potential

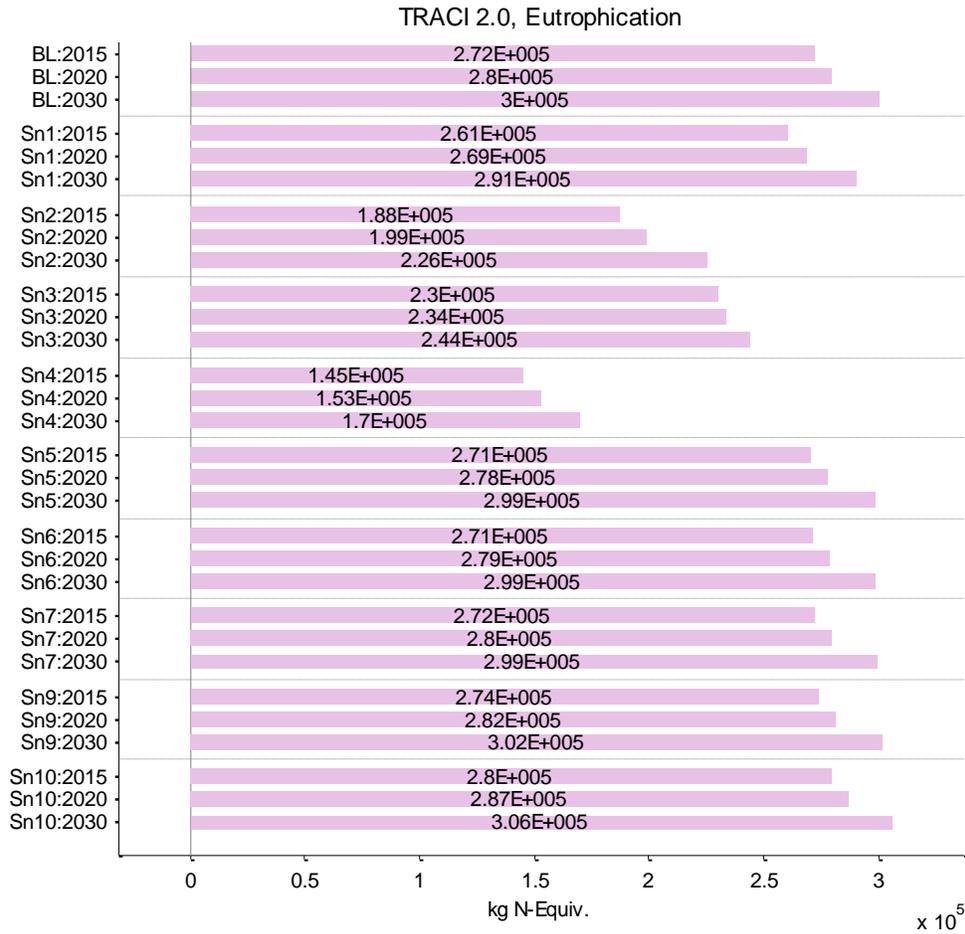


Figure 34: Net Eutrophication Potential for all scenarios in kg N equivalent.

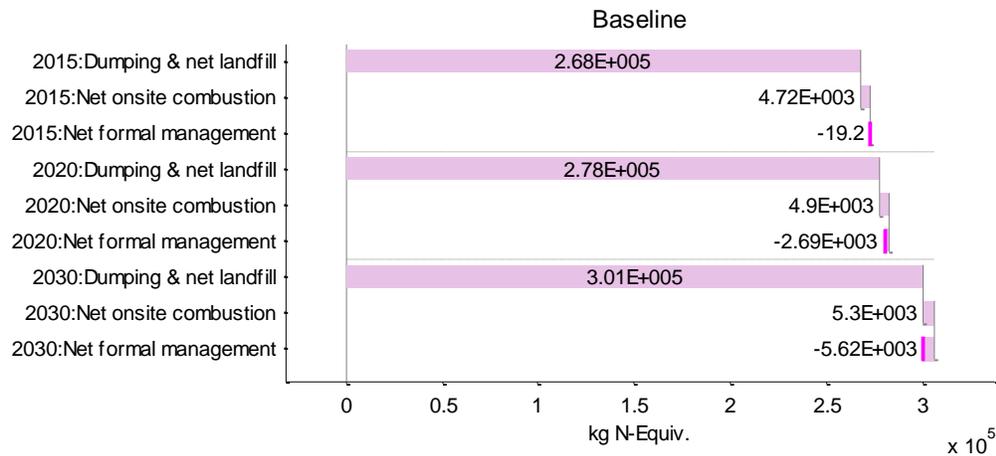


Figure 35: Eutrophication Potential of Baseline life stages in kg N equivalent.

5.4.4 Ecotoxicity Potential

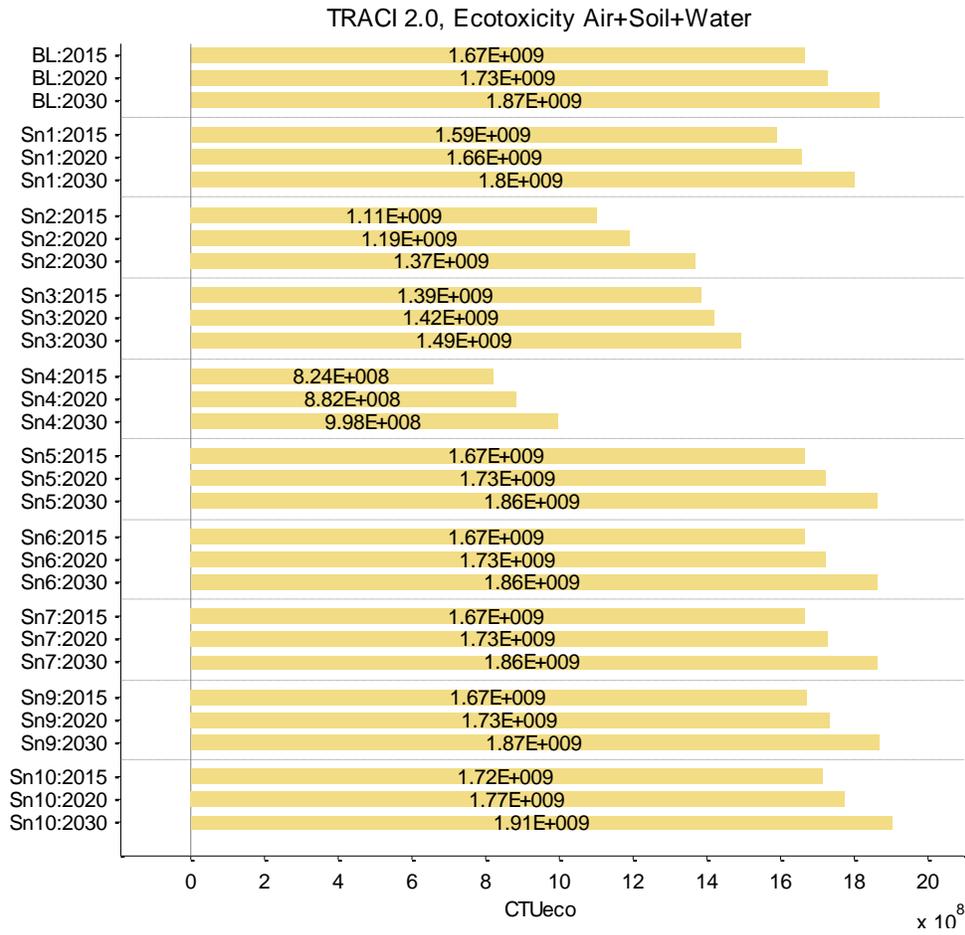


Figure 36: Net Ecotoxicity Potential for all scenarios in CTUeco equivalents.

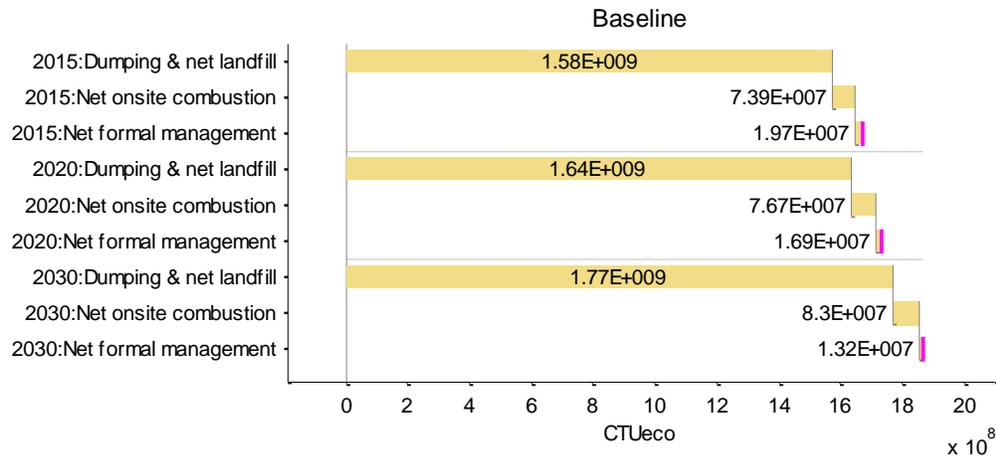


Figure 37: Ecotoxicity Potential of Baseline life stages in CTUeco equivalents.

5.4.5 Human Health Cancer Potential

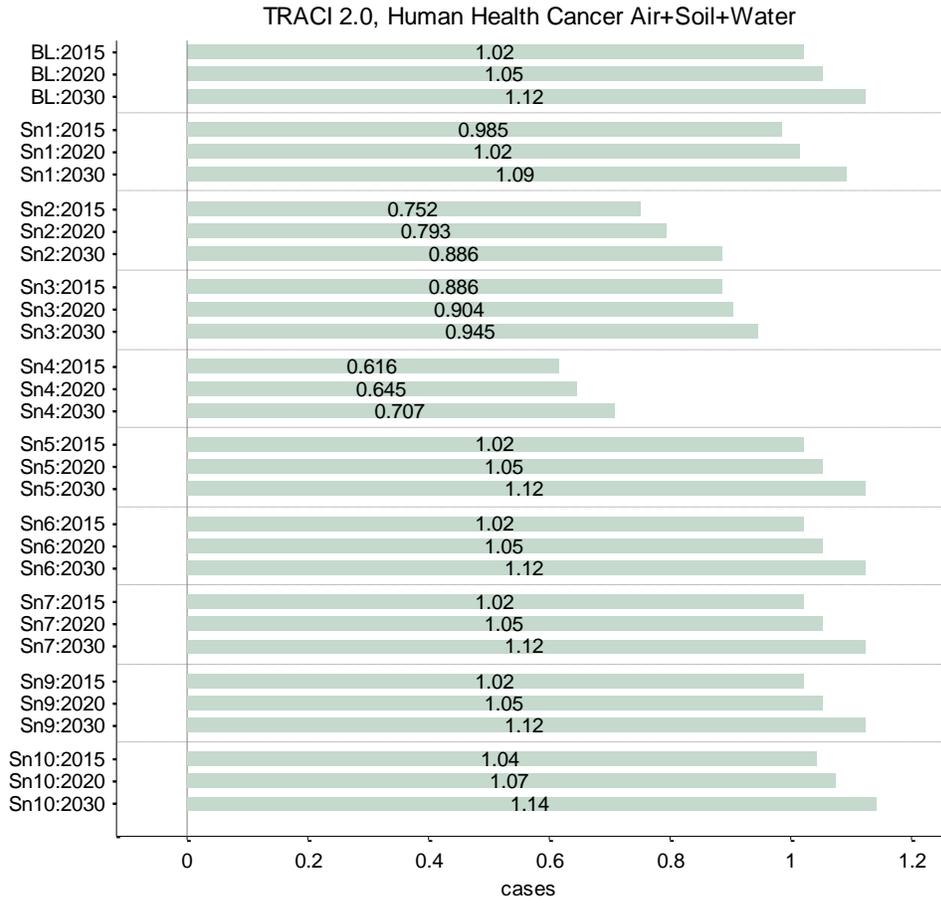


Figure 38: Net Human Health Cancer Potential for all scenarios in cases.

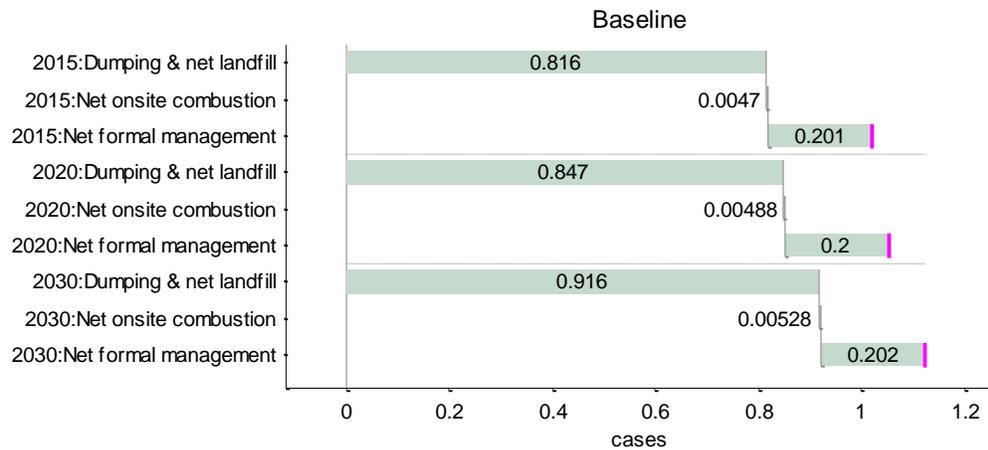


Figure 39: Human Health Cancer Potential of Baseline life stages in cases.

5.4.6 Human Health Non-Cancer Potential

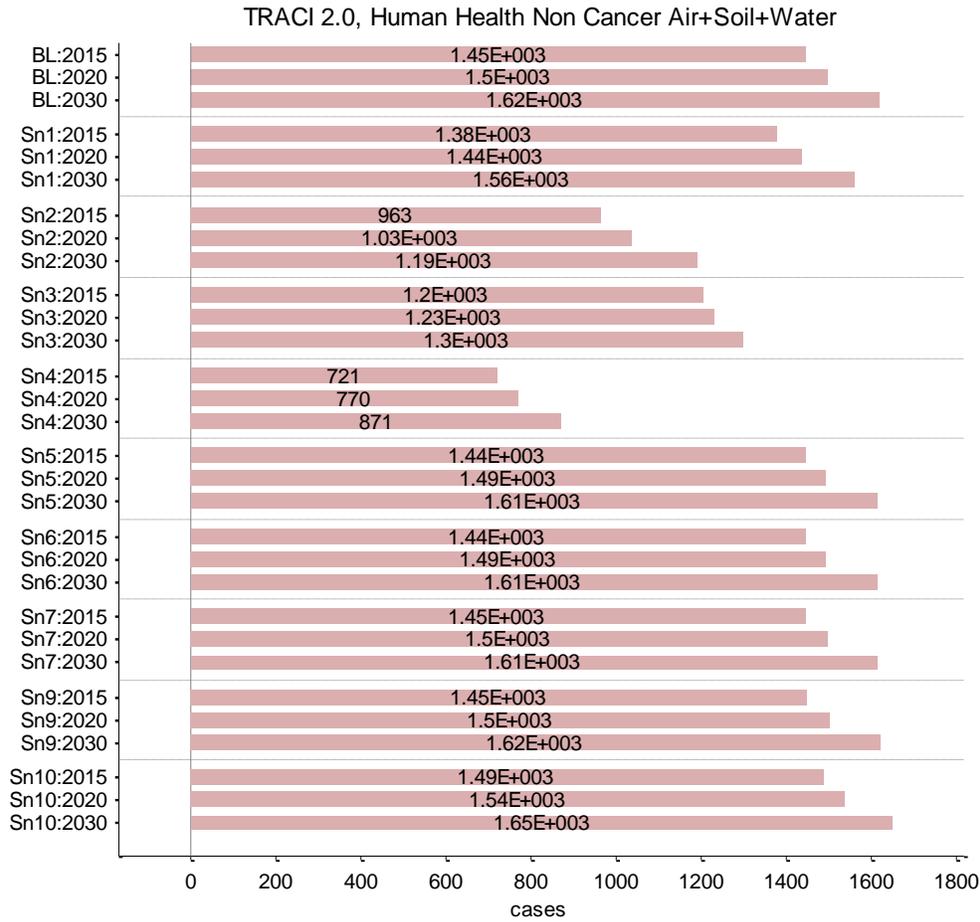


Figure 40: Net Human Health Non-Cancer Potential for all scenarios in cases.

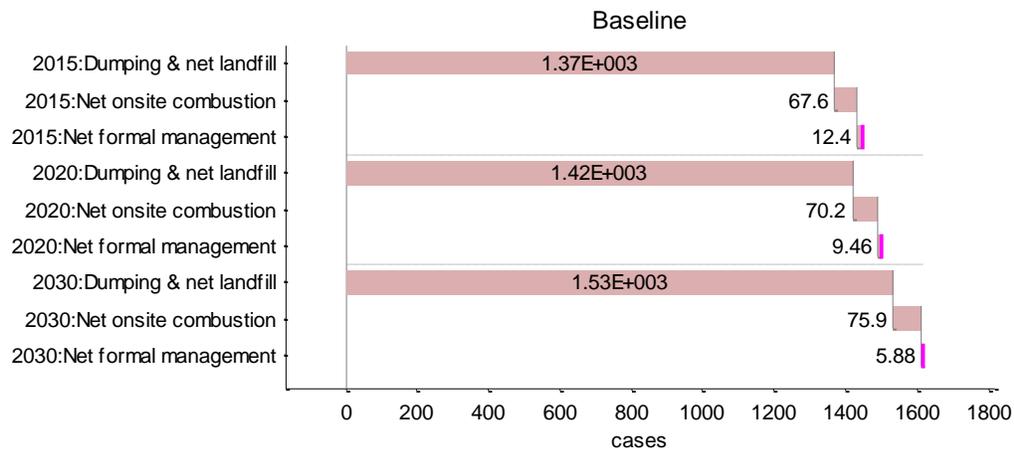


Figure 41: Human Health Non-Cancer Potential of Baseline life stages in cases.

5.4.7 Human Health Criteria Air Potential

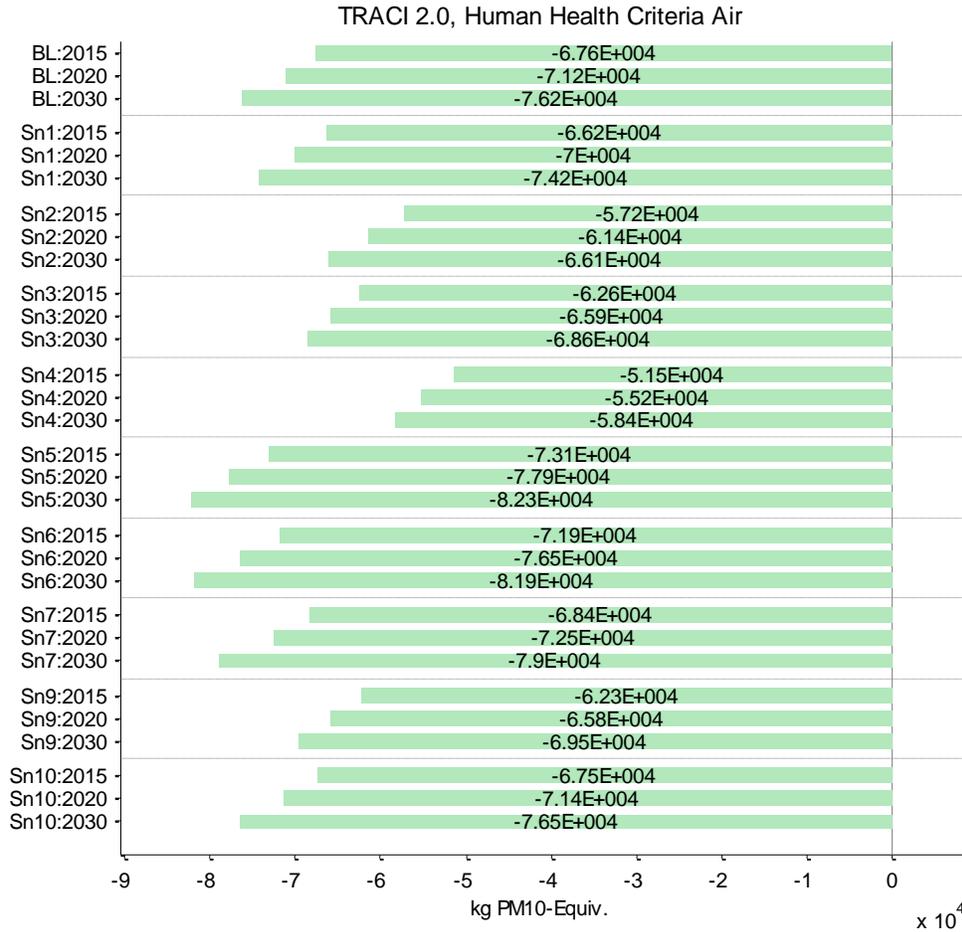


Figure 42: Human Health Criteria Potential for all scenarios in kg PM10 equivalent.

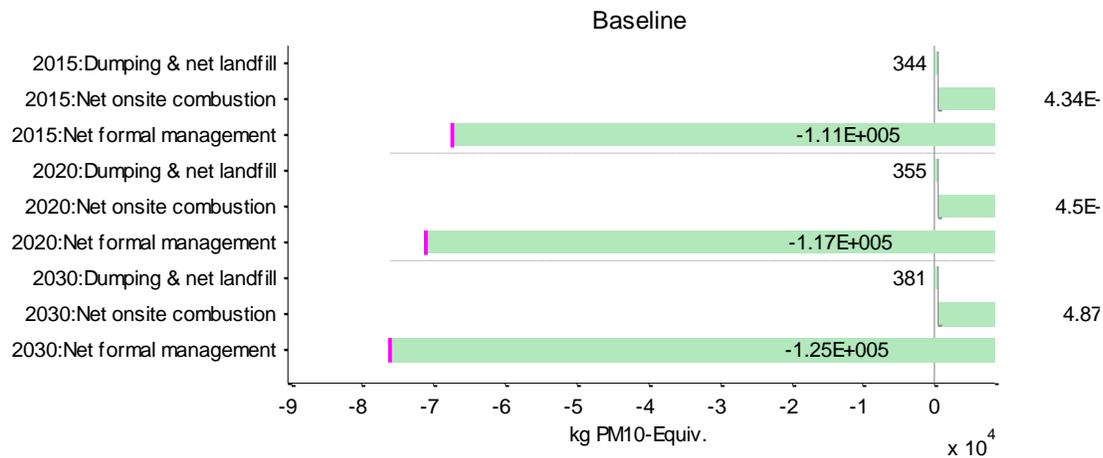


Figure 43: Human Health Criteria Potential of Baseline life stages in kg PM10 equivalent.

5.4.8 Smog Potential

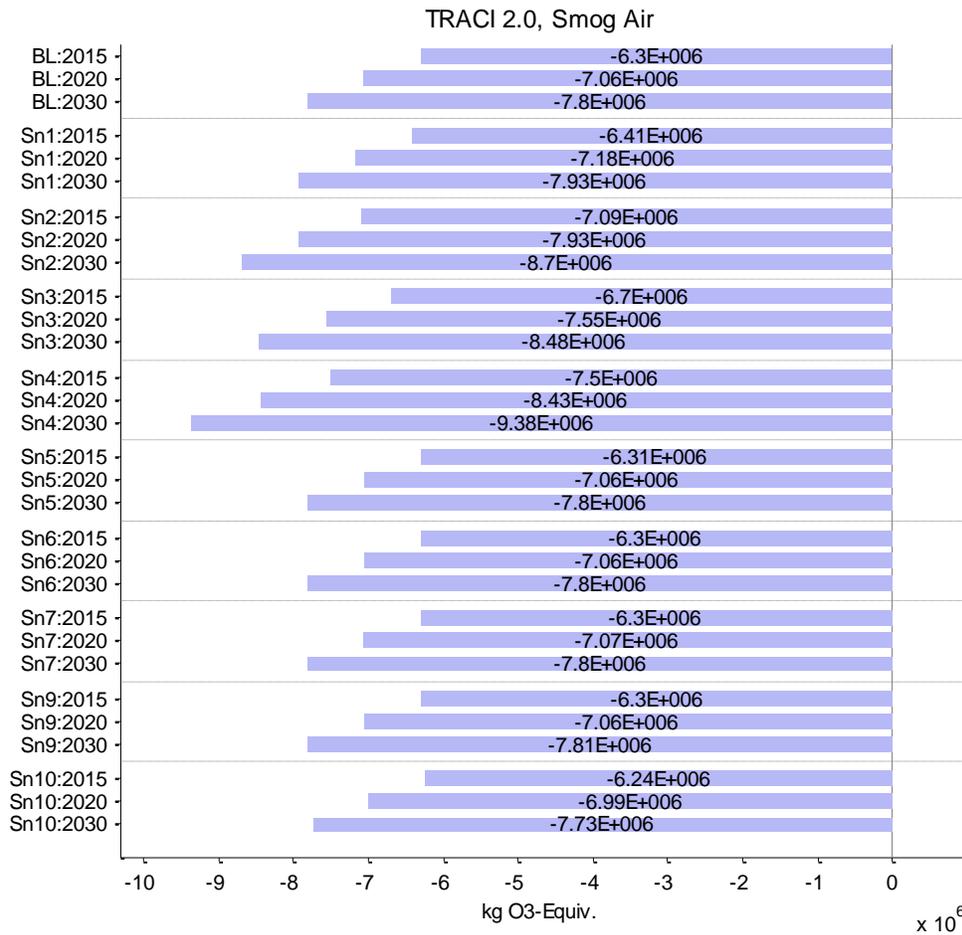


Figure 44: Net Smog Potential for all scenarios in kg O₃ equivalent.

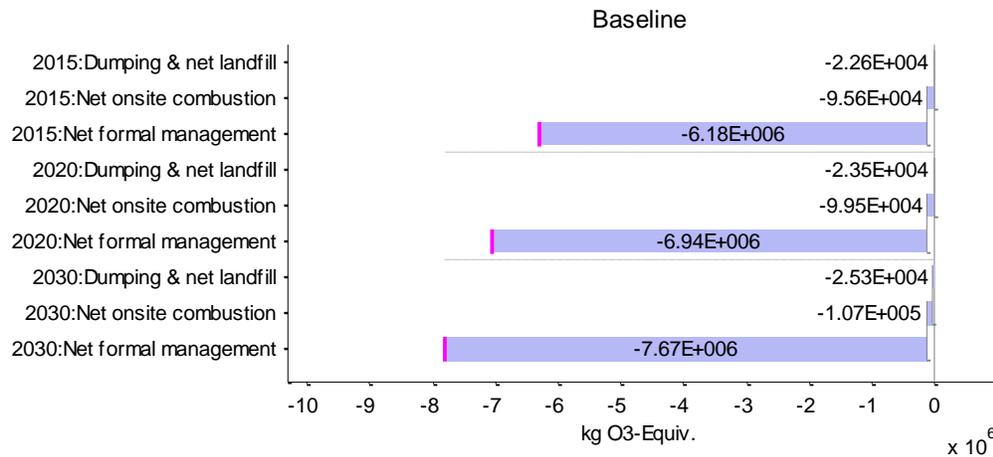


Figure 45: Smog Potential of Baseline life stages in kg O₃ equivalent.

5.5 Statutory Scenarios

SB 546 requires CalRecycle to “evaluate the positive and negative impacts of the testing requirements established in Section 25250.29 of the Health and Safety Code, the tiered fee on lubricating oil established in Section 48650, and the tiered incentive payments established in Section 48652, on used oil collection rates.”

The effects of the new testing requirements are primarily economic. There is no significant environmental burden from the testing requirements themselves, although changes in the operations of industry participants may have had a net environmental impact. In the current model, changes brought about by economic factors are represented in the inputs from the Direct Impacts Model.

Data from the used oil material flow analysis could reflect changes in exports of used oil from California or in other flows, but it would be difficult to attribute any observations to SB 546. The coverage period of the material flow analysis, from 2007 to 2011, is too brief to yield insights about the effects of specific regulatory changes.

6 Life Cycle Interpretation

6.1 Identification of Significant Issues

6.1.1 Informal Management

Informal management consists of three different used oil fates. Used oil could simply be dumped on soil or into sewers or storm drains, it could be landfilled, or it could be used as a fuel on-site. Dumping causes large impacts in the categories of eutrophication, ecotoxicity, and human health cancer and non-cancer than the other informal management routes. In fact, dumping dominates the impacts from the entire used oil management system in ecotoxicity, and human health cancer and non-cancer. On the other hand, it causes relatively small climate change impacts and negligible impacts in the categories of acidification, human health criteria air, and smog creation.

Landfilling, which assumes no leaching of landfilled used oil, has negligible impacts in all impact categories. A shift from dumping to landfill reduces all impacts with the exception of climate change and smog creation, both of which are impacted by the assumption that some landfilled waste would be incinerated. On-site combustion is similar to the recycled fuel oil disposition route, but is assumed to have poorer emission control. As a result the balance between used oil combustion impacts and avoided impacts from displaced fuel production and combustion is less favorable than in the case of recycled fuel oil. A shift toward on-site combustion from dumping leads to increases in acidification and criteria pollutants due to combustion emissions, but a decrease in all other categories due to displaced emissions.

The most significant issue regarding informal used oil management is that a shift from formal to informal management significantly increases environmental impacts in all studied categories. As a result, any decision or action that moves used oil from informal to formal management will reduce environmental impact across all categories.

6.1.2 Formal Management

The formal management route consists of collection and waste disposal, used oil reprocessing, use of the secondary products, and avoided production and use of displaced products. Used oil reprocessing consists of re-refining, distillation, and recycled fuel oil production.

With the exception of human health cancer, the impacts of collection and waste disposal are small compared to the other stages. With the exception of re-refining, the environmental impacts from formal used oil management are dominated by combustion process impacts, both incurred and avoided. Impacts from reprocessing are typically small compared to combustion and are typically smaller than avoided impacts from displaced refinery production processes. Frequently, incurred and avoided combustion impacts are similar or very similar. As a result, the net environmental benefits of used oil reprocessing come mostly from avoided production processes.

It is important to keep in mind that the activity levels of the extreme scenarios do not account for any technical, economic, logistical, capacity or feasibility constraints. Nevertheless, the following observations can be made by analyzing the results of the base year and the extreme reprocessing scenarios in their default parameter settings:

- All three disposition routes generate net reductions in global warming potential, acidification potential, and smog creation potential.

- In addition, re-refining generates net reductions in eutrophication potential, ecotoxicity potential, human health non-cancer potential, and human health criteria air potential.
- In addition, distillation generates net reductions in eutrophication potential, and human health criteria air potential.
- Re-refining generates the largest net reductions in global warming potential, eutrophication potential, ecotoxicity potential, human health non-cancer potential, and human health criteria air potential.
- Recycled fuel oil generates the largest net reductions in acidification potential. Although both recycled fuel oil and marine distillate oil can be expected to have the same sulfur content, only recycled fuel oil is burned in facilities with potentially high sulfur retention.
- All three disposition routes have about the same net impact in human health cancer potential and smog creation potential.
- The net impacts in eutrophication potential in the extreme recycled fuel oil scenario are driven by phosphorus emissions during recycled fuel oil combustion. This finding depends on both the phosphorus content of used oil and the assumed retention rate of phosphorus in combustion. The default assumption of 50 percent was made in the absence of any corroborating data. The range of retention rates studied in sensitivity analysis was 0-99 percent.
- The net impacts in ecotoxicity potential in the extreme recycled fuel oil scenario are driven by zinc emissions during recycled fuel oil combustion. This finding relies on the characterization factor for zinc emissions found in USEtox.
- The net impacts in human health non-cancer potential in the extreme recycled fuel oil scenario are driven by zinc emissions during recycled fuel oil combustion.
- All disposition routes have better environmental performance in all impact categories than used oil dumping.
- Many impact indicator results are driven by a few or even a single elementary flow. This is particularly true for toxicity impact categories.
- Sensitivity results for human health cancer potential are dominated by non-methane volatile organic compounds emitted during combustion,

A life cycle assessment of California's used oil management system contains a considerable amount of uncertainties and requires a multitude of assumptions. Sensitivity analyses of six sets of important assumptions have been integrated into the main results. The main results are thus reported in six sets of ranges, rather than point values, based on these sensitivity analyses. The following are some important observations regarding these result ranges:

- Different reverse logistics assumptions have a significant effect on the degree of impacts in global warming potential and smog creation potential; however, the changes are not large enough to influence overall life cycle assessment results.

- Assumptions about the level of non-methane volatile organic compounds and polycyclic aromatic hydrocarbons emissions only impact human health cancer potential and smog creation potential. The main driver of human health cancer potential in all disposition routes is non-methane volatile organic compound emissions. This is an area where the inventory model is very weak. Better characterization of organic emissions from combustion of used oil co-products and displaced products is an urgent research need if human health cancer potential impacts are of interest.
- All net negative impact assessment results depend on the assumption that primary production is displaced through recycling. If this assumption is waived, re-refining outperforms the other routes in all categories because most used oil co-products from re-refining are not combusted, and thus the route has the lowest forward (attributional) impacts.
- Assumptions about recycled fuel oil displacement have dramatic impacts on the global warming potential, acidification potential, human health criteria air potential, and smog creation potential of the recycled oil's disposition route. Different displacement assumptions can lead to different rank ordering of the three formal disposition routes in these impact categories.
- The net impacts of the recycled fuel oil disposition route are very sensitive to emission retention rate assumptions for the categories eutrophication potential, ecotoxicity potential, human health non-cancer potential, and human health criteria air potential. However, different retention rate assumptions do not lead to different rank ordering of disposition routes in these impact categories.
- The assumed level of methane leakage during natural gas production and distribution has a significant impact on the global warming potential of the recycled fuel oil disposition route. It can lead to different rank ordering of disposition routes in this impact category.
- Different used oil compositions have a relatively small impact on the results. Different used oil compositions do not lead to different rank ordering of disposition routes in any impact category.

6.1.3 DIM Scenarios

The Direct Impacts Model scenarios are 10 variations on the 20-year baseline (2010-2030). The mass flow inventory inputs for all years following 2010 are the results of the economic contractor's model. No other changes to the life cycle assessment model are made in these scenarios. In general, the scenarios result in a change in the amount of used oil that is collected and/or that ends up going to different disposition routes.

All 10 scenarios report the same amount of collectable used oil, which increases slightly from 446 million gallons to 452 million gallons between 2015 and 2030. In scenarios 1, 2, 3, and 4, informal management decreases and formal management increases with respect to the baseline, with the largest differences being found in scenario 4. Scenarios 5, 6, 7, 9, and 10 show no change in the amount of oil being informally or formally managed relative to the baseline. Scenarios 1, 2, 3, 4, and 9 all show an increase in the amount of recycled fuel oil being produced, whereas 5, 6, 7, and 10 all show a decrease in the amount of recycled fuel oil being produced relative to the baseline. Scenarios 1, 2, 3, 4, and 5 all show an increase in the amount of

secondary base oil being produced, whereas scenarios 6, 7, 9, and 10 all show a decrease in secondary base oil relative to the baseline. The amount of secondary marine distillate oil being produced does not appear to change significantly in any scenario.

The net results for all scenarios in all years for global warming potential, acidification potential, human health criteria air potential, and smog creation potential are negative, meaning that the used oil system as a whole has a net benefit for the environment in all of these categories, no matter what scenario or year is looked at. The net results for all scenarios in all years for eutrophication potential, ecotoxicity potential, human health cancer potential, and human health non-cancer potential are positive, meaning used oil system as a whole has a net impact on the environment in all of these categories, no matter what scenario or year is looked at.

However, it is important to note that in every single impact category, the most environmentally beneficial scenario is number 4, in which informal management is decreased the most (~ -50 percent) and formal management is increased the most (~ +18 percent) relative to the baseline. This emphasizes the importance of increased collection and reprocessing rates relative to on-site combustion and dumping or landfilling. The difference is particularly marked in instances in which the baseline contribution analysis shows that impacts are dominated by improper disposal. Another interesting observation is that in every instance in which impacts are dominated by improper disposal, the net impacts for all scenarios are positive, but for all other impact categories the net impacts for all scenarios are negative.

Since several inputs to the used oil system are changing at once in the Direct Impacts Model scenarios, it is difficult to draw absolute conclusions regarding the correlation between any one disposition route and the change in impacts relative to the baseline. The advantage of the Direct Impacts Model scenarios is to show the relative impacts of different realistic and economically driven changes to the used oil management system. Absolute differences in impacts between the disposition routes can more clearly be seen in the extreme scenarios. The life cycle assessment impacts of the Direct Impacts Model scenarios are most useful when viewed in the context of the economic incentives and potential policy changes upon which they are based.

6.2 Other Model Uncertainties

6.2.1 Toxicity Impact Assessment

Calculation of potential adverse environmental impacts due to toxic emissions is an exceedingly complex and highly uncertain task. In standard life cycle assessment, an impact assessment methodology consists of a set of categories, each of which comprises a list of elementary flow characterization factors. Potential impacts are computed by first determining the quantity of a substance emitted (life cycle inventory, or LCI result), multiplying each substance total by a characterization factor for a given impact category, and summing the products to determine a category score (life cycle impact assessment result, or LCIA result).

Table 133 shows a simple hypothetical example of life cycle impact assessment for global warming potential. Inaccuracies in this process can occur at the inventory step, at the characterization step, or as a combination of the two.

Elementary Flow units	Total Emission (LCI results) kg	Characterization Factor kg CO2 eq. / kg flow	Category Score kg CO2 eq.
Carbon Dioxide	3.2	1	3.2
Methane	0.016	25	0.4
Nitrous Oxide	0.0054	290	1.566
Total (LCIA result):			5.2 kg CO2 equiv.

Table 133: Hypothetical example case to illustrate life cycle impact assessment.

Inaccuracies in inventory analysis arise from uncertainties in the activity levels of processes, and in the quantities of emissions that occur during the operation of a process. These are commonly addressed during life cycle inventory development and parametric sensitivity analysis, as was done in previous sections of this report. Inaccuracies in the characterization step are more fundamental and arise from the difficulty of quantifying environmental impact generally. The characterization factor is meant to describe how strongly a given flow contributes to a given source of environmental stress by comparing it to a reference compound. The third form of inaccuracy comes from the intersection of the other two forms. In order for a particular flow to contribute to a given impact category, the flow must be present in the inventory and also present in the characterization model. Omission of either will result in zero contribution of the flow to the category score.

For instance, when computing smog potential, a naïve impact characterization model may provide characterization factors for nitrogen monoxide (NO), nitrogen dioxide (NO₂), and nitrogen trioxide (NO₃); if a given process inventory only reports “oxides of nitrogen (NO_x),” then the process will generate zero contribution to the smog category score, even though nitrogen oxides are being emitted, because of a mismatch between the inventory model and the impact assessment model.

In the example in Table 133, the goal is to quantify the potential contribution to global warming arising from emissions. There is a straightforward relationship between the chemical species emitted and its contribution to the atmosphere’s capacity to trap solar energy. Chemical species are characterized in terms of their potency relative to carbon dioxide; the result is given in terms of an equivalent amount of carbon dioxide. Importantly, a scientific consensus exists about both the *identity* of these chemicals and their *relative potency* with respect to global warming. As a result, every life cycle impact assessment methodology includes a characterization model for global warming that is consistent with this consensus understanding.

As with global warming, chemistry relating to acidification, smog, and many other impact categories is well enough understood, and reporting of emissions sufficiently mature, that errors are rare. For non-toxicity impact categories the number of significant elementary flows is often small, so the completeness of life cycle inventory data can be reviewed manually.

The same cannot be said of toxicity assessment. Both the identities of potentially toxic chemicals and their relative potency with regard to toxicity are highly uncertain and controversial. Inventory data sets are often generated independently under a wide range of conditions; consequently they may report different sets of emissions or report them inconsistently. There are several toxicity



impact assessment methodologies available; all of them include a wide variability in the substances characterized, the routes or pathways of environmental fate and transport, the toxicity endpoints (ecosystem effects, carcinogenicity, non-carcinogenic adverse health effects) and in the characterization of the severity of potential impacts.

Because toxicity impacts are of prime importance to this study, it was desirable to include toxicity impact characterization despite its high uncertainty. Every reasonable effort was made to include key toxic emissions in a consistent way across inventory data sources. This study uses the TRACI 2.0 life cycle impact assessment methodology, which adopts the USEtox toxicity model. USEtox was developed out of the need to address the above-described uncertainties. Though USEtox is a consensus model and makes great progress in reducing fundamental uncertainties in toxicity impact assessment, it is still itself highly uncertain.

In order to evaluate the robustness of study results with regard to toxicity, impact assessment results were computed under a variety of other toxicity life cycle impact assessment methodologies, and the sensitivity of the model under these different methodologies was compared. The methods used for comparison differ in fundamental ways from the TRACI 2.0 method, and so category scores cannot be compared directly or ratiometrically; however, their sensitivity to model changes can be compared. These comparisons are presented in the following sections. For ecotoxicity categories, the three individual TRACI 2.0 categories (Ecotoxicity arising from emissions to air, water, and soil respectively) are compared against the CML (November 2010 edition) and ReCiPe (version 1.07) impact assessment methods, each of which considers midpoint toxicity at freshwater, marine, and terrestrial midpoints. For human health toxicity, TRACI 2.0 is the only methodology that distinguishes among air, water, and soil emissions, so these were aggregated for comparison to the others. The TRACI 2.0 aggregated categories for cancer and non-cancer effects are compared against CML human toxicity potential, ReCiPe Human toxicity potential, and Impact 2002+ version 2.1 (IO2+ v 2.1) cancer and non-cancer effects, respectively. All comparison methods are midpoint methods.

6.2.2 Informal Management – Toxicity Sensitivity

First, the ecotoxicity impacts of the informal management scenarios were considered. The results are shown in Figure 46, with comparison categories on the top and reference (TRACI 2.0) categories on the bottom. Figure 47 shows a comparison of human health toxicity endpoints. A comparison of the two ends of each bar will indicate the relative significance of combustion versus dumping (circle indicators always represent a 50 percent onsite combustion mix, while x's indicate 90 percent dumping and 10 percent onsite combustion).

Figure 46 shows generally that there is not a significant difference in outcomes across ecotoxicity impact assessment methodologies. All methods show that management has superior performance to informal management, and almost all indicate that on-site combustion is less damaging than dumping. TRACI 2.0 air is the only category for which dumping is less damaging than combustion from a toxicity perspective; but this finding is unremarkable because dumping has no direct air emissions. Reductions in this category are made up for by increases in the others. TRACI 2.0 air emissions have no direct analogue in the other methods; the burdens from air emissions are distributed among the other endpoints. In ReCiPe as well as TRACI, terrestrial impacts (from dumping to soil) are the greatest in magnitude; in CML, by contrast, marine emissions have the greatest magnitude. This characteristic is well-known about the CML methodology and has to do with its handling of heavy metals, which are assumed to persist



indefinitely. The controversy surrounding long-term ecotoxic effects of metals has not yet been resolved in USEtox, and so conclusive interpretation of these results is not possible.

In Figure 47, the results are less consistent. All models agree only that formal management is superior to informal management. The ReCiPe human toxicity indicator is the only one to show that dumping is less damaging than combustion, suggesting that it applies higher weights to air emissions than the others. Impact 2002+ shows very significant avoided burdens from formal management, but this seems likely to indicate an under-valuation of adverse impacts from dumping rather than an over-valuation of avoided burdens.

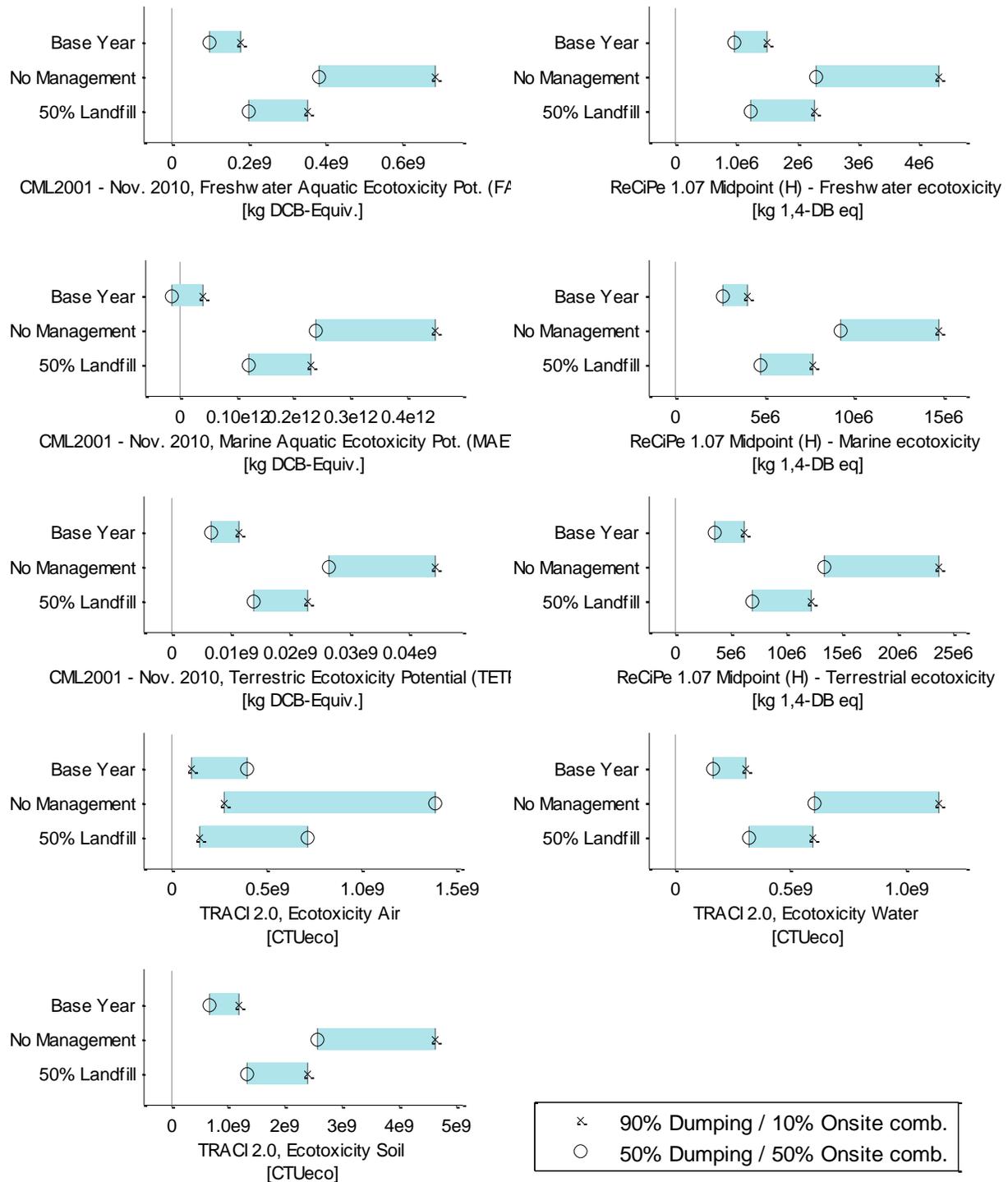
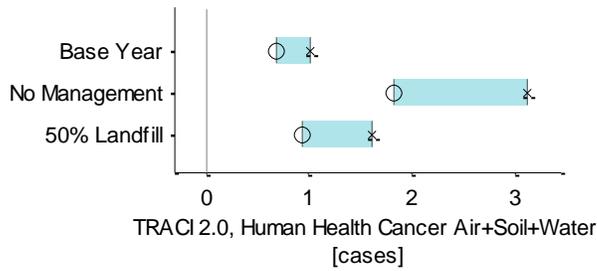
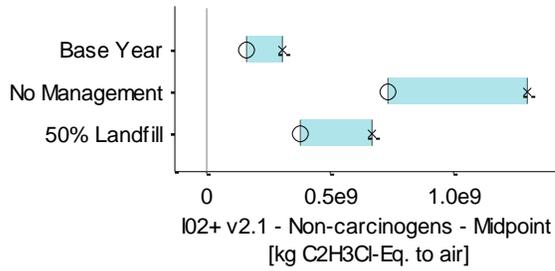
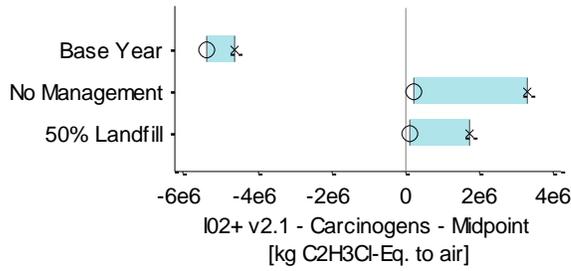
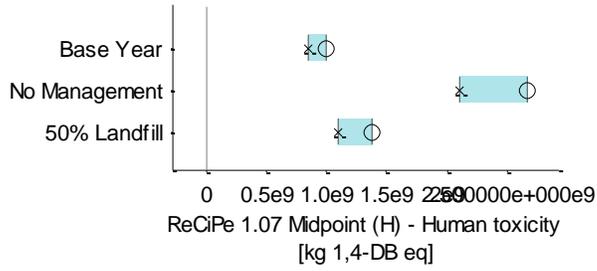
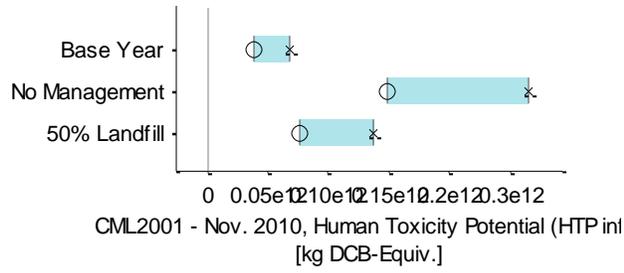
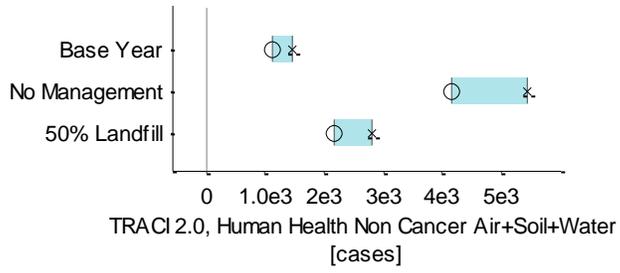


Figure 46: Comparison of ecotoxicity indicator scores resulting from informal management scenarios.





- × 90% Dumping / 10% Onsite comb.
- 50% Dumping / 50% Onsite comb.

Figure 47: Comparison of human health toxicity indicator scores resulting from informal management scenarios.

6.2.3 Base Case and Extremes – Toxicity Sensitivity

Three sensitivity ranges from Section 5.2 with bearing on toxicity were chosen as test cases: SA1 Retention rates; SA3 recycled fuel oil displacement; and SA6 used oil composition. For each sensitivity case, impact assessment results were computed for all comparison cases and shown together so that the relative significance of the changes in each category would be visible. The same nine ecotoxicity and six human health categories and impact models are shown as in the informal management study.

Figure 48 shows ecotoxicity scores and Figure 49 shows human health toxicity scores for the Retention Rate sensitivity analysis. Figure 50 and Figure 51 show scores for the recycled fuel oil displacement sensitivity analysis. Figure 52 and Figure 53 show scores for the used oil composition sensitivity analysis.

Unsurprisingly, the re-refining case shows no detectable sensitivity to combustion emission retention rates. The marine distillate oil and recycled fuel oil scenarios, however, behave differently depending on life cycle impact assessment method used. In the reference case, impacts from emissions to air have by far the greatest magnitude; emissions to water and soil do not change in the sensitivity case and are smaller in any case. Under ecotoxicity indicators CML is the only method to show significant sensitivity in the marine distillate oil case; in this case, the low-retention-rate scenario has the lowest impacts, implying that the range is due to avoided emissions and not forward emissions. It is likely that No. 2 distillate oil contains one or several metal compounds in the current composition model that are significant in CML but not in TRACI 2.0, the emissions of which are increased under a low-retention-rate scenario and are subsequently avoided through the combustion of marine distillate oil.

The CML method also generates a rank reversal relative to the base year model. Using TRACI 2.0, marine distillate oil and ReRe are shown to have lower or negative environmental impacts versus recycled fuel oil. However, using the CML indicator with default assumptions, recycled fuel oil is the route with lower impacts. CML indicators also present two cases (freshwater aquatic ecotoxicity in the base year route; marine aquatic ecotoxicity in the recycled fuel oil route) in which results under the default retention rate assumption are not bounded by the low and high retention rate assumptions, indicating a complex relationship between incurred and avoided impacts that would require further study to evaluate. Under ReCiPe, results are highly similar to the TRACI 2.0 results, except that in the high-retention-rate limit, all three routes are indistinguishable. Thus one finding of the study, that recycled fuel oil is inferior to marine distillate oil and ReRe for ecotoxicity, is reversed or nullified under alternative toxicity impact assessment methods.

The study's default TRACI 2.0 human health cancer indicator shows that for marine distillate oil, higher retention rates lead to higher net emissions, indicating the importance of avoided rather than forward emissions to this route. Under a high-retention rate scenario the marine distillate oil and recycled fuel oil impact scores are indistinguishable. Human health category scores from non-TRACI methods are consistent with ecotoxicity category scores. Impact 2002+ can be seen as less sensitive to air emissions altogether than the other methods. Under Impact 2002+, re-refining is far and away the best option due to avoided refinery emissions during base oil production. This also reverses findings of the study for human health effects.

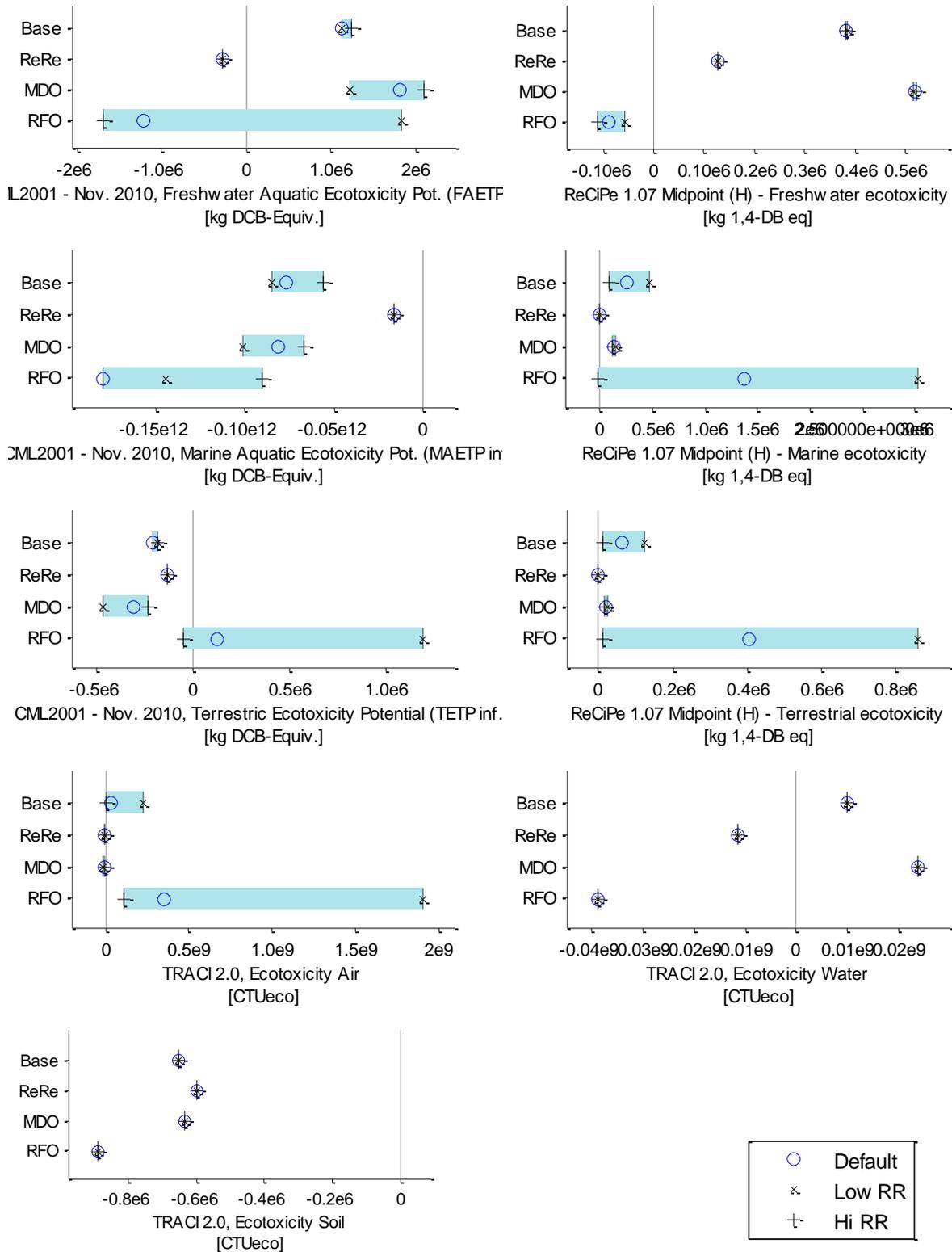


Figure 48: Comparison of ecotoxicity indicator scores for the retention rate sensitivity analysis.

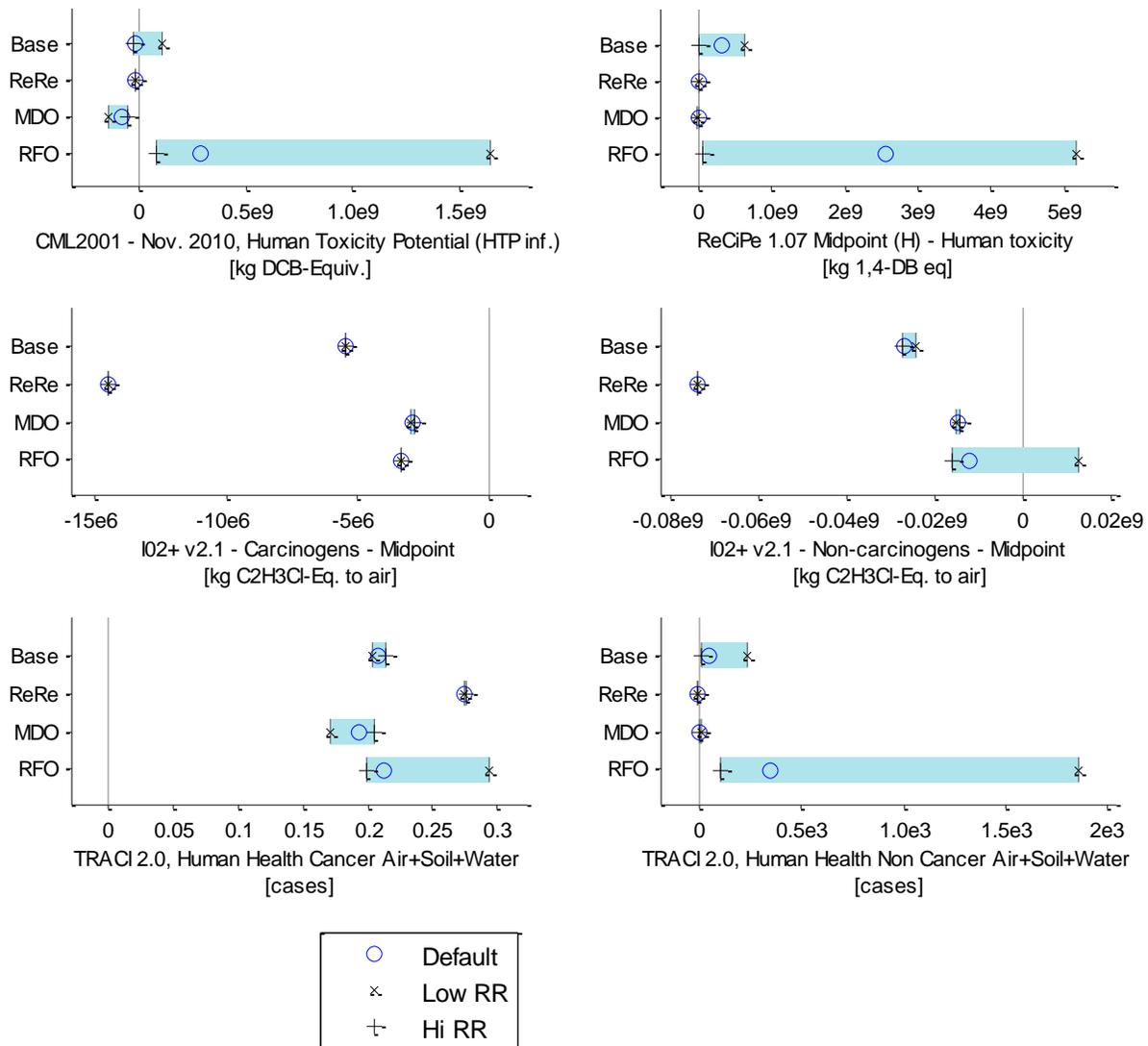


Figure 49: Comparison of human health toxicity indicator scores for the retention rate sensitivity analysis.

Figures 50 and Figure 51 show sensitivity to recycled fuel oil displacement. In this sensitivity scenario, ReRe and marine distillate oil are unaffected. The reference case using TRACI 2.0 indicates that No. 6 fuel oil is the preferred option, dominated by emissions to air during combustion. Avoided natural gas emissions to soil are significant during production, but the difference is not great enough to outweigh the avoided air emissions from residual oil combustion.

Under the CML ecotoxicity indicators, the model's sensitivity to recycled fuel oil displacement choice dominates other model aspects. Displacement of No. 6 oil leads recycled fuel oil to be dramatically better than the other routes. The ReCiPe ecotoxicity categories are reflective of the TRACI 2.0 results. In terms of human health impacts, all indicators are roughly consistent, with the exception noted above that Impact 2002+ shows dramatic avoided burdens for re-refining.

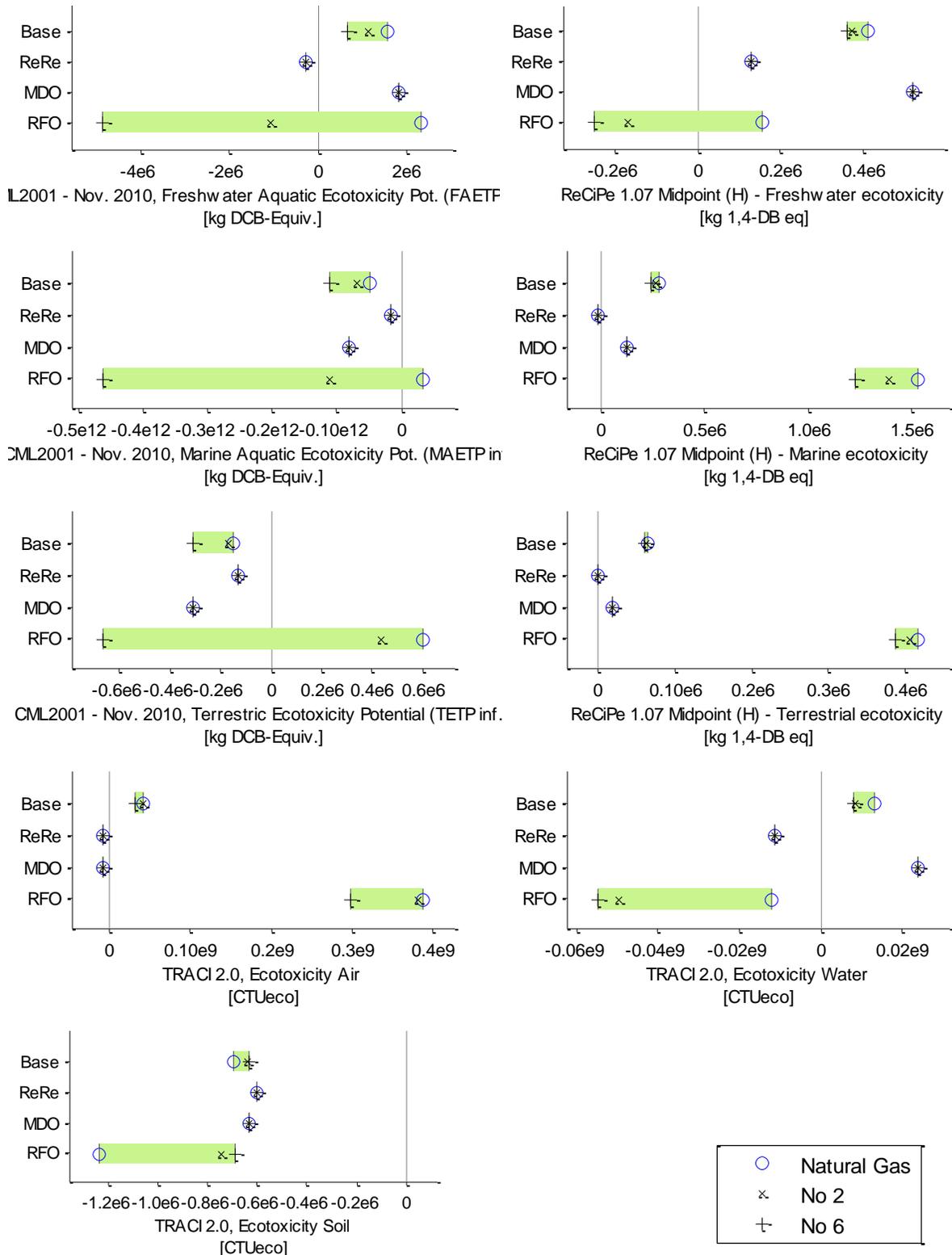


Figure 50: Comparison of ecotoxicity indicator scores for the RFO displacement sensitivity analysis.

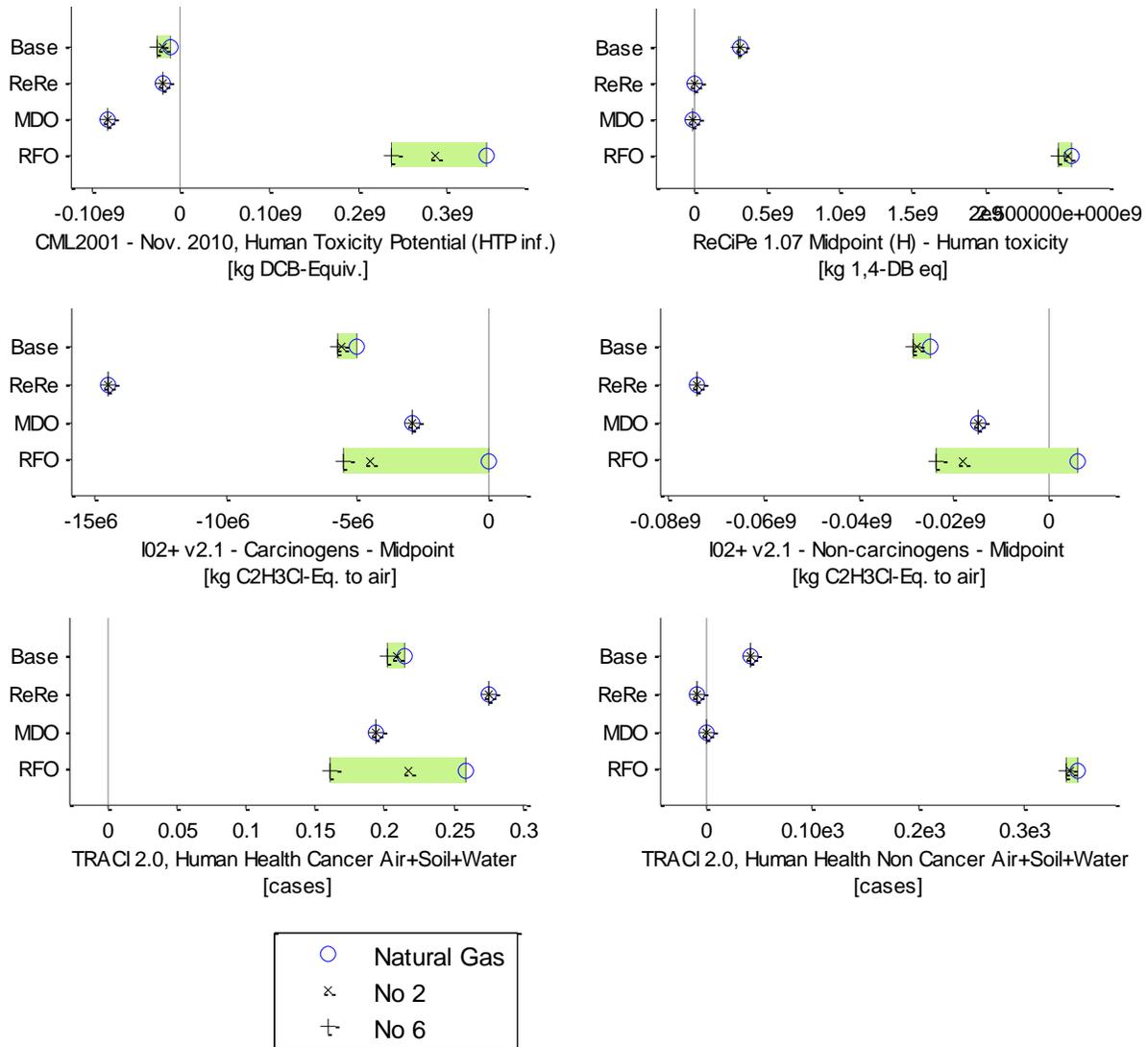


Figure 51 Comparison of human health toxicity indicator scores for the RFO displacement sensitivity analysis.

Figure 52 and Figure 53 show results for the used oil composition case. Note that informal management is not included in the base case and extremes, so these charts do not show the significance of dumping on impact results. These results largely mirror the results of the retention rate sensitivity case, except that avoided emissions due to marine distillate oil production are not significant. Generally, the sensitivity range is smaller for the composition case than it is for the retention case. This is probably due to the fact that retention rates are varied over a wider range (between 0 and 99 percent for some technologies) than composition factors. Used oil composition can be seen to have very little effect on CML marine toxicity and, strangely, ReCiPe freshwater toxicity. Other results are consistent with expected variations across the methods.

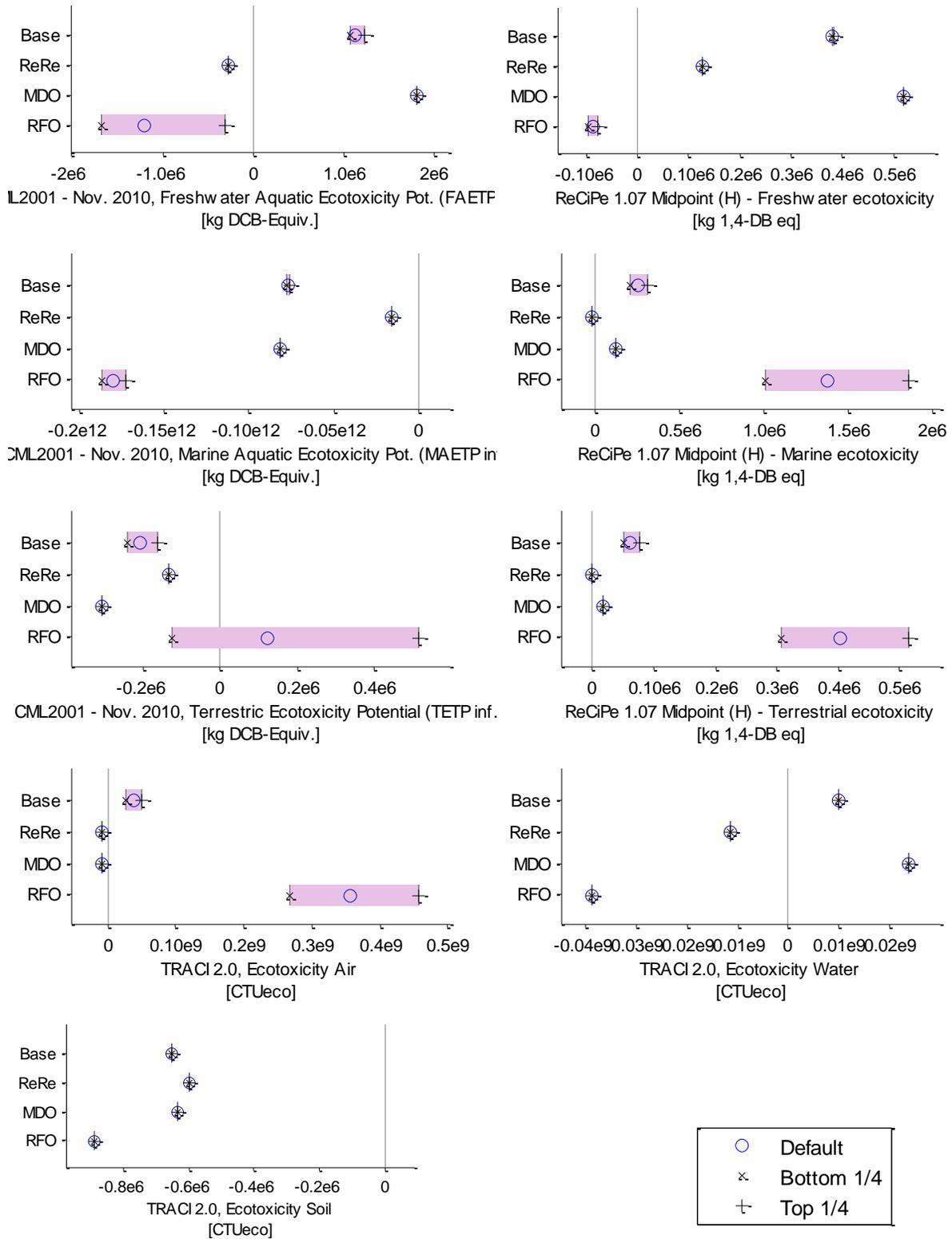


Figure 52: Comparison of ecotoxicity indicator scores for the used oil composition sensitivity analysis.

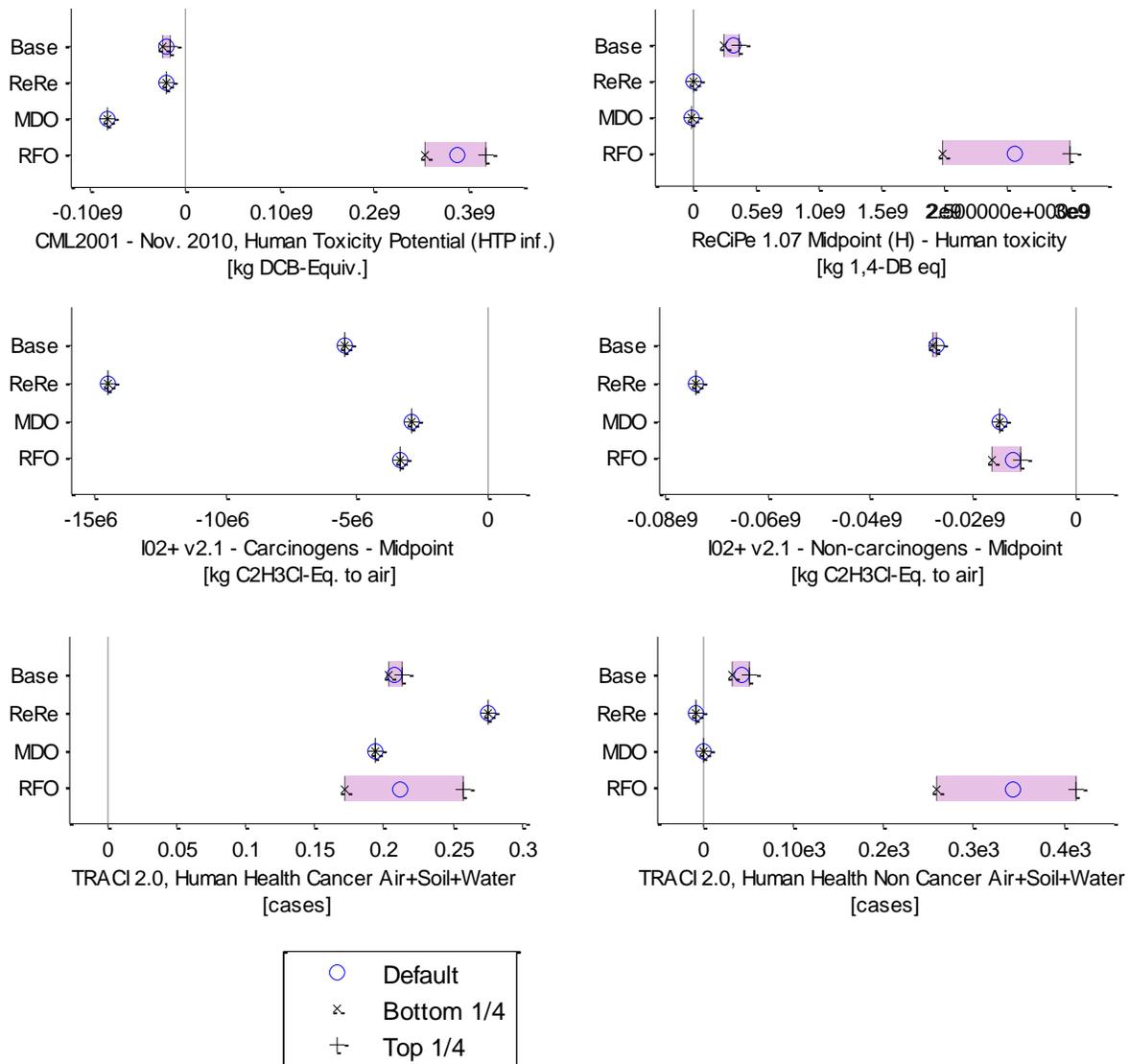


Figure 53: Comparison of human health toxicity indicator scores for the used oil composition sensitivity analysis.

6.2.4 Other Toxicity Concerns

Data not shown suggest that inventory data selection can also have a profound effect on impact results. Decisions regarding selection of life cycle inventory databases are complex and multifaceted; accurate representation of toxic emissions is only one of many factors. While some data development was conducted for this project, notably for the combustion model, the majority of inventory data came from established secondary resources. Combustion emissions were synthesized from secondary data sources when available, with limitations noted. During model construction, the relative impacts of chemical production processes from the PE GaBi professional database were compared to emissions from comparable products in the Ecoinvent

database. Even after accounting for differences in the scope and system boundary definitions between these two databases, toxicity impacts from the one inventory database were consistently many times higher than equivalent impacts from the other data source. The source ultimately selected for the project was chosen for its consistency with other data sources used, irrespective of evaluations of the completeness of its toxicity data. This is a limitation of life cycle assessment at the current state of the art and resolving it is beyond the scope of this study.

Life cycle inventory assessment is also somewhat decoupled from efforts elsewhere to characterize toxicity. For instance, many toxic substance regulatory agencies deal with toxicity potential in terms of “risk factors” which indicate the relative likelihood that one of a set of pollutants could lead to an adverse health effect (e.g. National Research Council, 1983; Risk Assessment Forum, 2005). Although a significant regulatory investment in risk-based methods has been made, there are also several acknowledged shortcomings of the risk assessment approach, including inadequacy of available empirical data; controversies regarding toxicity potentials; inappropriate dependence on value judgments by regulatory agencies; and broader epistemic uncertainties (Crane & Giddings, 2004; Ramsey, 2009; Rudén, 2006; Wilson & Schwarzman, 2009). While some attempts have been made to reconcile risk assessment with life cycle assessment (Kuczynski, Geyer, & Boughton, 2011; Socolof & Geibig, 2006; Udo de Haes, Sleeswijk, & Heijungs, 2006), the efforts remain highly preliminary.

In fact, risk factors of the sort published and used for rule making by regulatory agencies themselves constitute a kind of life cycle impact assessment methodology. Both the California Office of Environmental and Health Hazard Assessment (OEHHA) and the U.S. EPA have published guidance documents which supply risk factors for specific emissions; however, these records are not comprehensive enough to generate a full life cycle impact assessment method. Additionally, they would remain subject to the uncertainties identified earlier in this section regarding inventory data.

Synthesis of new life cycle impact assessment data or methods, as well as intensive critical review of existing data or methods, is beyond the scope of this study.

6.2.5 Toxicity Methods – Conclusion

The selection of toxicity impact indicator can be seen to have a significant effect on the results of impact assessment. Although there are several methods to choose from, none of them is ideal or even necessarily correct on its own. Important factors germane to the study, including characterization factors for heavy metals, have yet to be settled in the scientific community. Consequently, toxicity indicator scores from one family alone should not be used as a basis for decision making (Pizzol, Christensen, Schmidt, & Thomsen, 2011; Querini, Morel, Boch, & Rousseaux, 2011). A panel of indicators from multiple methods is more likely to lead to meaningful conclusions.

6.2.6 Primary Petroleum Refining

Displacement of primary production drives many of the study’s results. Petroleum refining is a highly complex process because of the variation in facility designs, the wide range of co-products produced, and the worldwide geography of the crude oil supply chain. No high quality, peer-reviewed life cycle inventory model of petroleum refining was available that met this study’s needs. For this reason, the process inventory model for primary refining used in the study was



developed under contract specifically for the present project by PE International, a consulting firm specializing in life cycle assessment. The underlying refinery model remains confidential and was not reviewed by the study authors or the critical reviewers.

As such, there are many uncertainties in the model characteristics. Life cycle inventory emissions were derived from reports to state and federal regulatory agencies. The allocation of reported emissions to crude oil throughput should be based on actual production and not on built capacity; however it is not clear whether this is the case. Differences in accounting practices and reporting requirements may lead to a measure of incomparability between the U.S. and California refinery models. For this reason, the U.S. refinery model was used to represent avoided production of both in-state and out of state products. It is not clear to what extent hydrogen production occurring off-site was included, or alternately whether on-site hydrogen production impacts are double counted, since proper accounting for this would require knowledge of individual refineries' operations.

Refineries also present a highly complex allocation problem, since they produce so many co-products and contain a multitude of unit processes. PE International describes the allocation scheme used in its refinery model documentation report. Table 134 shows a comparison of the PE refinery models to other sources on a greenhouse gas emission basis.

Global Warming Potential (kg CO2-eq)						
	PE US	PE CA	GREET	Ecoinvent	US LCI	NETL 2008
1kg Diesel	0.57	0.68	0.90	0.49	0.57	0.68
1 kg Gasoline	0.72	0.78	0.94	0.70	0.58	0.75
1 kg HFO	0.56	0.69	0.60	0.43	0.53	0.52
1 kg Lubricants	1.18	1.25	1.06	1.05		
1 kg Bitumen	0.37	0.40		0.43		

Table 134: Comparison of cradle-to-gate greenhouse gas emissions from primary refining for various life cycle inventory databases.

The global warming potential results suggest that the energy usage in the PE model, and thus the major share of environmental emissions, is roughly consistent with other available estimates. One unusual characteristic of the PE refinery model is its high allocation of energy to residual fuel oil, or HFO. This is a consequence of an allocation scheme in which products are allocated burdens for all the processes they pass through even if they are residual products of that process. A consequence of the PE allocation scheme would be a proportionately higher burden allocated to users of residual fuels, such as power plants and ocean tankers, over light fuel users, than would occur under an economic allocation. Another observation is the relatively greater impact of refining in California versus the rest of the U.S. This discrepancy is thought to arise from differences in reporting and/or regulatory requirements, and was the main driver in the decision to use strictly U.S. refinery processes to model displaced production in the study.

6.3 Conclusions

The goal of the life cycle assessment was to generate a quantitative environmental profile of the management system for all of the used oil generated in California. This report contains a detailed quantitative environmental profile of used oil management in California in 2010 and of a variety of scenarios.

The three objectives of the life cycle assessment are:

- Quantify and aggregate the potential environmental impacts of managing used oil generated in California
- Model the California used oil management system in a way that allows sensitivity and scenario analysis with regards to system parameters
- Generate results that can be used by CalRecycle to provide any recommendations for statutory changes that may be necessary to promote increased collection and responsible management of used oil.

Environmental impacts for eight impact categories have been quantified and aggregated in a highly parameterized fashion, which facilitates extensive sensitivity and scenario analysis as demonstrated in Sections 5 and 6 and Appendices A-D. UCSB will support CalRecycle in conducting additional sensitivity and scenario analysis as deemed necessary by CalRecycle.

In accordance with the goal and scope of this life cycle assessment, it is not appropriate for the LCA practitioner to make any recommendations to promote increased collection and responsible management of used oil, since this will be done by CalRecycle, which commissioned the life cycle assessment. UCSB will continue to support CalRecycle in this task by providing help and guidance in the interpretation of the results, including their underlying assumptions and limitations.

7 Critical Review

The critical review process is complete and feedback from critical reviewers has been incorporated into the final document. Responses to the reviewers' comments will be prepared once the critical reviewers' final report is made available.

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9 Appendix A: Material Flow Analysis (MFA) Methodology

9.1 Introduction

In California, used oil is regulated as a hazardous waste. Every shipment of used oil between facilities must be reported to the state's Department of Toxic Substances Control (DTSC) on a legal form called a hazardous waste manifest (California Department of Toxic Substances Control, 2008). Information on hazardous waste hauling in the state is made publicly available in an annual report to the counties (California Department of Toxic Substances Control, 2013a). The report comprises a list of waste transfers between a origin facilities and destination facilities for all state-regulated (but not federally-regulated) hazardous wastes throughout the year. Each listed transfer is a summary of one or more hazardous waste manifests. As of late 2006, the DTSC has used the same uniform manifest form that the U.S. EPA mandates for federally regulated hazardous wastes (California Department of Toxic Substances Control, 2007). Waste flows are nominally reported by the original generator of the waste, but large quantities of used oil are collected by “consolidated transporters” who operate routine collection routes (California Department of Toxic Substances Control, 2008). On manifests from consolidated transporters, the transporter is listed as the generator of the waste.

Table 135: California waste codes related to used oil (California Code of Regulations, 2005b)

Code	Description	Total mass hauled in 2011 ¹	Oil Content ²
221	Waste oil and mixed oil	480,000 t	95%
222	Oil/water separation sludge	21,000 t	50%
223	Unspecified oil-containing waste	75,000 t	15% / 65%

- 1- Total mass of waste reported on manifests, including double counting. From DTSC Hazardous Waste Tracking System [HWTS].
- 2- Assumed average volume fraction of recoverable oil, based on available data and information provided by used oil LCA project stakeholders. Values may vary on a facility basis.

Different hazardous wastes are identified through numeric waste codes established by regulation (California Code of Regulations, 2005b). Table 135 shows the three California waste codes included in the study. The descriptions make implicit reference to the statutory definition of used oil. The accurate identification and classification of waste streams as coded hazardous wastes is the responsibility of the waste generator and is to be based on the generator's expertise and knowledge of the waste's origin, as well as analytical methods. Waste code 221 embodies all used oil and is mainly made up of spent engine lubricants. Waste codes 222 and 223, both considerably smaller, are also thought to contain appreciable quantities of used oil. Waste code 222 describes sludge from oil/water separators, which are in common use at refineries as well as auto maintenance and other industrial facilities. Waste code 223 is predominantly oily water but also includes solid wastes contaminated with oil.



9.2 Methods

The recovery rate of lubricating and industrial oil products in California is estimated by using hazardous waste hauling data as a composite measurement of the used oil material flow. Transfers of used oil and related wastes are aggregated on a facility basis in order to develop a network model of oil movement through the state in each year of the study. The network model was used to measure the quantity of used oil collected in the state, the freight requirements of reverse logistics, and the facilities at which the oil reached its final disposition. The model outputs were linked to information about the industrial activities of major facilities in the network to determine the fate of the oil. The scope of the study includes oil generated by the end user at a facility within the state of California during the five-year period from 2007–2011. The actual material flow will be larger than the measurement contained in the manifest data, because of used oil informally managed outside of regulatory oversight.

9.2.1 The Facility Network Model

The hazardous waste manifest is the building block of the material flow analysis. Each manifest reports the type and quantity of waste hauled from an origin facility, known as the generator, to a destination facility, known by its statutory description, “Transfer, Storage, and Disposal Facility,” or TSDF. The manifest also reports the identity of each transporter who handles the waste between the generator and the TSDF, but that information was omitted from the model. TSDFs are required to report a “Management method code” for each type of waste listed on the manifest, indicating the expected fate of the waste after it is received. Management method codes are generic to all wastes and all facilities, so interpretation of a given code depends on knowledge of the receiving facility's activities and the waste's composition. Information contained in the manifest is illustrated schematically in Figure 54. Each transfer listed in the hazardous waste hauling report is an aggregation of one or several manifests with identical origin, destination, and waste type and is considered in this report to be equivalent to a single manifest.

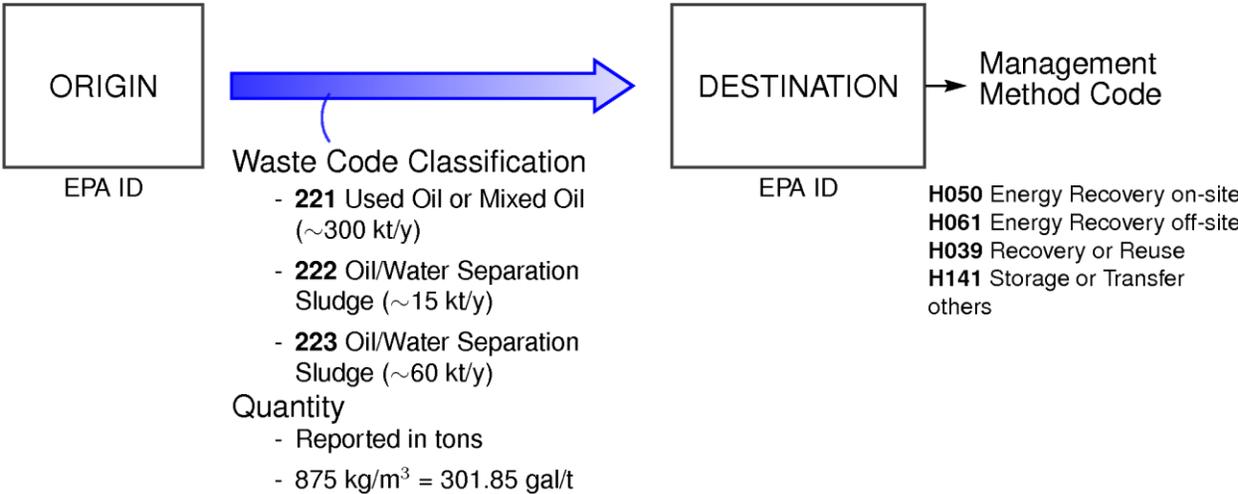


Figure 54: Information contained in a hazardous waste manifest and used in the MFA.

Under the state’s hazardous waste tracking system, a quantity of used oil may appear on multiple manifests. This is because oil that is accumulated at a transfer station before being shipped to a final destination may be included on both the inbound and outbound legs of its journey on separate manifests. Therefore, the sum of quantities of used oil over all manifests would overstate the amount of used oil generated. A network model was constructed in which each facility mentioned on a manifest was a node. By applying the mass balance principle, it was possible to determine the apparent net generation or disposition of oil at each facility.

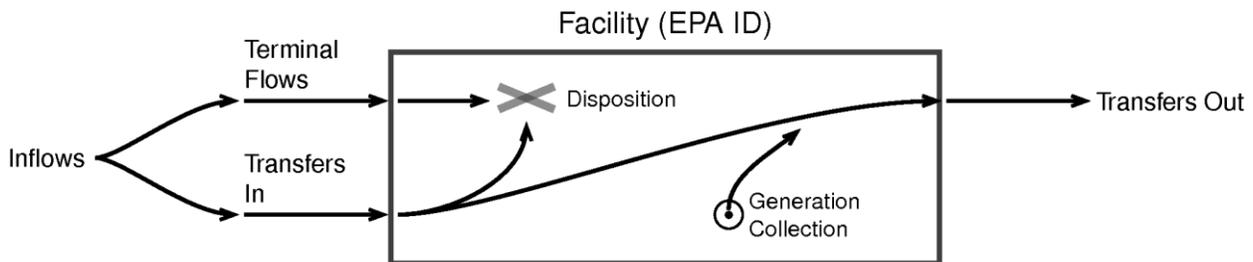


Figure 55: Computation of the facility mass balance from inflows and outflows.

Figure 55 illustrates the facility mass balance. For each facility, all hazardous waste transfers involving the facility as either origin or destination were identified. The total inflow was computed as the sum of quantities over all manifests listing the facility as destination, and the total outflow as the sum of quantities over all manifests listing the facility as the origin. Some inflows were considered to be “terminal,” meaning the oil reported on the manifest met its final disposition at the destination facility, on the basis of the management method code supplied; other flows were regarded as ambiguous. The net outflows for each facility were computed according to the following formula:

$$B = \text{Outflows} - (\text{Inflows} - \text{Terminal Inflow}) \quad \text{A.1}$$

The value B is known as the “mass balance discrepancy” and indicates the apparent generation ($B > 0$) or consumption ($B < 0$) of oil by the facility. Facilities for which $B > 0$ had a net outflow of waste and were considered net generators. Net generator facilities represent the facilities that are first responsible for reporting on the flow of used oil under the hazardous waste framework and are regarded as the “true” generators of used oil. Although transfer stations appear as generators on individual manifests, at the network level they often function as net disposers of oil.

Facilities for which $B < 0$ had a net inflow and were thus considered net disposers of used oil. These facilities are regarded as used oil “processors” and the fate of used oil processed at each facility is determined based on the industrial activities of that facility. The sum of net generation for all net generators equals the sum of net disposition for all processors. This sum is the estimated amount of waste collected in the state.

The mass balance discrepancy can be normalized to the total flow through the facility, defined as the total inflows or outflows, whichever is greater, with the resulting indicator denoted as b . In the special case where $-0.1 < b < 0$, facilities were considered to be transfer stations, and the mass balance discrepancy was taken to indicate transfer losses of used oil. Figure 56 shows the

distribution of b for all facilities receiving used oil in 2010. The vertical axis indicates mass balance discrepancy b , as described in Equation A.1. The horizontal axis indicates facilities sorted in order of the mass balance discrepancy. Facilities for which $-0.1 < b < 0$ were assumed to be transfer stations.

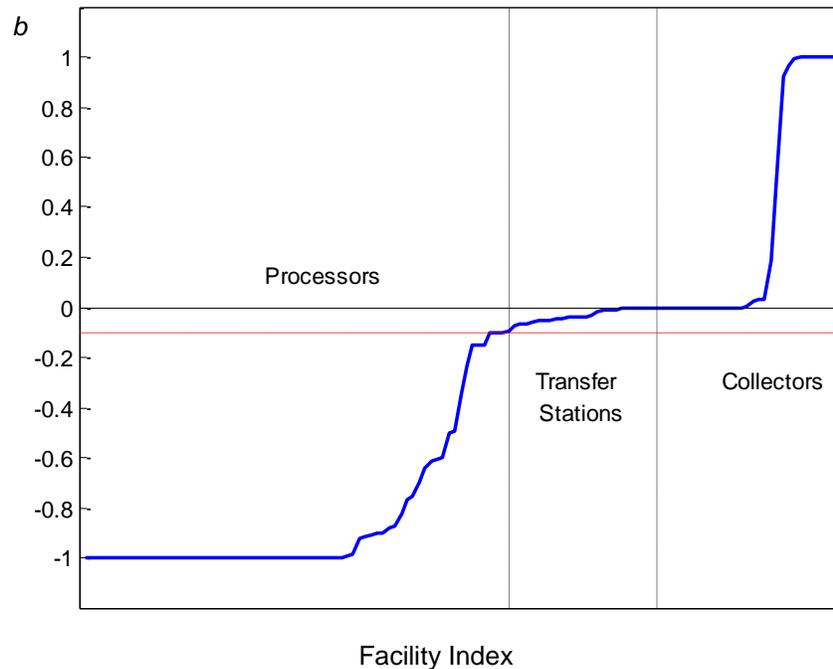


Figure 56: Mass balance discrepancy as a fraction of total mass flow for facilities receiving used oil during 2010.

9.2.2 Facility Specific Information

The hazardous waste hauling reports make reference to approximately 45,000 distinct facilities that handled wastes related to used oil over the study period. Information about the characteristics and activities of specific facilities was used to develop the model. Public records and information provided by DTSC were used to identify the business name, address, location (latitude and longitude), and industry classification (by NAICS codes) for each facility. Information was also available on the permitting status of facilities authorized to receive used oil (California Department of Toxic Substances Control, 2013b).

CalRecycle maintains a database of self-reported information from used oil haulers and processors, collected through administration of state used oil recycling programs. This database was used to inform the model design, to corroborate the results of the manifest data, and to integrate the material flow analysis results into the life cycle assessment.

Finally, information about activities conducted at destination facilities was used to predict the fate of oil disposed at those facilities. For facilities whose operators were involved in the stakeholder process, information came directly from the operators regarding the likely fate of oil. For other facilities, publicly available data sources such as company web pages, marketing materials, news reports and other media were used. A facility's NAICS code is considered to be representative of its industrial activity.

9.2.3 Flow Measurement

Used oil is presented as a fraction of estimated consumption of lubricant products in California. The material flow of used oil through California is inferred from self-reported data by generators, haulers and processors. For each waste code, a used oil content was assumed as noted in Table 135, with the remaining volume as water. The flow measurement was made by summing the net disposition of used oil over all facilities in the network. The origin of the flow is the collection of facilities that act as net generators of used oil. Flow origin is characterized on the basis of industry classification and geography.

The flow's scope includes all manifests of waste code 221. Manifests containing waste code 222 originating from refineries were assumed to contain primary petroleum products rather than "used oil," and were excluded from the scope of the flow measurement on the basis of the NAICS code of the origin facility (32411). For waste code 223 only flows delivered as liquid wastes were included in the scope. The higher oil content estimate (65 percent) was assumed for loads reported destined for energy recovery, and the lower estimate (15 percent) for all other loads.

Although DTSC manifest data are reported by weight (in short tons), most industrial operators deal with used oil on a volume basis. State regulations have established a standard conversion of 7.5 pounds per gallon (899 g/L). The density of dry used oil is assumed to be 894 g/L, consistent with a water content of 5 percent by volume.

In characterizing the used oil flow, it was important to distinguish between oil reported to the DTSC by the original generators and oil reported by consolidators or collection facilities. Net generator facilities were characterized as "consolidators" if they received large quantities of manifested oil in addition to their net generation. Consolidators were also identified based on their permitting status with DTSC, and by NAICS code (facilities with codes 562112, "Hazardous Waste Collection," or 562119, "Other Waste Collection," were taken to be consolidators). Consolidator facilities file manifests on behalf of actual generators, thus masking the oil's true origin. Oil from non-consolidator facilities was considered to be "direct from generator," i.e. reported directly to the state by the original end-user. Figure 57 shows the breakdown of oil reported directly by generators versus consolidators over the MFA period.

As each manifest had geographically explicit endpoints, the distance from origin to destination could be computed and freight requirements could be estimated. Transport distance was considered to be 120 percent of the great-circle distance between the two facilities. Total freight was the sum for all manifests of the product of load mass and transport distance.

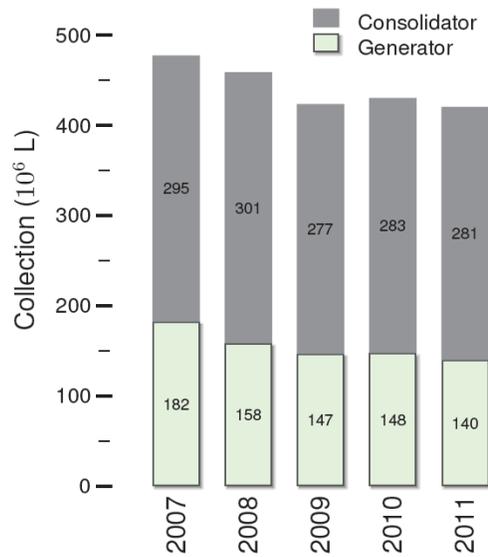


Figure 57: Consolidation versus direct generation for used oil during the MFA period.

The flow's terminus is in the aggregated consumption by the facilities with a net disposition of used oil. Each consuming facility was taken to apportion its net inflow among a limited set of outputs: re-refining, distillation, dielectric fluid rejuvenation, consumption by the California recycled oil market, export from California, wastewater to treatment, hazardous waste to disposal or incineration, and other or unknown. Figure 58 shows the distribution of the flow terminus by facility NAICS code. These are the same numbers that were delivered to the economic direct impacts model as inputs for its baseline.

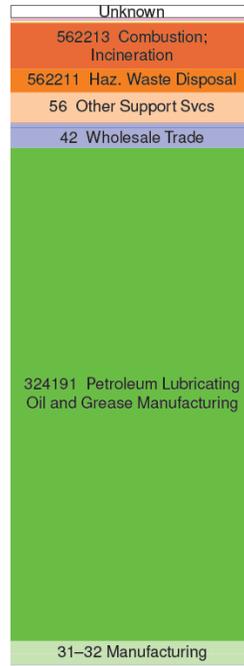


Figure 58: Used oil disposition facility by NAICS code, 2007-2011.

	2007	2008	2009	2010	2011	Density
In-state						
Light fuel	1.02E+08	1.15E+08	1.24E+08	1.18E+08	1.36E+08	0.85
Asphalt product	5.46E+07	6.03E+07	6.80E+07	7.75E+07	6.26E+07	0.93
RFO to combustion	7.56E+07	7.06E+07	5.32E+07	4.04E+07	4.92E+07	0.894
Re-refined base oil	3.24E+07	2.91E+07	3.14E+07	3.31E+07	1.18E+07	0.855
Waste to disposal	3.28E+07	2.30E+07	1.94E+07	2.44E+07	2.20E+07	
Lost or unknown	1.13E+07	6.47E+06	6.68E+06	8.00E+06	8.16E+06	
Dielectric fluid rejuvenation	5.26E+06	4.63E+06	4.45E+06	3.61E+06	3.68E+06	
Recycled oil exported	8.27E+07	6.63E+07	4.79E+07	4.47E+07	5.00E+07	0.894
Out-of-state						
RFO to combustion	4.74E+07	3.51E+07	2.33E+07	1.73E+07	1.40E+07	0.894
Asphalt product	4.61E+06	4.15E+06	3.23E+06	3.68E+06	4.91E+06	0.93
Re-refined base oil	2.03E+07	1.78E+07	1.46E+07	1.70E+07	2.29E+07	0.855
Light fuel	2.50E+06	2.06E+06	1.61E+06	1.81E+06	2.40E+06	0.85

Table 136: Material Flow Analysis results delivered to the Direct Impacts Model.

10 Appendix B: Combustion Model

10.1 Introduction

10.1.1 Objectives

Initially, the combustion emissions inventory was going to be constructed using established literature and inventory data, as is typical for life cycle assessment. However, the significance of fuel combustion and fuel substitution to the study outcome, combined with the shortage of suitable inventory data, prohibited that approach. Stakeholder feedback received in response to the release of the advance draft report made it clear that the compilation of a custom emissions inventory would be necessary for the project to achieve satisfactory results.

The combustion model was constructed with four main objectives, chosen to satisfy the expectations of CalRecycle and the stakeholder group.

1. **Empirical basis.** The primary objective was to construct a credible, bounded scientific estimate of the emissions resulting from the combustion of used oil in conditions thought to be typical for the reference flow. The emission factors were to be based on primary data to the greatest extent possible, with secondary sources used only to the degree that their representativeness could be demonstrated.
2. **Incorporation of fuel composition.** One of the main motivating factors for regulation of used oil is the expectation that heavy metal contaminants contained in the oil will be emitted into the environment when the oil is burned or otherwise disposed. Moreover, the composition of lubricants can be expected to change as time progresses due to changes in additive packages and/or wear metal composition. Therefore it was necessary for the combustion model to incorporate information about the material composition of the fuels modeled, including the presence of contaminants.
3. **Parametric model implementation.** Most combustion emission inventories used in life cycle assessment are static; however, for this study it was important for each model parameter to be available for sensitivity analysis.
4. **Lower heating value equivalency.** The lower heating value of a fuel was judged to be the primary characteristic indicative of its functional utility for modeling displacement. Reference emission factors were thus developed on a heating value basis.

Due to the shortage of data on used oil combustion, it was necessary to make inferences based on studies of limited and disparate scope. Through the accumulation of primary test results, it was possible to develop statistically robust inferences about the combustion behavior of fuels in some situations. Even when the collected data fall short of a statistical sample, having a range of measurements from a variety of facilities permits certain conclusions to be drawn and supports order of magnitude estimates and an evaluation of uncertainty.

kg / MJ LHV	RFO	No 2 Distillate	No 6 Residual oil	Natural Gas	Light Ends	Marine Distillate	Bunker Fuel
Technology:			Zero Retention			Marine	Marine
CH4	3.1E-06	3.2E-06	3.1E-06	1.1E-06	3.1E-06	3.7E-07	4.0E-07
CO2	7.2E-02	7.4E-02	7.7E-02	5.5E-02	7.2E-02	7.4E-02	7.9E-02
N2O	6.1E-07	6.4E-07	6.2E-07	1.1E-07	6.3E-07	5.1E-06	5.5E-06
CO	3.4E-06	3.3E-06	3.5E-06	2.9E-06	2.7E-05	7.0E-05	6.0E-05
NOx	7.3E-05	3.7E-05	1.7E-04	1.6E-05	6.8E-05	9.3E-04	1.4E-03
Sox	2.0E-04	8.6E-05	5.5E-04	3.9E-07	4.6E-07	8.9E-05	1.7E-03
PM Total	7.3E-05	1.9E-06	2.5E-05	8.2E-07	2.7E-07	6.5E-05	4.0E-05
PM10	5.8E-05	9.3E-07	2.1E-05	8.2E-07	2.7E-07	3.3E-05	3.5E-05
NM VOC	3.1E-06	1.4E-06	4.0E-06	4.5E-06	1.8E-06	3.7E-05	4.0E-06
PAH	2.0E-08	1.2E-08	3.7E-09	2.9E-10	1.1E-08	7.9E-07	8.4E-07

Table 137: Summary of fuel-specific emission factors with no pollutant retention.

10.1.2 Summary of Results

The complete combustion model includes seventeen unit processes, formed from the combination of seven distinct fuels and five combustion technologies:

- Recycled fuel oil combusted in three different devices: boilers, kilns, and space heaters.
- Natural gas, No. 2 Distillate and No. 6 Residual oil in the same three devices;
- Light ends combusted in boilers and kilns, as a variant of diesel fuel;
- Marine distillate from primary and secondary refining, combusted in marine auxiliary engines;
- Bunker fuel combusted in marine main engines, using residual oil composition profile.

*Note: Combustion of bunker fuel was included in the combustion model in case CalRecycle should desire an assessment of the displacement of bunker fuel by marine distillate oil in marine engines. However, it was decided that it does not currently displace bunker fuel and thus this process is not used in the current model.

The boiler category refers to industrial or commercial size boilers, which generate heat in the form of steam. Those included in this analysis ranged from 5-300 MW capacity (MACT, AP42, Shaaban & Salavani, 1996). Space heaters are small heating devices that may use either atomizing or vaporizing technology. Those included had heat capacities of less than 0.3 MW (AP42, Dyke, Vermont). The kilns technology refers here to cement or asphalt plant kilns, which use direct-fired technology. Those included had capacities of 15-30 MW (AP42, Entropy). The marine engine data are for ocean-going vessels that have engines ranging from 8,000 to 40,000 kW average propulsion capacity (Agrawal, ICF 2009).

Fuel specific emission factors are shown in summary form in Table 137 above. Default technology-specific retention rate values are shown in Table 138. Further details on their determination can be found in section 10.4.

	Metals	PM	Halogens	Sulfur	Phosphorus
Boiler	0.85	0.2	0.1†	0.15	0.5†
Atomizing Heater	0.4	0	0.1†	0.05	0.5†
Vaporizing Heater	0.998	0.95	0.1†	0.35	0.99
Kiln	0.99	0.98	0.2†	0.6	0.5†
Marine	0.4†	0	0.1†	0.02	0†

Table 138: Default retention rate values by combustion technology. Rates based on highly limited or no data are marked with a dagger symbol †.

10.2 Methodology

10.2.1 Inventory Design

The emission inventory consists of a combination of fuel-specific emission factor ranges and technology-specific retention rates. Emission factors are thus dependent on fuel composition. Each combustion unit process reports emission factors for carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), carbon monoxide (CO), other nitrogen oxides (NO_x), total particulate matter (PM), polycyclic aromatic hydrocarbons (PAH), and volatile organic compounds (VOC, excluding methane and PAH). The same emission factors for a given fuel are used across all combustion technologies, except for particulates, which were modeled as a maximal emission factor that is fuel-specific, combined with a mitigation rate that is technology-specific.

The combustion model includes estimates of the average concentration of select elements in fuels. Technology-specific retention rates are used to indicate the amount of a given constituent substance that is retained within the combustion equipment or otherwise mitigated prior to release to the environment. Elemental flows, including metals such as nickel and vanadium, and nonmetals such as sulfur and chlorine, are modeled on a mass balance basis, in which a portion of the constituent element is retained within the equipment and the rest is released into the environment.

All metals included in the composition estimate are assumed to have the same retention rate. Constituent metals that are retained within the combustion equipment are assumed to be disposed of properly as collected bottom and/or fly ash. The subsequent fate and environmental impacts of those trace flows is not modeled.

To accommodate displacement of primary fuels by secondary co-products, emission factors for the combustion of virgin No. 2 distillate, No. 6 residual oil, and natural gas in similar facilities are also developed. Natural gas combustion in a marine engine is not modeled. Although light ends are a co-product of the used oil management system, no adequate inventory data to describe the combustion of the light ends flow were available. In the current model, light ends are modeled as a variant of No. 2 distillate. More details are included in the results section.

10.2.2 Retention Rate Estimates

In order to satisfy the study objective to reflect fuel composition in combustion emissions, many emission factors are derived from fuel composition measurements in terms of the amount of a given component that is retained in the combustion device itself or in residual ash. Each combustion technology is described in terms of four elemental retention rates: one each for metals, halogens, sulfur compounds, and phosphorus, and a mitigation rate for particulates. Retention rates may take on a value between 0 and 1 (zero indicating complete emission of the constituent and one indicating complete retention).

Retention rate estimates are based on data from the combustion model. Paired measurements of fuel composition and elemental emissions with the same unique identifier were used to compute the emitted fraction of a given constituent, EF_{avg} / C_{avg} . When this resulted in a value of less than 1 (i.e. the emitted quantity was less than the composition measurement), a retention rate measurement was made in the form of $RR = 1 - EF_{avg} / C_{avg}$.

Emitted fractions greater than 1 provided insight into combustion emissions, and are discussed in the results section. However, they were not used in calculations of average retention rates. More detail on the computation of specific retention rates is provided in the results section.

10.2.3 Censored Samples

Measurements of fuel contaminants or emissions frequently return a result of no detectable amount of the pollutant due to technical limitations of the testing apparatus. This is known as a censored sample or a “non-detect.” Although no reading is returned, the result does not necessarily indicate the absence of a constituent within the sample. Incorporation of non-detection results is important because improper handling of non-detects can bias results (Cohen, 1991). Omitting non-detects will have the effect of biasing the sample toward higher measurements.

An alternative approach is to replace the censored result with a proxy value based on the detection limit, e.g. taking the detection limit itself as the value of the measurement. The standard practice of the U.S. EPA in the context of the MACT database is to use half the detection limit as a proxy measurement (Fed Reg 13 Sep 2004, p. 55283). The most correct approaches include estimating the expected value of the censored sample using moment or maximum likelihood estimators, which require an iterative algorithm or linear programming optimization to implement. They were not adopted for this study due to the computational complexity of these approaches.

Four different simplistic estimation strategies were considered for handling non-detects:

- Omission of non-detects
- Replacing non-detects with zero
- Replacing non-detects with half the detection limit
- Replacing non-detects with the detection limit

The sensitivity of model results to non-detection handling strategy was evaluated. By reviewing individual test groups, it was found that assuming a nonzero proxy value was more consistent

with the maximum likelihood approach than assuming zero or omitting non-detects. Zero values are also incompatible with the calculation of a geometric mean, which was frequently used as it was the most appropriate average.

It was decided to use half the detection limit as a proxy measurement because it is consistent with the EPA approach and simple enough to implement. This approach was used when computing average composition and emission measurements for a given test (match ID). When computing retention rate averages, non-detects were omitted because of the high sensitivity of the results to detection limit strategy.

10.2.4 Data Handling

Distinct primary data resources were collected into a database of measurements stored in a common format.

All database entries are normalized to the mass of fuel consumed. Thus composition and emission measurements are dimensionless mass, but can be thought of as kg pollutant per kg fuel. Composition measurements (C) are reported as the mass fraction of the contaminant in the combusted fuel. Emission factors (EF) are reported as the mass of emission per unit mass of fuel combusted. Measurements of higher heating value are reported in MJ/kg.

For entry into the database, each measurement was associated with a distinct set of reference information consisting of:

- Data source
- Type of fuel
- Date or year of test
- Distinguishing combustion technology or device

This information was used to construct a unique identifier for each collection of composition and emission measurements, known as a “Match ID,” or MID. Match IDs were used to group related measurements when computing averages and when estimating retention rates.

10.2.5 Measurements and Unit Conversions

Computations were often necessary to render the findings of individual studies compatible with the database. In most cases these were trivial unit conversions. Measurements reported as a mass or molar fraction in exhaust gas under a reference condition (e.g. parts per million at 7 percent excess O₂) can be expressed as an emission factor if certain chemical properties of the fuel and pollutant are known. The ones that required the use of physical principles are described below.

REFERENCE CO₂ CONCENTRATION; MASS OF POLLUTANT

Given measurements of pollutant mass concentration in a dry gas under known CO₂ concentration (e.g. ng/m³ × 10⁻⁹ @ 12% CO₂), the concentration of contaminant in the fuel can be written as:

$$EF = t \times \frac{RT}{P} \times \frac{1}{p} \times \frac{1}{MC} \times C_{fuel} \quad \text{B.1}$$

where t = the mass of pollutant per volume of exhaust gas;

R = the ideal gas constant;

T, P = temperature and pressure of the reference condition;

p = the mole fraction of CO₂ in the reference condition (e.g. for 12% CO₂, p=0.12);

M_C = the molecular weight of carbon;

C_{fuel} = the mass fraction of carbon in the fuel converted to CO₂.

Derived conversion factors (EF in kg/kg):

$$EF = t \times 0.03068 \quad \text{for } t \text{ in grains per DSCF at 12\% CO}_2$$

REFERENCE O₂ CONCENTRATION; MASS OF POLLUTANT

Given measurements of pollutant mass concentration in a dry gas under known excess O₂ (e.g. ppmvd × 10⁻⁶ @ 3% O₂), the mass of an emitted compound per unit mass of combusted fuel can be written as:

$$EF = t \times \phi(k) \times \frac{0.209}{0.209 - p} \quad \text{B.2}$$

where

t = the mass concentration of the pollutant in the exhaust;

k = the ratio of C to H in the fuel (e.g. for fuel C_aH_b, k = a/b); 0.25 ≤ k ≤ 0.5

$$\phi(k) = (4.78 k + 0.945) / (12 k + 1)$$

p = the molar fraction of oxygen in the exhaust gas (e.g. for 3% O₂, p = 0.03).

This equation can be derived from combustion stoichiometry. $\phi(k)$ represents the ratio of the moles of exhaust generated per unit mass of fuel combusted, and depends on the concentration of oxygen in ambient air. The equation above assumes 20.9 percent oxygen in air, which is consistent with EPA Method 19. Note that emission factor estimates based on this equation are relatively insensitive to fuel composition. For methane, k=0.25 and $\phi(k) = 0.535$. For heavier fuels, k approaches 0.5 and $\phi(k)$ approaches a limit of 0.4764.

Derived conversion factors (EF in kg/kg):

$$EF = t \times 1.73 \times 10^{-11} \quad \text{for } t \text{ in ng/DSCM at 7\% O}_2$$

<http://www.epa.gov/ttn/emc/promgate/m-19.pdf>

REFERENCE CO₂ CONCENTRATION; MOLE FRACTION OF POLLUTANT.

Given measurements of pollutant mole fraction or molar concentration (e.g. ppmvd × 10⁻⁶ @ 12 percent CO₂), Equation B.1 above delivers a result in moles of pollutant per unit mass of fuel; the desired emission factor can be obtained by multiplying by the molar mass of the pollutant:

$$EF = t \times M_t \times \frac{RT}{P} \times \frac{1}{p} \times \frac{1}{M_C} \times C_{fuel} \tag{B.3}$$

where

t = the mole or volume fraction of pollutant in exhaust gas;

M_t = the molar mass of the pollutant;

R = the ideal gas constant;

T, P = temperature and pressure of the reference condition;

p = the mole fraction of CO₂ in the reference condition (e.g. for 12 percent CO₂, p=0.12);

M_C = the molecular weight of carbon;

C_{fuel} = the mass fraction of carbon in the fuel.

REFERENCE O₂ CONCENTRATION; MOLE FRACTION OF POLLUTANT

Similarly, Equation B.2 can be modified to obtain the emission factor as follows:

$$EF = t \times M_t \times \phi(k) \times \frac{0.209}{0.209 - p} \tag{B.4}$$

where

t = the mole or volume fraction of the pollutant in the exhaust;

M_t = the molar mass of the pollutant;

k = the ratio of C to H in the fuel (e.g. for fuel C_aH_b, k = a/b) (0.25 ≤ k ≤ 0.5)

φ (k) = (4.78 k + 0.945) / (12 k + 1)

p = the molar fraction of oxygen in the exhaust gas (e.g. for 3 percent O₂, p = 0.03).

Derived conversion factors (EF in kg/kg):

EF = t × M_t × 5.60 × 10⁻⁷ for t in ppmvd @ 3 percent O₂

EF = t × M_t × 7.21 × 10⁻⁷ for t in ppmvd @ 7 percent O₂

EF = t × 2.56 × 10⁻⁵ for t in ppmvd @ 3 percent O₂ as propane (used in VOC measurements)

MEASUREMENTS OF CONCENTRATION OF POLLUTANT BY HEATING VALUE

Many pollutant emissions in the MACT database were provided in terms of mass per unit of higher heating value. Therefore, it was necessary to determine higher heating values of fuels on both a source-specific and study-generic basis. Emission measurements given in terms of the heating value of the fuel were converted to mass fractions using the heating value reported by the source whenever possible; when heating value was not reported, the reference higher heating values for the study were used. Reference higher heating values were developed for the study by taking the average higher heating values reported in the MACT database by fuel. These values are shown below. Conversion of emission factors to mass fractions was the only use of higher heating values in the study.

Fuel	Count	Higher Heating Value (MJ / kg)
Natural gas	134	53.0
No. 2 Distillate	496	45.2
No. 6 Residual oil	694	44.0
Used Oil	119	42.8

Table 139: Average higher heating values of fuels in the MACT database.

10.2.6 Averaging and statistical characterization

A geometric mean is the average order of magnitude of a set of numbers; it is thus appropriate to use when measurements have low precision and a wide dynamic range. A geometric mean is computed as the n^{th} root of the product of n samples, or the exponent of the mean of the logarithm of n samples. Emission factors, like most other life cycle inventory data, are bounded at zero and thus can be expected to follow a lognormal distribution, which was borne out in graphical representations of the data. Therefore, average emission factors computed for this study use geometric means. Composition measurements can legitimately be zero-valued and do not necessarily follow a lognormal distribution. For computing average fuel contaminant compositions, an arithmetic mean was used. Retention rates used either the arithmetic or the geometric mean, depending on the distribution of the data.

For all measurements with bounds, the lower and upper bounds reported represent the 10th and 90th percentiles of the data set, excluding outliers. All data sets were cleared of outliers at 95 percent confidence using the Dixon Q test prior to computing averages or bounds. Measurements of data sets with fewer than eight members used the maximum and minimum values as bounds.

10.2.7 Limitations

- High-quality, comparative data were available for only one broad technology (boilers)
- Emission factors for kilns and space heaters were found only for used oil; their non-composition-dependent emission factors are thus modeled identically to boilers for completeness and comparability
- Limited used oil-specific data

- Lack of scientific consensus on the fate and transport of elemental contaminants during combustion, stemming from a lack of primary data
- Lack of composition data for used oil-derived fuels, particularly marine distillate oil
- Lack of data on magnitude and speciation of organic compounds
- Halogenated organic emissions were omitted from the model.

10.3 Data resources:

10.3.1 MACT database

Under the Clean Air Act, the U.S. EPA is authorized to establish national emission standards for hazardous air pollutants (NESHAPs) originating in industrial facilities that exceed an annual emissions threshold of either 10 tons of any one hazardous air pollutant or 25 tons of any combination of hazardous air pollutants (CFR Title 40: Part 63). The Boiler MACT (Maximum Achievable Control Technology) program was first established in 2004 to reduce hazardous air pollutant emissions from major sources. The EPA subsequently conducted an extensive study of boiler emissions in order to develop data for a revised rule (Sector Policies and Programs Division, U.S. EPA, 2009).

Data in the Boiler MACT database were collected by boiler operators either in the course of their operations or by specific request from EPA. The data were placed into a common database to support the rule making process, and were made available to the public. The population of data contributors was selected to be a statistically representative sampling of facilities meeting the criteria for inclusion in the program. Since the objective of the program was to profile the best performing facilities, emission data are likely to be representative of cleaner-burning facilities than the national average.

The MACT database is valuable because it contains data on combustion of a variety of fuels from a large number of facilities, reported to a common specification. For the current study, a subset of the MACT data was selected that included facilities burning virgin petroleum-based oils, used oil, or natural gas, and were not burning mixtures of multiple fuels. The data set includes a total of 346 distinct facilities reporting emission factors and 406 facilities reporting composition measurements. Both major sources (facilities that emit more than 10 tons of any hazardous air pollutant, or more than 25 tons of hazardous air pollutants generally per year) and area sources (those that emit less) are included.

10.3.2 Composition data

The Composition database has the following profile:

- Used Oil (114,885 measurements of 2,534 used oil samples)
- No. 2 Distillate (2,215 measurements at 225 facilities)
- No. 6 Residual oil (3,707 measurements at 151 facilities).

COMPOSITION DATA SOURCES

- MACT database (U.S. Environmental Protection Agency, 2011b)

The portion of the MACT database analyzed includes 7,416 fuel composition measurements from 386 facilities and 1,500 higher heating value measurements from 254 facilities. These include:

- 1,316 measurements of used oil
- 2,652 measurements of No. 2 distillate or diesel fuels
- 257 measurements of No. 4 fuel oil
- 4,286 measurements of No. 6 residual oil
- 179 measurements of natural gas

The data set includes at least one measurement of each of the following constituents: Ar, Be, Cd, Cl, Co, Cr, F, Hg, Mn, N, Ni, P, Pb, Sb, S, Se, ash, and moisture.

- Cal/EPA High Efficiency Oil Filter study; composition measurements of used motor oil (n=533). Data collected in support of a study of high-efficiency oil filter adoption in the California state vehicle fleet (Adams, Brown, Peace, Petersen, & Leary, 2008).

Includes 23,985 distinct measurements from 533 vehicles. Measured constituents included Al, Sb, Ba, B, Ca, Cr, Cu, Fe, Pb, Mg, Mo, Ni, P, K, Si, Ag, Na, Sn, Zn, water, and Ash.

- Shell Taxi cab study (n=1750). A longitudinal study of 78 taxi cabs including regular samples of used oil after every oil change.

Includes 78,390 distinct measurements. Measured constituents included: Al, Sb, Ba, B, Ca, Cr, Cu, Fe, Pb, Mg, Mo, Ni, P, K, Si, Ag, Na, Sn, Ti, Zn.

- A variety of literature and stakeholder-provided measurements. Data sources included: (Boughton & Horvath, 2004; Fehrenbach, 2005; Resources, 1996; Shaaban & Salavani, 1996), and analytic results provided by stakeholders.
- A collection of reports of heavy fuel oil composition from literature sources: (Abbas, Maqsood, & Ali, 2010; Jang et al., 2007; Sippula, Hokkinen, Puustinen, Yli-Pirilä, & Jokiniemi, 2009; Zheng, Tang, Asa-Awuku, & Jung, 2010).

10.3.3 Emission data

Emission Factors: 368 facilities or references reporting

5,839 positively-detected emission measurements or emission factor reports

476 Used Oil and blends

968 No. 2 Distillate

166 No. 4 Fuel oil

1,410 No. 6 Residual oil

3,881 Natural gas

92 Marine fuels

1,154 non-detects

The bulk of the data originates in the MACT database.

LARGE-SCALE DATA SOURCES

Large scale data sources are defined as those containing data from more than five facilities.

- MACT database emission factors from industrial boilers and process heaters. Includes 5,400 distinct EF measurements over all fuels, many derived from continuous emission monitoring systems. Boiler capacities range from 5-300 MW.

For combustion emissions, conversion calculations used the F-factor standardized value reported, as calculated by U.S. EPA based on Method 19, determination of sulfur dioxide removal efficiency and particulate matter, sulfur dioxide, and nitrogen oxides emissions rates, from Appendix A of CFR Title 40, Chapter 1, Part 60-Test Methods. F-factors are ratios of combustion gas volumes to heat inputs, used to determine rates of emissions when they are originally reported as an emission per unit time.

- AP42 regulatory guidance documents for the Clean Air Act giving reference values for emission factors for stationary sources. Data are derived from stack / device testing. The current revision dates primarily from late 1990s, with incidental revisions (U.S. EPA, 1996a, 1996b, 1996c).
 - Chapter 1.3—Fuel Oils, including No. 2 distillate, No. 4 fuel oil, and No. 6 residual oil;
 - Chapter 1.4—Natural Gas in large utility and industrial boilers;
 - Chapter 1.11—Waste Oil combusted in small boilers and space heaters.
- ICF International (2009)—A study on emissions due to port activity for the U.S. EPA. The authors referred to an earlier study, (Entec, 2002), for emission factors from auxiliary marine engines burning distillate fuels.

SMALL-SCALE DATA SOURCES

Small-scale data sources are defined as those containing data from five or fewer facilities.

Entropy (1996)—This report, titled “Quantification of Metals Emissions from Burning Used Oil Fuel,” was performed for the National Oil Recyclers Association and was released in 1996. Its objective was to study the release of metals during used oil combustion. The study involved stack testing at two asphalt plants with baghouse filters and tested emissions of six different metals. They also considered the metal content of the used oil being combusted. Results were reported in terms of the metal removal efficiency of the combustion technology.

- Vermont Agency of Natural Resources (1996)—The agency conducted a study of waste oil composition and emissions resulting from combustion in small space heaters with no emission controls.

- (Shaaban & Salavani, 1996)—The study titled “Heat Recovery of Used Petroleum, Oil, and Lubricants” was performed for the U.S. Air Force/Department of Defense. The paper was presented at the Energy Conversion Engineering Conference in 1996. Testing was performed using an atomizing boiler and a variety of different types of used oil combined with diesel. Composition and emission data were reported for nine metals and several other components.
- (Dyke, 2007)—In this study, Lubrizol tested the combustion of used oil in a small vaporizing space heater. The used oil was collected from heavy-duty trucks that had been using the oil for 50,000 to 100,000km. Fuel samples were analyzed and emissions were tested for a comprehensive range of criteria pollutants, metals, dioxin/furans, and organic compounds. Results were reported for composition, emission, and metal retention rate for the combustion of two different samples. The testing was performed in 2007.
- (Agrawal, Welch, Miller, & Cockert, 2008)—An academic study of emissions from ultra-high-volume oil tankers, including emissions measurements for several different operating points of main and auxiliary marine engines according to ISO testing specifications.

Author / Source of Data	Title	Year	Facility	Combustion Type	Output Capacity (MMBTU / hr)	Emission Controls	Fuel Comp
Entropy	Quantification of Metals Emissions from Burning Used Oil Fuel	1996	Asphaltic concrete plants	Single oil burner mounted on a short rotary drier	75 - 100	Baghouse fabric filter	Y
EPA	AP42, Ch. 1.11 Waste Oil Combustion	1988	Various	Small Boilers	0.5 - 20	None	Avg only
EPA	AP42, Ch. 1.11 Waste Oil Combustion	1988	Various	Small space Heaters; 1.) Vaporizing 2.)Atomizing	1.) 0.12 2.) 0.25	None	Avg only
Shaaban, A.	Heat Recovery of Used Petroleum Oil and Lubricants	1996	Tyndall Air Force Base	Atomizing Boiler	0.5	None	Y
EPA	Boiler MACT Draft Emissions and Survey Results Databases. 2012.	2007	Various	Industrial Combination Boiler	5 - 1000	Various	Y
Dyke, P.	Emissions from Small Waste Oil Burner Burning Drained Lubricating Oil	2007	Lubrizol	Thermobile AT400 vaporizing space heater	0.14	None	Y
ICF/EPA	Current Methodologies in Preparing Mobile Source Port-related Emission Inventories	2009	Various	Marine Engines	< 3.4 - >10.2	None	N
Agrawal et al	Emission Measurements from a Crude Oil Tanker at Sea	2008	Suezmax Tanker	Marine Engines	3.0 - 53	None	Y

Table 140: Data sources included in the development of the used oil combustion model.

10.4 Results

Because of the relatively small size of the assembled data set, many of the findings may not be considered statistically robust. However, in most cases the data do support the estimation of emission factors to a single significant figure and an order of magnitude. In cases where no statistically significant difference was detected between fuels, the same emission factor was used for both fuels, but fuel-specific upper and lower bounds were assigned.

10.4.1 Graphical Presentation of Results

Results are presented in two types of figures. Tabular EF charts show reported emissions from distinct sources or groups in a horizontal aspect. The horizontal axis is emitted mass fraction (kg emission per kg fuel combusted) on a logarithmic scale. The vertical axis indicates distinct



facilities or groups of facilities or tests. For each group, statistical information about the number of samples (n) and the number of facilities or sources (N) included in the sample is provided.

Data are shown as a horizontal bar whose extents reflect the range of the data in that group. For large sample sets, the 10th and 90th percentile are indicated by a heavy line terminating in vertical bars, and the 0-100 percentile are shown as whiskers. The geometric mean of the data is marked by a point.

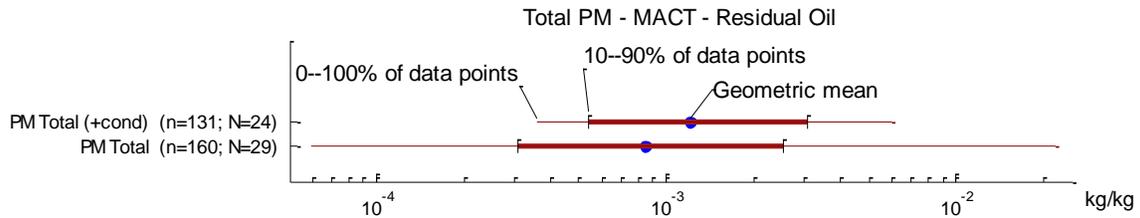


Figure 59: Tutorial description of tabular emission factor charts.

An example is shown in Figure 59. This figure reports measurements of particulate matter emissions from the combustion of residual oil in the MACT database. There are two flows reported: PM Total including condensibles (+cond), and PM Total, with condensibles unspecified. Statewide, 29 facilities report a total of 160 measurements of unspecified “PM Total,” while 24 facilities report “PM Total (+cond)” in 131 measurements.

A retention rate plot is used to compare matched composition and emission measurements across a variety of facilities. In these plots, composition measurements are shown as green circles, with the average for each test shown with a heavy green vertical bar. Emission measurements are shown as black Xs, with the average emission shown as a heavy red vertical bar. Composition measurements not matched with emission measurements are shown in a single population at the top of the chart; unmatched emission measurements are shown in a single population at the bottom of the chart.

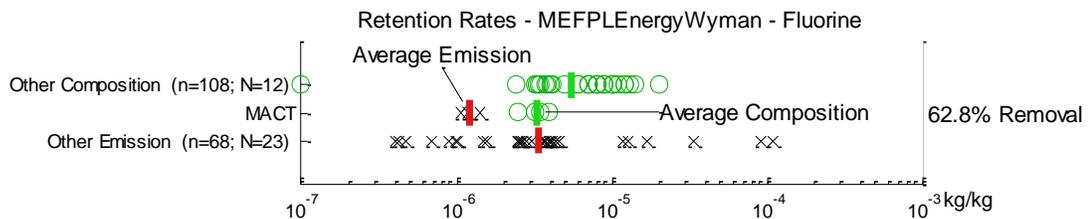


Figure 60: Tutorial description of retention rate charts.

An example is shown for fluorine composition and emissions. Only one facility, known in the MACT database as MEFPLEnergyWyman, has provided a matched set of combustion and emission measurements (excluding non-detects). The facility's data indicated that 62.8 percent of the fluorine measured in the fuel appeared to be retained in the stack, suggesting that the remaining 37.2 percent entered the environment.

10.4.2 Composition measurements

USED OIL

Table 141 shows the average used oil compositions reported by the three source groups as well as the default values used in the 2010 base year model. The default values were arrived at by taking the unweighted average of the HEOF and Shell data when available, and taking the unweighted average of the other collected samples when Shell and HEOF data were not available. Several contaminants with high toxicity characterizations are sparsely represented in the composition data; composition estimates of those contaminants are not statistically representative of used oil.

NO. 2 DISTILLATE AND NO. 6 RESIDUAL OIL

Composition measurements for No. 2 distillate and No. 6 residual oil were taken from the MACT database and are reported in Table 142. Table 142 also shows the sensitivity of composition averages to non-detection strategy. Average compositions using each of the four candidate non-detect strategies are shown alongside one another. For each contaminant and each fuel, the table reports the total number of samples (n), the number of distinct facilities reporting measurements (N), and the number of non-detects within the sample set (NDs). For the 2010 base year model, the column corresponding to the half-detection-limit strategy was used.

The results show that for many contaminants there is not a statistically significant difference between the compositions of No. 2 and No. 6 fuel oil. Examples are Cd, Cl, F, Pb, Mn. Other substances are much more abundant in residual oil, for example Ba, Ni, P, S, Zn. A few substances (As, Cr, Se) appear to congregate more heavily in No. 2 than in No. 6, but the finding is not robust.

The results also show that composition measurements are highly sensitive to non-detection strategy. A larger corpus of data would be necessary to draw definitive conclusions about primary fuels composition.

Table 141: Composition measurements of used oil in the study. Revised values are indicated with a dagger symbol †.

Contaminant	Shell		HEOF		Other Sources		Base Year Model
	kg/kg	n	kg/kg	n	kg/kg	n	kg/kg
Aluminum	3.12E-06	1555	1.77E-06	532	2.34E-05	7	2.77E-06
Antimony	1.46E-06	113	1.35E-05	400	7.90E-07	2	1.09E-05
Arsenic					6.93E-07	108	6.93E-07
Ash			1.00E-02	248	6.35E-03	52	1.00E-02
Barium	1.62E-06	355	1.00E-06	269	1.24E-05	32	1.35E-06
Beryllium					1.92E-07	63	1.92E-07
Boron	3.38E-05	1732	1.08E-04	400	4.00E-06	2	4.77E-05
Cadmium					6.90E-07	131	6.90E-07
Calcium	2.42E-03	1742	2.67E-03	399	1.97E-03	8	2.46E-03
Chlorine					2.16E-04	106	2.16E-04
Chromium	1.23E-06	363	1.39E-06	532	2.19E-06	159	1.32E-06
Cobalt					8.21E-06	2	8.21E-06
Copper	1.16E-05	928	7.04E-06	532	3.53E-05	10	9.97E-06
Glycols					1.20E-03	2	1.20E-03
Halogens					2.94E-04	3	2.94E-04
Organic Halogens					3.64E-04	12	3.64E-04
Iron	1.30E-05	1742	2.37E-05	532	3.22E-05	3	1.55E-05
Lead	1.16E-06	93	1.05E-05	404	2.94E-05	147	8.79E-06
Magnesium	8.70E-06	1718	6.49E-05	270	1.58E-04	7	1.63E-05
Manganese					4.89E-06	85	4.89E-06
Mercury					1.47E-07	70	9.08E-08 [†]
Molybdenum	1.03E-04	1733	8.22E-05	270	1.00E-06	2	1.00E-04
Nickel	1.11E-06	436	1.06E-06	403	3.97E-06	102	1.09E-06
Nitrogen					4.07E-04	26	4.07E-04
Oxygen					1.18E-02	1	1.18E-02
Phenanthrene					9.90E-06	2	9.90E-06
Phosphorus	8.01E-04	1742	1.02E-03	400	7.64E-04	9	8.42E-04
PCB					1.09E-05	3	1.09E-05
PAH					2.19E-02	2	2.19E-02
Sediment					2.13E-03	6	2.13E-03
Selenium					5.28E-07	67	5.28E-07
Silicon	1.44E-05	1742	1.16E-05	400	6.80E-05	10	1.39E-05
Silver	1.00E-06	1	4.92E-07	404	1.32E-06	3	4.94E-07
Sodium	6.61E-06	1692	1.37E-05	400	5.73E-05	4	7.96E-06
Sulfur					4.37E-03	62	3.51E-03 [†]
Thallium					3.15E-05	1	3.15E-05
Tin	1.45E-06	74	2.42E-06	404	7.84E-06	6	2.27E-06
Titanium	1.72E-06	134			3.22E-06	3	1.72E-06
Vanadium					1.40E-05	4	5.00E-07 [†]
Zinc	9.88E-04	1742	1.23E-03	400	1.02E-03	36	1.03E-03

Table 142: Composition measurements of No. 2 and No. 6 fuels.

No. 2 Distillate				Mass Fraction by nondetect strategy (kg/kg)			
Contaminant	n	N	NDs	omit	zero	half	full
Aluminum	2	2	0	4.15E-06	4.15E-06	4.15E-06	4.15E-06
Antimony	58	8	41	1.25E-06	1.93E-07	1.32E-06	2.27E-06
Arsenic	104	22	80	1.49E-06	2.33E-07	1.25E-06	2.16E-06
Barium	6	4	4	3.00E-07	1.00E-07	5.42E-06	1.07E-05
Beryllium	96	17	72	8.95E-07	1.73E-07	3.51E-07	4.93E-07
Cadmium	99	20	79	4.07E-07	1.21E-08	2.41E-07	4.28E-07
Chlorine	111	22	41	6.58E-05	4.08E-05	4.73E-05	5.37E-05
Chromium	107	24	78	2.16E-06	4.34E-07	1.12E-06	1.67E-06
Cobalt	57	7	42	4.31E-07	1.13E-07	2.69E-07	4.24E-07
Copper							
Fluorine	35	5	17	9.78E-06	3.63E-06	1.06E-05	1.62E-05
Lead	97	24	63	1.32E-06	4.45E-07	1.62E-06	1.88E-06
Manganese	102	18	55	1.42E-06	6.48E-07	8.15E-07	1.04E-06
Mercury	109	20	71	1.49E-08	5.19E-09	6.36E-08	1.22E-07
Nickel	100	20	72	2.77E-06	5.31E-07	1.05E-06	1.44E-06
Phosphorus	57	7	31	4.65E-06	2.08E-06	5.02E-06	7.54E-06
Selenium	96	17	73	1.41E-06	2.58E-07	1.65E-06	2.96E-06
Sulfur	685	202	94	0.002206	0.001904	0.001947	0.00199
Tin							
Vanadium	1	1	0	1.60E-06	1.60E-06	1.60E-06	1.60E-06
Zinc	6	4	2	2.13E-06	1.42E-06	3.63E-06	5.84E-06

No.6 Residual oil				Mass Fraction by nondetect strategy (kg/kg)			
Contaminant	n	N	NDs	omit	zero	half	full
Aluminum	2	2	0	2.50E-06	2.50E-06	2.50E-06	2.50E-06
Antimony	89	10	62	3.67E-07	1.08E-07	6.92E-07	1.26E-06
Arsenic	160	26	123	3.31E-07	7.79E-08	3.80E-07	6.80E-07
Barium	2	2	0	2.46E-05	2.46E-05	2.46E-05	2.46E-05
Beryllium	166	23	122	2.55E-07	6.53E-08	2.15E-07	3.66E-07
Cadmium	174	26	133	2.89E-07	6.56E-08	2.08E-07	3.26E-07
Chlorine	163	25	66	8.60E-05	5.10E-05	7.23E-05	9.61E-05
Chromium	194	29	94	3.77E-07	1.90E-07	4.81E-07	7.72E-07
Cobalt	87	9	31	8.39E-07	4.36E-07	9.26E-07	1.20E-06
Copper	1	1	1	NaN	0	5.00E-07	1.00E-06
Fluorine	64	6	34	5.96E-06	2.79E-06	4.05E-05	7.81E-05
Lead	203	30	74	7.13E-07	4.49E-07	6.47E-07	8.45E-07
Manganese	194	25	52	1.18E-06	8.62E-07	2.24E-06	2.39E-06
Mercury	222	24	116	8.97E-08	4.24E-08	7.25E-08	1.03E-07
Nickel	258	35	7	3.40E-05	3.30E-05	3.31E-05	3.32E-05
Phosphorus	75	8	32	3.50E-05	1.81E-05	2.07E-05	2.33E-05
Selenium	145	22	98	4.06E-07	1.28E-07	5.41E-07	9.45E-07
Sulfur	935	134	6	0.011628	0.011553	0.011601	0.011649
Tin	2	1	0	9.05E-07	9.05E-07	9.05E-07	9.05E-07
Vanadium	10	5	0	7.50E-05	7.50E-05	7.50E-05	7.50E-05
Zinc	4	3	1	1.94E-05	1.46E-05	1.46E-05	1.46E-05

Legend: **Bold** Marked concentration exceeds corresponding concentration for other fuel by more than 2x

Red Marked concentration exceeds corresponding concentration for other fuel by more than 5x

MARINE DISTILLATE

Reliable metals composition data for MDO, either primary or from distilled used oil, were not available. The No. 2 distillate composition was assumed for primary MDO. A small number of individual laboratory results were averaged together to generate a composition profile for recycled MDO, shown in Table 143 below. Contaminant concentrations were capped at the used oil concentration from above. Missing entries were adopted from No. 2 distillate composition.

Recycled MDO	kg/kg		kg/kg
Aluminum	2.77E-06	Manganese	8.15E-07
Antimony	3.00E-06	Mercury	1.47E-07
Arsenic	6.93E-07	Molybdenum	0.00E+00
Barium	1.35E-06	Nickel	4.00E-07
Beryllium	5.00E-08	Phosphorus	7.39E-06
Cadmium	2.00E-07	Selenium	5.28E-07
Chlorine	4.73E-05	Silver	2.00E-07
Chromium	4.00E-07	Sulfur	2.00E-06
Cobalt	6.00E-07	thallium	0.00E+00
Copper	6.00E-07	tin	0.00E+00
Fluorine	0.00E+00	Vanadium	4.00E-07
Lead	1.05E-06	Zinc	3.47E-06

Table 143: Metals concentration for marine distillate oil produced from recycled oil.

10.5 Emission Factors

10.5.1.1 GREENHOUSE GASES

Carbon Dioxide, CO₂

CO₂ emissions are a direct function of the carbon content of the fuel and can be stated generally as:

$$EF_{CO_2} = C_{fuel} \times 44/12 \tag{B.5}$$

where C_{fuel} is the mass fraction of carbon in the fuel. Methane has the lowest carbon mass fraction of any pure hydrocarbon, at 75 percent; the maximal carbon content for a fuel made of saturated long-chain hydrocarbons is 85.7 percent.

CO₂ EFs are given in Table 144. The values in the study were drawn from (U.S. EPA, 2008) except for natural gas, which was computed based on a typical composition provided in EIA (2012).

Fuel	Carbon dioxide	EF		Source
	kg/MJ LHV	low	kg/kg high	
RFO	0.0719		2.98	EPA GHG
No 2	0.0740		3.18	EPA GHG
No 6	0.0772		3.12	EPA GHG
Natural Gas	0.0553		2.71	Composition
Light Ends	0.0723		3.18	as Diesel

Table 144: Emission Factors for CO₂.

Methane, CH₄

Reference values for methane emissions are reported in (U.S. EPA, 2008) and are used in the base year model. Methane emissions were also reported by several facilities in MACT. An EF chart for methane grouped by data source and fuel is shown in Figure 61.

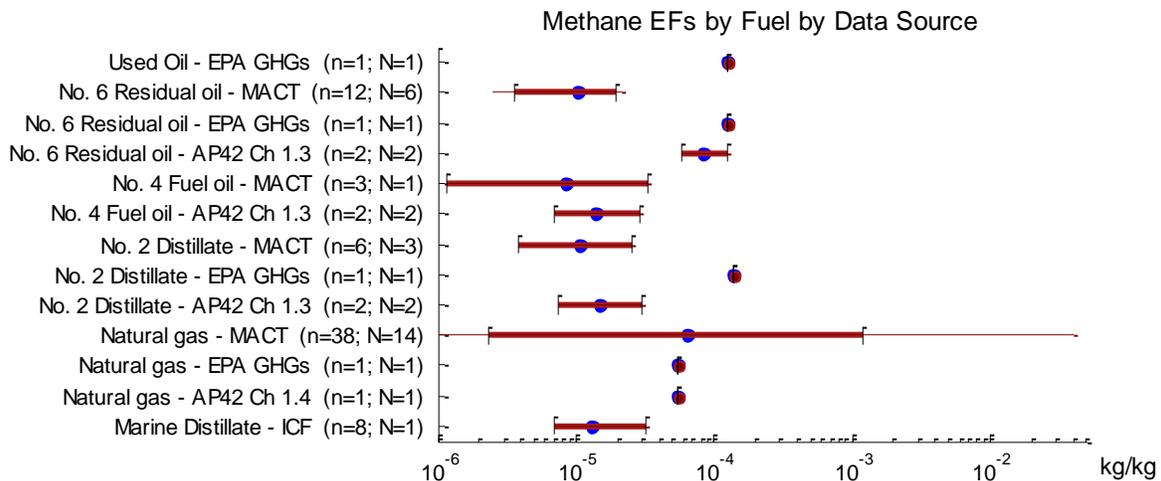


Figure 61: Measured emissions of methane in the combustion model.

CH₄ emission factors are given in Table 145. Low and high values were taken from the MACT data set 10th and 90th percentiles.

Fuel	Methane		EF		Source
	kg/MJ LHV	low	kg/kg	high	
RFO	3.07E-06		1.27E-04	4E-04	EPA GHG
No 2	3.20E-06	3E-06	1.38E-04		EPA GHG + MACT
No 6	3.10E-06	2E-06	1.25E-04		EPA GHG + MACT
Natural Gas	1.12E-06	2E-06	5.50E-05	1E-03	EPA GHG + MACT
Light Ends	3.13E-06		1.38E-04		as Diesel

Table 145: Emission factors for methane.

Nitrous oxide, N₂O

Very little data on N₂O emissions were found. Reference values were taken from EPA (2009). Insufficient data were available to enter low and high ranges. Emission factors are shown in Table 146.

Fuel	N ₂ O		EF		Source
	kg/MJ LHV	low	kg/kg	high	
RFO	6.14E-07		2.54E-05		EPA GHG
No 2	6.40E-07		2.75E-05		EPA GHG
No 6	6.21E-07		2.51E-05		EPA GHG
Natural Gas	1.12E-07		5.50E-06		EPA GHG
Light Ends	6.26E-07		2.75E-05		as Diesel

Table 146: Emission factors for nitrous oxide.

INORGANICS

Carbon monoxide, CO

Carbon monoxide was the most abundantly measured pollutant in the data set, with 1,974 measurements from 296 facilities. Many facilities measuring CO were equipped with continuous emission monitoring systems that were used to establish the measurement. The majority of measurements (1,566) were of natural gas facilities.

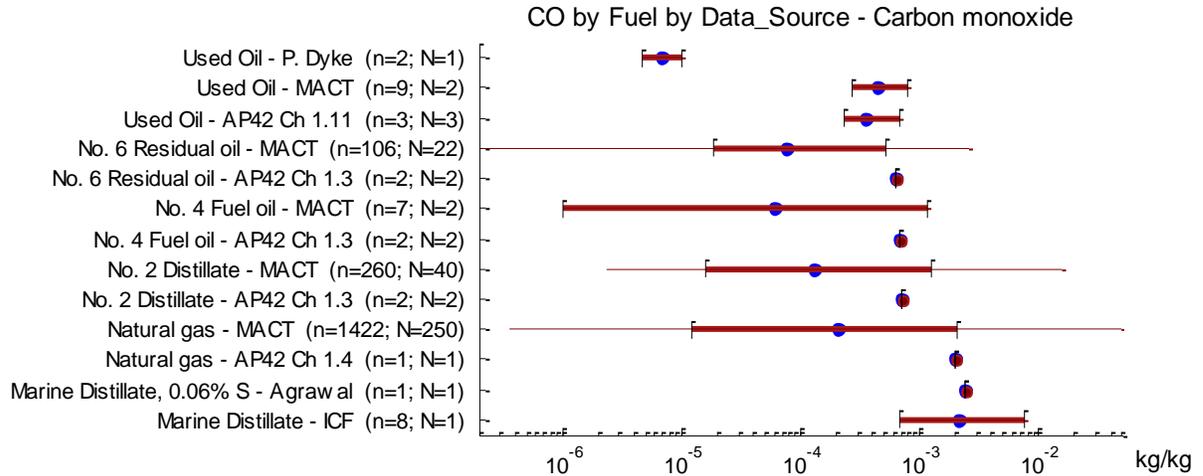


Figure 62: Distribution of emission measurements for carbon monoxide.

Figure 62 shows the distribution of emission factor measurements by fuel and data source. The data show wide variability in CO measurements. Figure 63 shows a histogram of the results on a log scale, highlighting the lognormal distribution of emission factors. (The peak in measurements centered around 1e-3 kg/kg can be partially attributed to an unusually large sample set from a single facility (n=137) with a tight grouping around a mean value of 9.6e-4 kg/kg.)

Although the histogram is dominated by natural gas measurements, the range is largely consistent for all fuels (see Figure 63) and spans 1e-5—2e-3 kg/kg). Used oil emissions appear modestly higher, but not in a way that is statistically significant. Thus, the same CO emission factor was used for all non-marine fuels in the study. The upper and lower bounds by fuel are shown in Table 147.

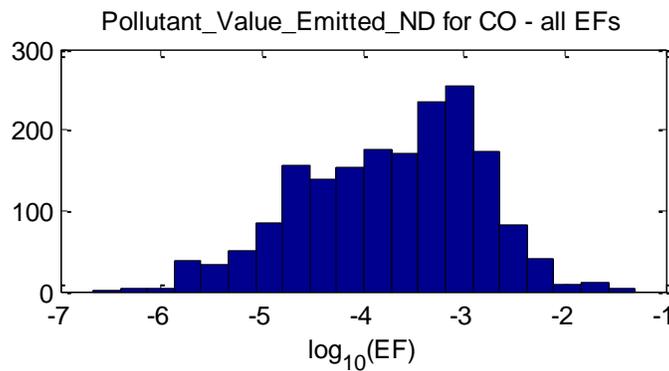


Figure 63: Histogram of carbon monoxide emission factor measurements.

Fuel	Carbon monoxide kg/MJ LHV	EF			Source
		low	kg/kg	high	
RFO	3.4E-06	7E-06	1.4E-04	8E-04	Combustion Model
No 2	3.3E-06	1.6E-05	1.4E-04	1.3E-03	Combustion Model
No 6	3.5E-06	1.8E-05	1.4E-04	5E-04	Combustion Model
Natural Gas	2.9E-06	1.2E-05	1.4E-04	2E-03	Combustion Model
Light Ends	2.7E-05		1.4E-04		as Diesel

Table 147: Emission factors for carbon monoxide.

Oxides of Nitrogen, NOx

NOx emissions were primarily reported in MACT and in the AP42 guidance, except for used oil, which was drawn from AP42 and P. Dyke. Although the sample sizes were relatively small, the data indicated a separation by fuel that appeared to be statistically significant. Because NOx emissions include both fuel NOx and thermal NOx, it is possible that differences observed across fuels are attributable to differing concentrations of nitrogen in the fuel.

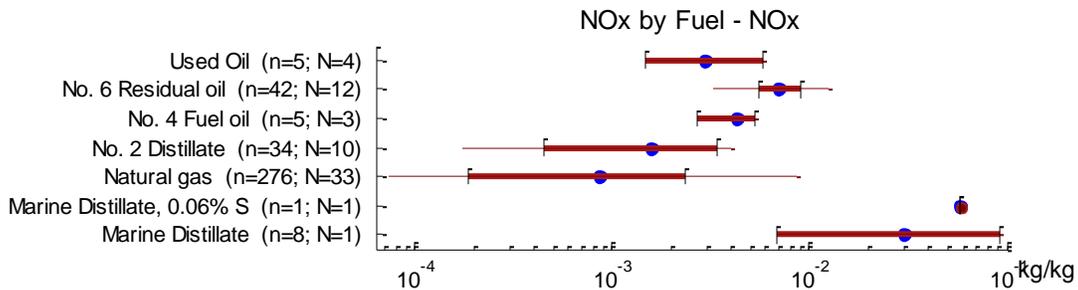


Figure 64: Emission measurements for oxides of nitrogen by fuel.

Figure 64 shows the distribution of NOx emission measurements aggregated by fuel. Table 148 shows NOx emission factors.

Fuel	Nitrogen oxides kg/MJ LHV	EF			Source
		low	kg/kg	High	
RFO	7.25E-05	1.5E-03	3.0E-03	6E-03	Combustion Model
No 2	3.72E-05	4E-04	1.6E-03	3.5E-03	Combustion Model
No 6	1.73E-04	5.5E-03	7.0E-03	9E-03	Combustion Model
Natural Gas	1.63E-05	1.9E-04	8.0E-04	2.3E-03	Combustion Model
Light Ends	6.82E-05		3.0E-03		as Diesel / High

Table 148: Emission factors for oxides of nitrogen.

Oxides of Sulfur, SOx

A conventional assumption in life cycle assessment is that the full sulfur content of a combusted fuel is emitted into the atmosphere as sulfur dioxide and sulfur trioxide. Consequently, SOx emissions are not often measured directly, but are estimated from fuel sulfur content. The model used in this study modeled sulfur emissions on the basis of a retention rate gathered from test measurements.

Figure 65 shows all reported matched sulfur composition and emission measurements in the model. Approximately two-thirds of the retention rates are literature values and are very close to zero.

Retention rates were assigned on a technology-specific basis. For atomizing heaters and marine engines, no appreciable retention was expected. For boilers, five MACT facilities reported sufficient information to estimate sulfur retention; of these, two reported essentially zero retention (slightly greater emission than composition measurement); two reported a 5-10 percent retention rate, and one reported approximately a 75 percent retention rate over two tests.

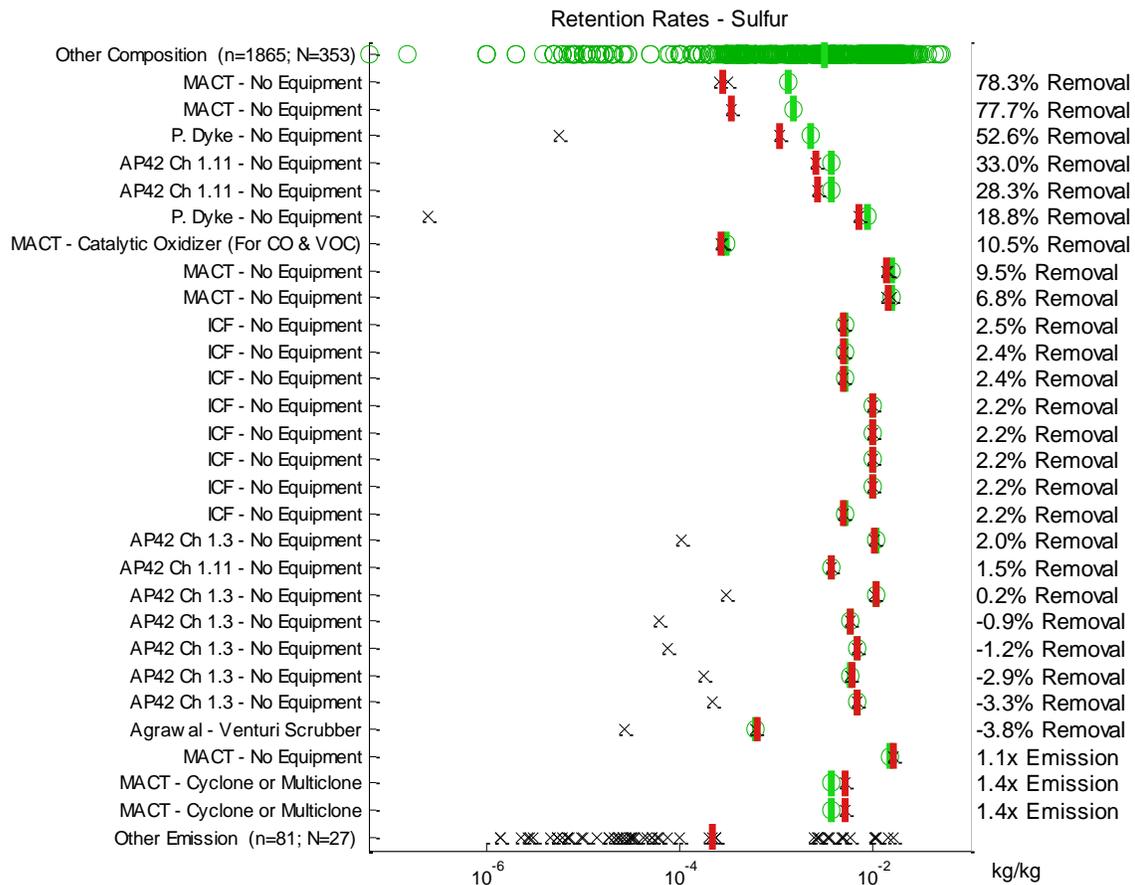


Figure 65: Measured and reported SOx retention rates.

For kilns with baghouses, a study from the Wisconsin Department of Natural Resources was drawn upon to suggest that 50 percent retention of sulfur in aggregate is typical in asphalt plants (Eagan, 2000), while literature reports suggest that the majority of sulfur in cement kilns is retained in the clinker (Kalnes et al., 2006). Finally, the Dyke (2007) study measured sulfur retention to be 18 percent and 50 percent in two successive tests; these results were used to bound the retention rates for vaporizing heaters.

The technology-specific retention rates are shown in Table 149 below.

	SOx Retention		
	low	default	High
Boiler	0	0.15	0.5
Atomizing Heater	0	0.05	0.2
Vaporizing Heater	0.15	0.35	0.5
Baghouse	0.25	0.6	0.75
Marine	0	0.02	0.2

Table 149: Retention rates for sulfur by technology.

Particulate Matter (PM)

Particulate emissions were fairly well characterized in the study, with multiple data sources reporting measurements that were mutually consistent for a given fuel. Because particulate matter can be measured and reported in a variety of ways, great care was taken to interpret measurements correctly and harmonize different data sources with one another.

The EPA distinguishes between “filterable” and “condensable” particulates. Filterable particulates are in the solid phase at the stack emission temperature, while condensable particulates are in the vapor or gas phase at stack temperatures but condense to the solid or liquid phase in ambient air. In the MACT data, some facilities reported total PM including condensables, while others reported filterable PM only. Standards for measurement and reporting of condensable PM are not well-established, and their inclusion in life cycle impact assessment methodologies is unclear.

In this study, “PM Total” refers to total filterable PM; “PM Total (+cond)” refers to total PM including both filterable and condensable; and “PM10” denotes filterable particulates below 10 microns in diameter, a subset of total PM. Emission factors were developed for PM Total and for PM10, with the ratio of PM Total to PM10 being fixed for each fuel.

Figure 66 shows particulate emissions as measured by sources with no reported control equipment, grouped by fuel and data source, and sorted in order of increasing category size (i.e. PM10, followed by total filterable PM, followed by total filterable PM including condensables). The data show, first, that the different category measurements are consistent both within and across data sets, in other words that measurements of PM including condensables are generally higher than measurements of filterable PM, which are in turn higher than measurements of PM10. Moreover, measurements made for the MACT database are largely consistent with guidance

contained in AP42. Finally, emission measurements clustered by fuel in a pattern that is consistent with a characteristic emission factor for each fuel.

Based on a review of the data, PM emissions were modeled as a maximal emission factor that is fuel-specific, combined with a mitigation rate that is technology-specific. The condensable portion was omitted when developing emission factors. Distinct mitigation rates were determined for boilers, atomizing space heaters, vaporizing space heaters, and kilns with fabric filters. The mitigating effects of control technologies were applied to PM Total and PM10 equally.

Figure 67 shows a detail of PM measurements for used oil from all sources and facilities, sorted by burner capacity. The data can be seen to fall into three clusters. Measured emissions from the five facilities in the Vermont study, from two facilities in the MACT database, and emission factors from the AP42 guidance for small boilers and atomizing heaters, all cluster between 0.002 and 0.006 kg PM per kg fuel, referred to below as the standard range for PM emissions from used oil. The data points in this group span a historical range of 11 years (1996-2007) and a capacity range of three orders of magnitude. The mean value of data points in the standard range was used to set the unmitigated PM emission factor for used oil.

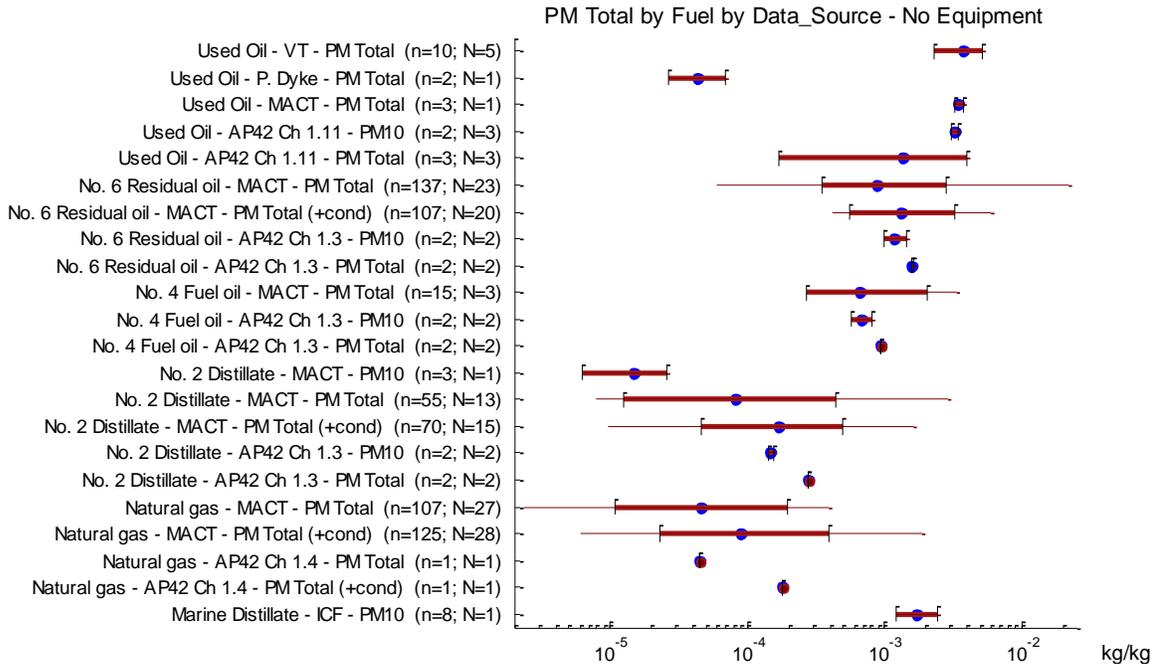


Figure 66: Particulate matter emissions by fuel for facilities with no control technology.

Other data in Figure 67 were used to estimate technology-specific mitigation rates. The lowest entry in this range, also the most recent, is from the Puunene Sugar Mill in the MACT database, a facility equipped with a cyclone and Venturi scrubber; the other facilities had no controls. The typical boiler PM mitigation rate was calculated as the ratio between the mean of the two MACT facilities and the unmitigated PM emission factor described above. Atomizing heaters were assumed to emit at the unmitigated rate.

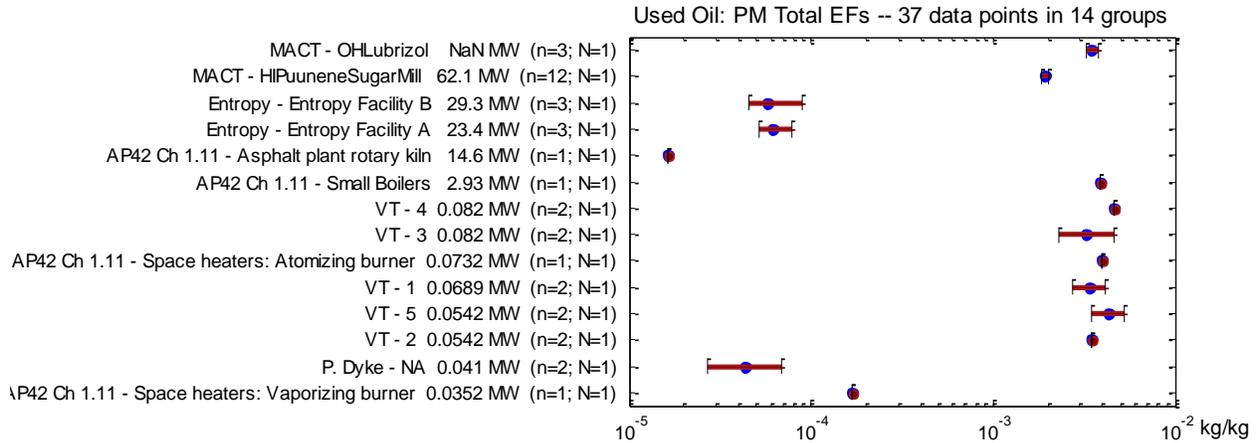


Figure 67: Particulate matter emission measurements for used oil by facility.

In the top left of the diagram is another cluster of emission measurements corresponding to direct-fired rotary kilns equipped with baghouse filters. This cluster includes AP42 guidance as well as two measurements from the Entropy study. The separation between these factors and the standard range above was used to estimate the mitigation rate for baghouse filters.

Finally, in the bottom left of the figure are two emission factors for vaporizing heaters, one from P. Dyke and the other from AP42. These points were used to estimate the mitigation rate for vaporizing heaters. Final unmitigated PM emission factors for each fuel are shown in Table 150. PM mitigation rates are shown in Table 151.

Fuel	PM Total kg/MJ LHV	EF		Source	PM10 / PM Total	PM2.5 / PM Total
		low	high			
RFO	7.25E-05	5E-04	4E-03	Combustion Model	0.8	0.5
No 2	1.86E-06	1.2E-05	4E-04	Combustion Model	0.5	0.12
No 6	2.48E-05	4E-04	3E-03	Combustion Model	0.86	0.56
Natural Gas	8.16E-07	1E-05	2E-04	Combustion Model	1	1
Light Ends	2.18E-07		1.2E-05	as Diesel / Low	1	1

Table 150: Particulate matter emission factors by fuel.

	PM Mitigation		
	low	default	High
Boiler	0	0.2	0.6
Atomizing Heater	0	0	0.5
Vaporizing Heater	0.75	0.95	0.99
Baghouse	0.92	0.98	0.99
Marine	0	0	0.5

Table 151: Particulate matter retention rates by technology.

ORGANICS

A wide range of volatile organic compounds are produced during combustion, and many of them have potentially deleterious environmental impacts. However, although the potential impacts of different species vary widely, there is no consensus estimation of the speciation profile of VOCs from combustion.

For the combustion model, differences in flow reporting and grouping by different data sources made it challenging to draw meaningful conclusions at any level of detail regarding flows of distinct compounds. Thus, the approach was adopted to estimate the total mass of compounds in each flow group and assign the aggregate a characterization factor equivalent to a weighted average of a representative basket of individual species. Because polycyclic aromatic hydrocarbons are of high environmental concern, they are modeled as a separate flow. Halogenated organics were not included in the model.

Organic compounds represent the model's largest area of uncertainty. Because of the large uncertainty associated with both the quantity and impact characterization of organics, a sensitivity analysis was performed in which the emission factors were varied over a wide range to determine the significance of the parameter. The results of that analysis are included in section 6.

Volatile organic compounds, excluding methane and PAH (NMVOC)

Emission Factors

Figure 68 shows emission factors in the combustion model for measurements of total organic carbon (TOC), total NMVOC, and summed speciated NMVOC, grouped by fuel. In this chart, measurements of unspecific TOC and NMVOC are treated differently from measurements of individual species. Directly reported measurements of TOC are grouped together and averaged by fuel. Distinct measurements of NMVOC are grouped and averaged similarly. Measurements of individual species are grouped by test and added together to determine the total speciated NMVOCs reported for each test. For speciated NMVOC, the small n refers to the number of tests; the number of measurements is larger.

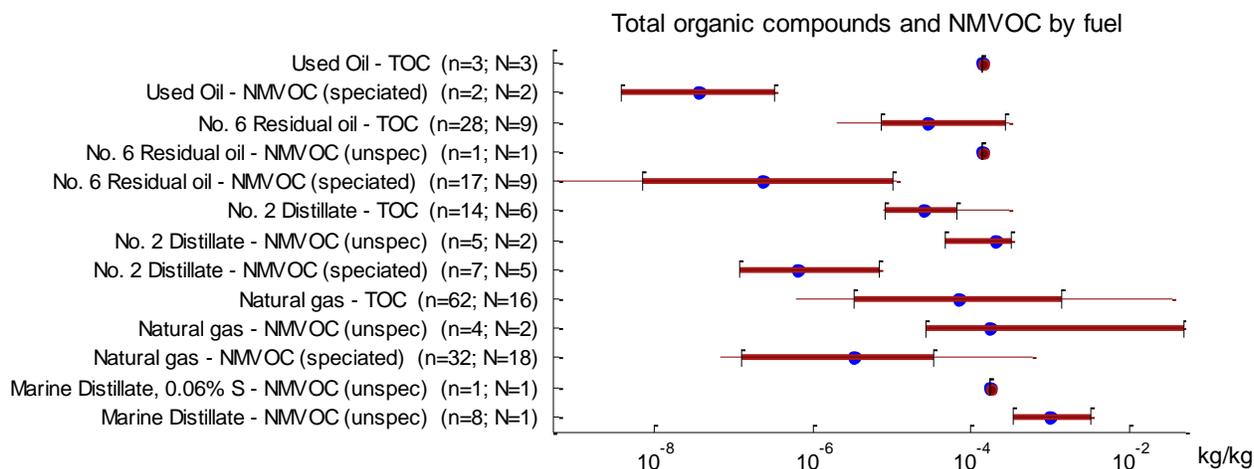


Figure 68: Organic emissions by fuel.

The data show primarily that there is a wide discrepancy between measurements of total NMVOC and individual compounds, often reaching orders of magnitude. The implication is that measurements of speciated VOCs are not suitable to estimate the total potential environmental load from organic compounds in aggregate. A second observation is that the range of NMVOCs observed in the data set do not appear to vary widely by fuel, except for natural gas, which appears to have somewhat higher emissions. The data also do not indicate a correlation between most control technologies and VOC emission (not shown).

NMVOC emission factors were taken from AP42 guidance documents for different fuels in the absence of clear empirical evidence contradicting the regulatory guidance, acknowledging that the supporting information for those factors indicates a low level of statistical robustness. Chapter 1.11 of AP42 guidance does not provide enough information to estimate NMVOC emissions for used oil; an arithmetic average of emission factors from No. 2 and No. 6 oil was used. High and low ranges were taken from MACT data, except for used oil, in which an order of magnitude was used. Emission factors are shown in Table 152 below.

Fuel	Generic NMVOC, combustion (non PAH) kg/MJ LHV	EF		Source	
		low	high		
RFO	3.14E-06	1E-05	1.3E-04	1E-03	AP-42, Combustion model
No 2	1.40E-06		6.0E-05	3E-04	AP-42, Combustion model
No 6	3.96E-06	1E-04	1.6E-04	2E-03	AP-42, Combustion model
Natural Gas	4.49E-06	3E-05	2.2E-04	4E-02	AP-42, Combustion model
Light Ends	1.82E-06		8.0E-05		as Diesel / High

Table 152: Emission factors for VOCs (non-methane, non-PAH) by fuel.

NMVOC Impact Characterization

The environmental impacts of VOC emissions depend strongly on the particular chemical species being modeled. Because the TRACI 2.0 impact assessment methodology does not include a generic VOC flow, it was necessary to design a custom flow. The approach in this study was to create a generic flow by selecting a basket of VOCs that are typical combustion byproducts and compute an average characterization factor weighted by the relative abundance of the various species in combustion exhaust. In order to select common flows and assess their prevalence, the EPA Speciate database was used; 27 representative species were selected based on data sets from external combustion sources in Speciate and in the combustion model. Weights equal to 10, 5, 1, or 0.5 were assigned on a heuristic basis to reflect the relative concentrations of the various flows in the combustion data. The weighted mixture of VOCs used to develop the flow characterization is shown in Table 153.

Flow Name	Weight	Characterization Factors (TRACI 2.0)			
		Ecotox A	HHC A	HHNC A	Smog
Acetaldehyde (Ethanal)	10	0.292	9.51E-08	4.88E-07	6.539
Acetone (dimethylcetone)	10	0.079		6.25E-09	0.356
Butane	10				1.151
Ethane	10				0.281
Ethene (ethylene)	10				8.995
Formaldehyde (methanal)	10	26.804	1.34E-05	1.71E-07	9.456
Propane	10				0.489
Propene (propylene)	10				11.665
Benzene	5	0.064	2.97E-07	7.52E-08	0.721
Butene (vinyl acetylene)	5				10.481
Butyraldehyde	5	0.122			5.974
Hexane (isomers)	5	0.000	9.93E-10	1.35E-07	1.244
iso-Butane	5				1.230
Pentane (n-pentane)	5	0.010			1.313
Butanone (methyl ethyl ketone)	1	0.058		9.03E-10	1.481
Cyclohexane (hexahydro benzene)	1	0.001		1.16E-08	1.250
Ethine (acetylene)	1				0.954
Glyoxal	1	4.917			12.504
iso-Butene	1		3.44E-09		6.293
Methyl glyoxal	1				16.561
Toluene (methyl benzene)	1	0.013	3.18E-12	5.30E-08	4.005
Xylene (dimethyl benzene)	1	0.011	4.75E-09	1.10E-07	7.764
Butylbenzylphthalate	0.5	84.108	3.58E-08	5.20E-08	
Di(2-ethylhexyl)phthalate	0.5	6.138	1.14E-07	1.59E-06	
Dibutylphthalate	0.5	97.813		5.67E-08	1.246
Ethyl benzene	0.5	0.028	3.34E-07	5.50E-09	3.038
Phenol (hydroxy benzene)	0.5	19.602		4.86E-08	2.756
Characterization Factors: Units (per kg generic NMVOC):		3.167 CTUEco	1.13E-06 cases	7.27E-08 cases	4.552 kg O3- equiv

Table 153: Composite VOC characterization factor calculation.

Polycyclic Aromatic Hydrocarbons (PAH)

Emission Factors

Very little in the way of consensus data is available on emissions of PAH from the combustion of fuel products. The most extensive data sources evaluated for this study are the AP42 guidance and the Dyke (2007) study. However, a review of the background documents supporting the AP42 guidance reveals that the speciated emissions reported therein are based on a very small number of tests, often from only one or two facilities or combustion devices (U.S. EPA, 1996a, 1996b, 1996c). The Dyke study is similarly limited in scope.

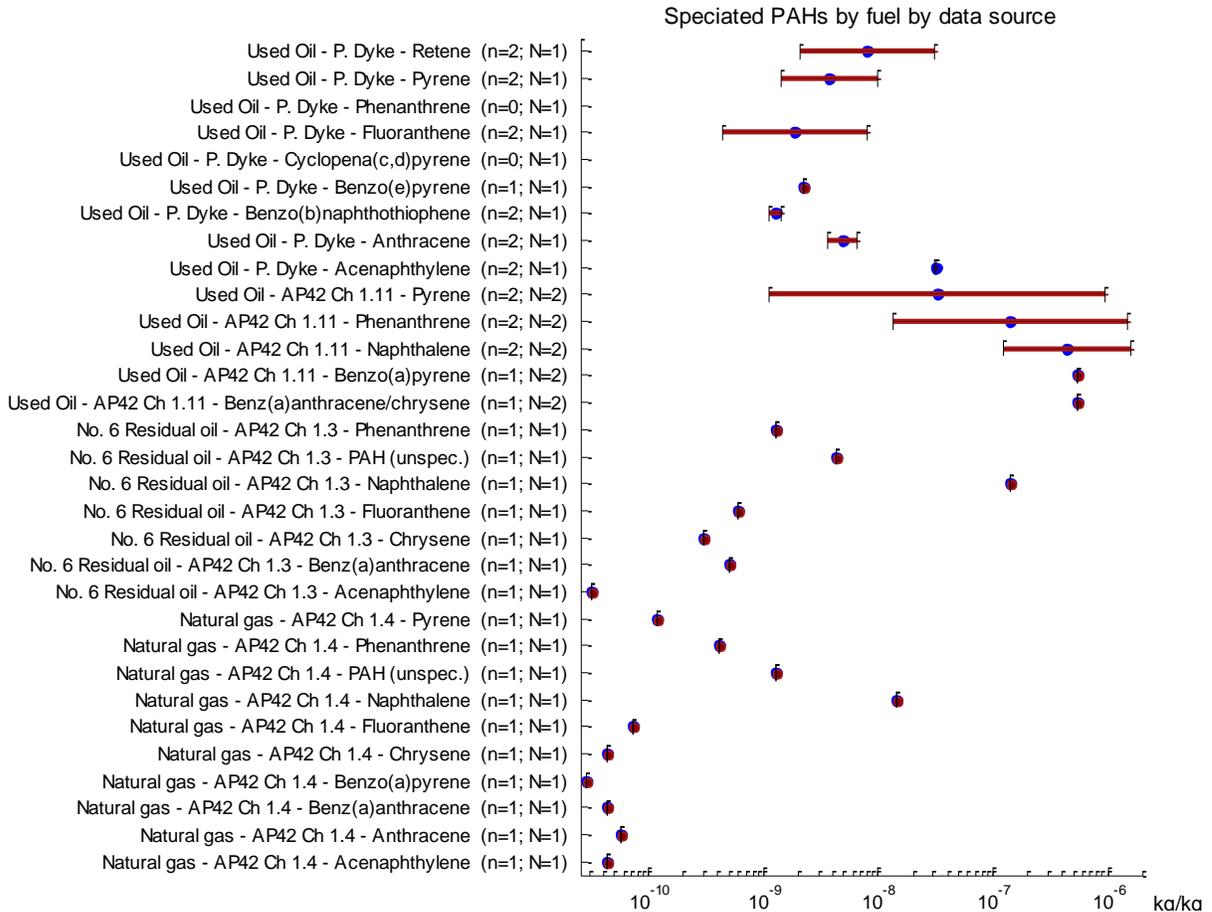


Figure 69: Polycyclic organic species by source and fuel.

Figure 69 shows speciated PAH emissions as reported in Dyke and in the AP42 guidance. In the estimation of the authors, very limited conclusions can be drawn from these data. One conclusion that can be drawn from the Dyke study in particular is that, even in sequential tests on a single combustor under laboratory conditions, concentrations of individual PAHs can vary across tests by more than an order of magnitude. This suggests that emission factors for individual species based on the data are bound to misrepresent likely emissions.

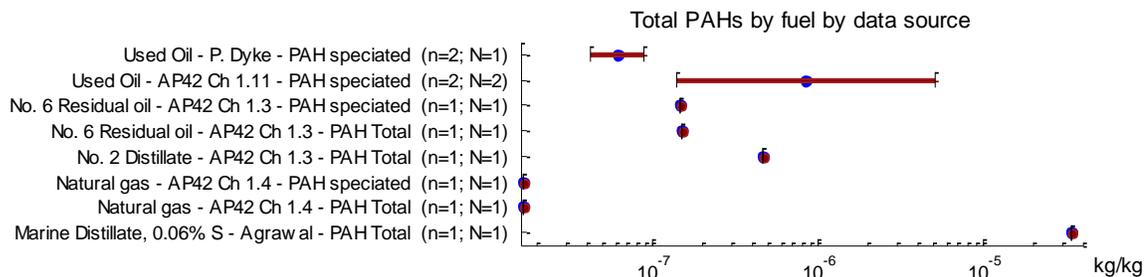


Figure 70: Total PAH by fuel by data source.

Figure 70 shows total PAH by fuel and is drawn primarily from AP42. These results were used to set emission factors for a generic PAH flow by fuel. A wide range of values was tested in sensitivity analysis. Emission factors are shown below.

Fuel	UO_Generic PAH, combustion kg/MJ LHV	EF			Source
		low	kg/kg	high	
RFO	1.93E-08	8E-08	8.0E-07	8E-05	AP-42, Combustion model
No 2	1.16E-08	5E-08	5.0E-07	5E-05	AP-42, Combustion model
No 6	3.71E-09	1.0E-08	1.5E-07	1.0E-05	AP-42, Combustion model
Natural Gas	2.86E-10	1E-08	1.4E-08	1E-06	AP-42, Combustion model
Light Ends	1.14E-08		5.0E-07		as Diesel

Table 154: Emission factors for PAH by fuel.

Characterization Factors

Similarly to VOCs, the characterization factors for speciated PAHs vary widely. A review of literature also supports the contention that the distribution tendency of individual PAH species cannot be generalized except for a few key observations (Mastral, Callén, & Garcia, 2000). Naphthalene, the simplest PAH, occurs far more frequently than the more complex species, a result borne out by the empirical data in the combustion model. Beyond that, no conclusions could be drawn.

The approach in this study was to create a generic flow by selecting a basket of PAHs and compute an average characterization factor weighted by the relative abundance of the various species in combustion exhaust. The weights were chosen heuristically based on review of the combustion model data as well as the literature cited above.

The weighted mixture is shown below.

Flow Name	Weight	Characterization Factors (TRACI 2.0)			
		Ecotox A	HHC A	HHNC A	Smog
Benzo{a}anthracene	1	3941			
Anthracene	1	689		7.54E-09	
Fluoranthene	5	653		1.57E-07	
Phenanthrene	5	115.0			
Benzo{a}pyrene	1	107.0	3.49E-05		
Dibenz(a)anthracene	1	34.65	1.43E-05		
Fluorene	1	12.27		6.34E-08	
Acentaphthene	1	3.030		2.80E-08	
Naphthalene	50	1.615	6.35E-07	8.74E-07	3.344
2,3-Dimethylnaphtalene	1	0.070			4.994
Characterization Factors:		129.943	1.21E-06	6.65E-07	2.570
Units (per kg generic PAH):		CTUEco	cases	cases	kg O3-eq.

Table 155: Composite PAH characterization factor calculation.

METALS

Having both fuel composition and emission factor data from the same facility permitted the automatic computation of contaminant removal efficiencies, referred to here as retention rates. A total of 233 retention rates were calculated from the data in the combustion model, of which 188 were for metals. Of these, 154 are self-consistent in that the measured emission does not exceed the measured emission capacity based on fuel composition (emission measurements within 105 percent of measured concentrations were considered to be essentially zero retention within the bounds of measurement and transcription precision).

Retention rates were found to have wide ranges and to vary by facility. Individual facilities tended to be consistent on successive measurements. Combustion and control technology can be seen to have discernible effects on retention rates, although the data set is too small to draw firm conclusions. All metal retention rates found in the study are shown in Figure 71, grouped by technology and sorted by decreasing emitted fraction of the group (geometric average). Retention rates are reported as emitted fraction of composition measurement and shown on a log scale.

Retention Rates by Technology

The retention rates for metals by technology in the study are estimated from the combustion model results as shown in Table 156. The default value is equal to one minus the geometric mean of the emitted fraction for the technology group. Lower and upper bounds were selected to match the 10th and 90th percentiles for the group.

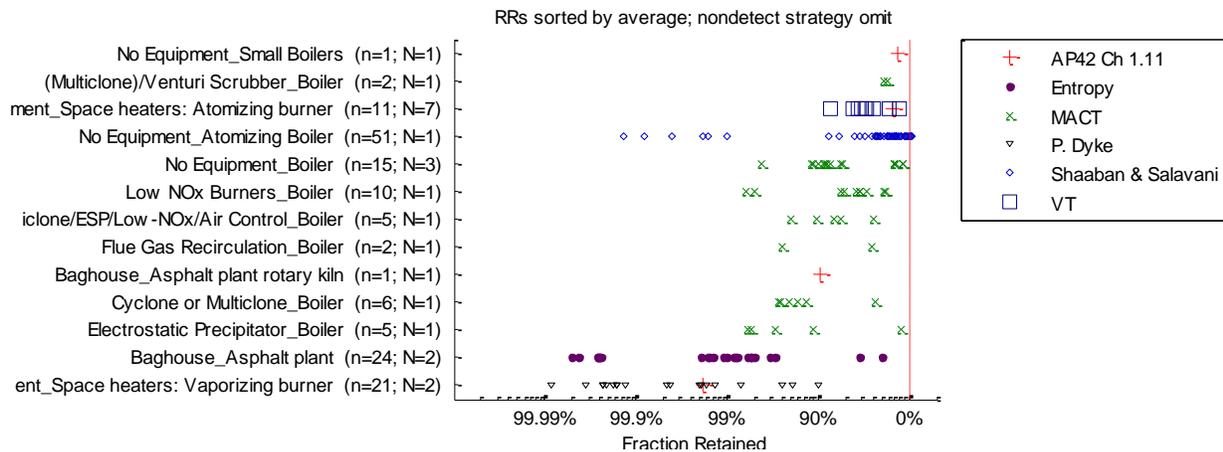


Figure 71: Retention rates for metals, grouped by technology.

Metals Retention			
	low	default	High
Boiler	0.2	0.85	0.95
Atomizing Heater	0	0.4	0.8
Vaporizing Heater	0.75	0.998	0.999
Baghouse	0.95	0.99	0.999
Marine	0	0.4	0.6

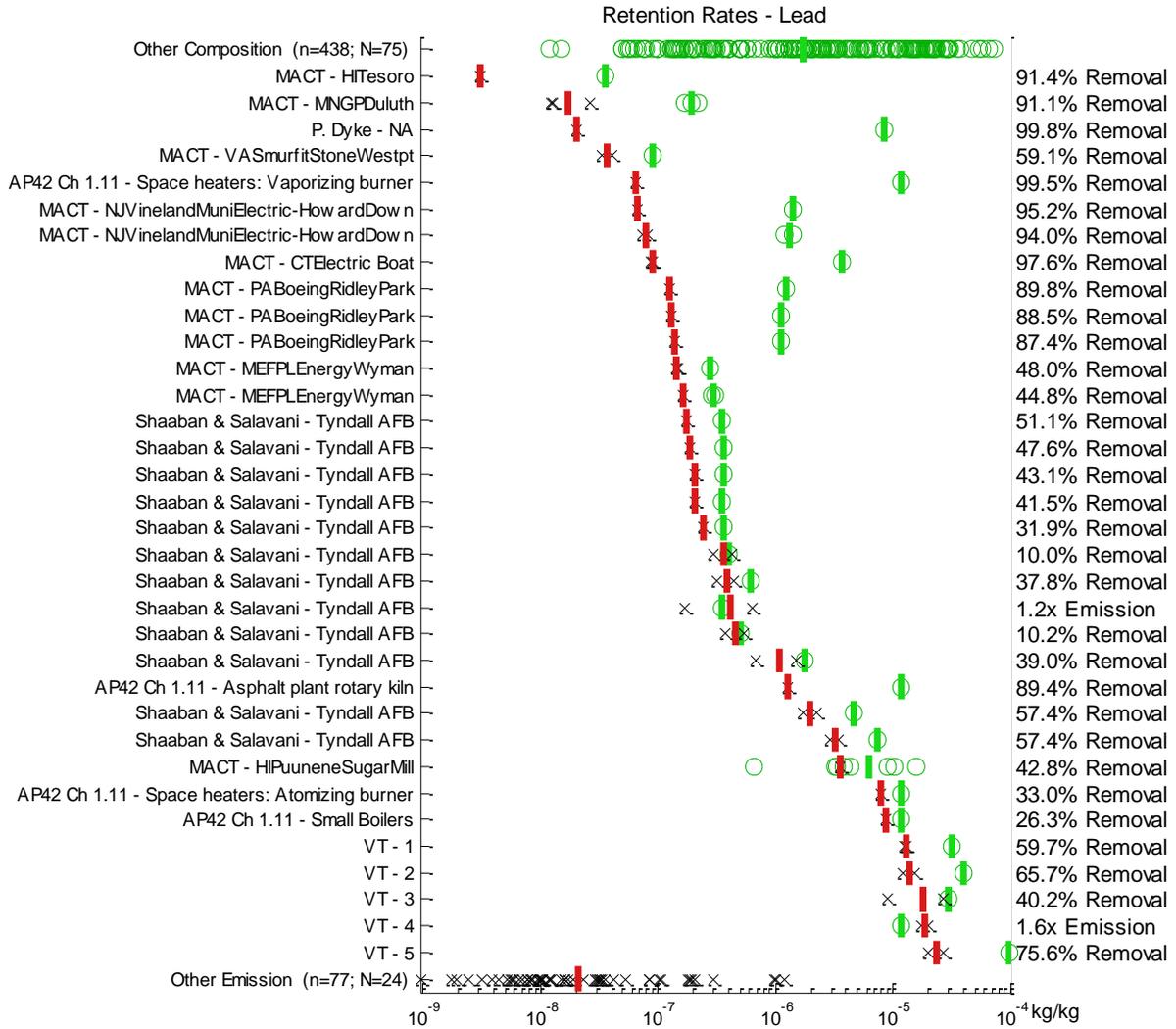
Table 156: Retention rates for metals.

Variability by Substance and Facility

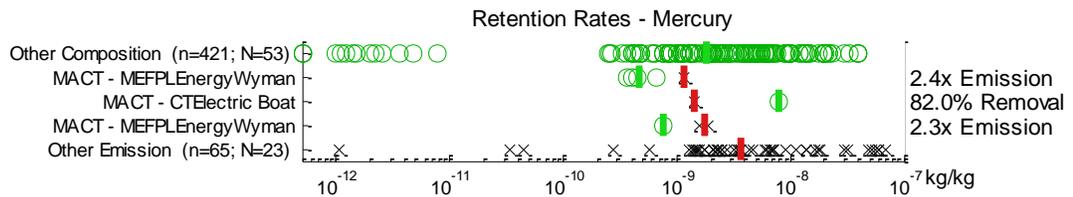
Figure 72(a)-(e) show retention rates for lead, mercury, arsenic, cadmium, and chromium measured across all facilities in the database, sorted by measured emission. Retention rates range from almost complete removal in vaporizing space heaters to low or negligible removal from small boilers and atomizing heaters (e.g. Shaaban & Salvani, Vermont). Facilities tend to be consistent on successive measurement. Retention rate profiles appear to vary by metal.

Chromium Oxidation State

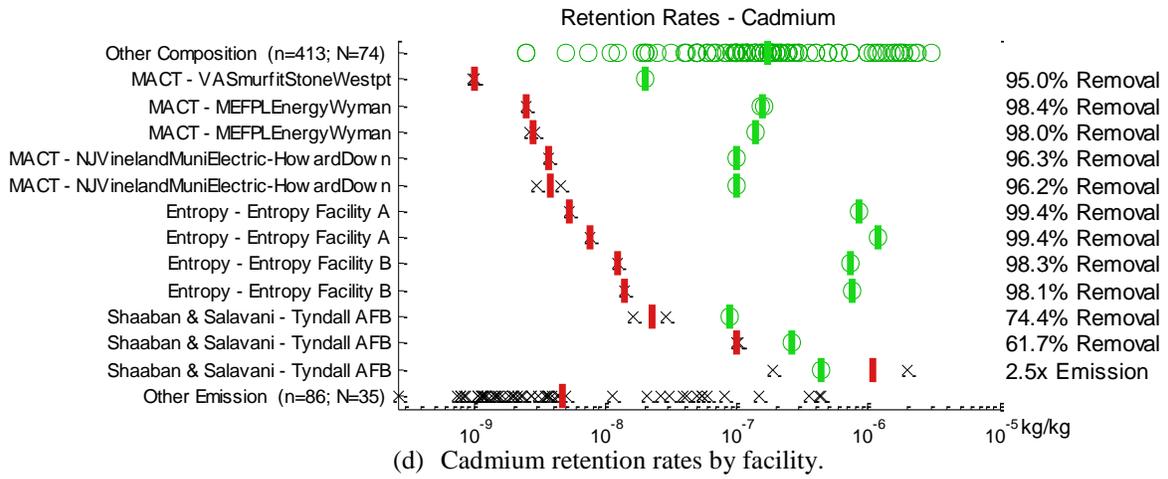
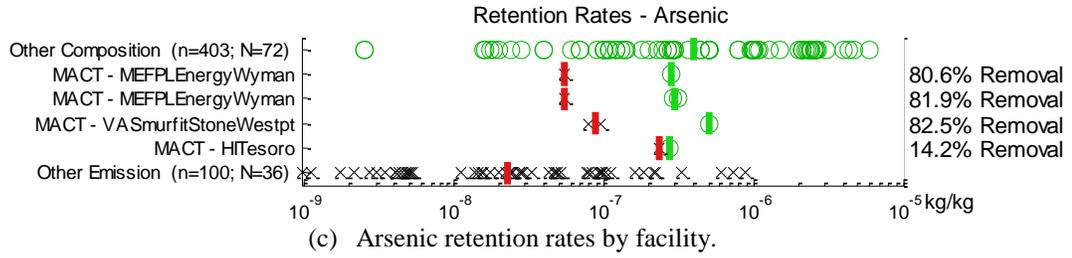
For some metals, particularly chromium, the toxicity of the metal depends strongly on oxidation state. Trivalent chromium (Cr+III) is regarded as substantially less hazardous than hexavalent chromium (Cr+VI). The California Air Resources Board assumes that chromium emitted from combustion of used oil and other wastes to be “principally in the trivalent state” (California Air Resources Board, 1987). In the combustion model, 80 percent of chromium emissions were described as trivalent and 20 percent hexavalent. This assumption was applied to all fuels. Model outcomes were not highly sensitive to this parameter.

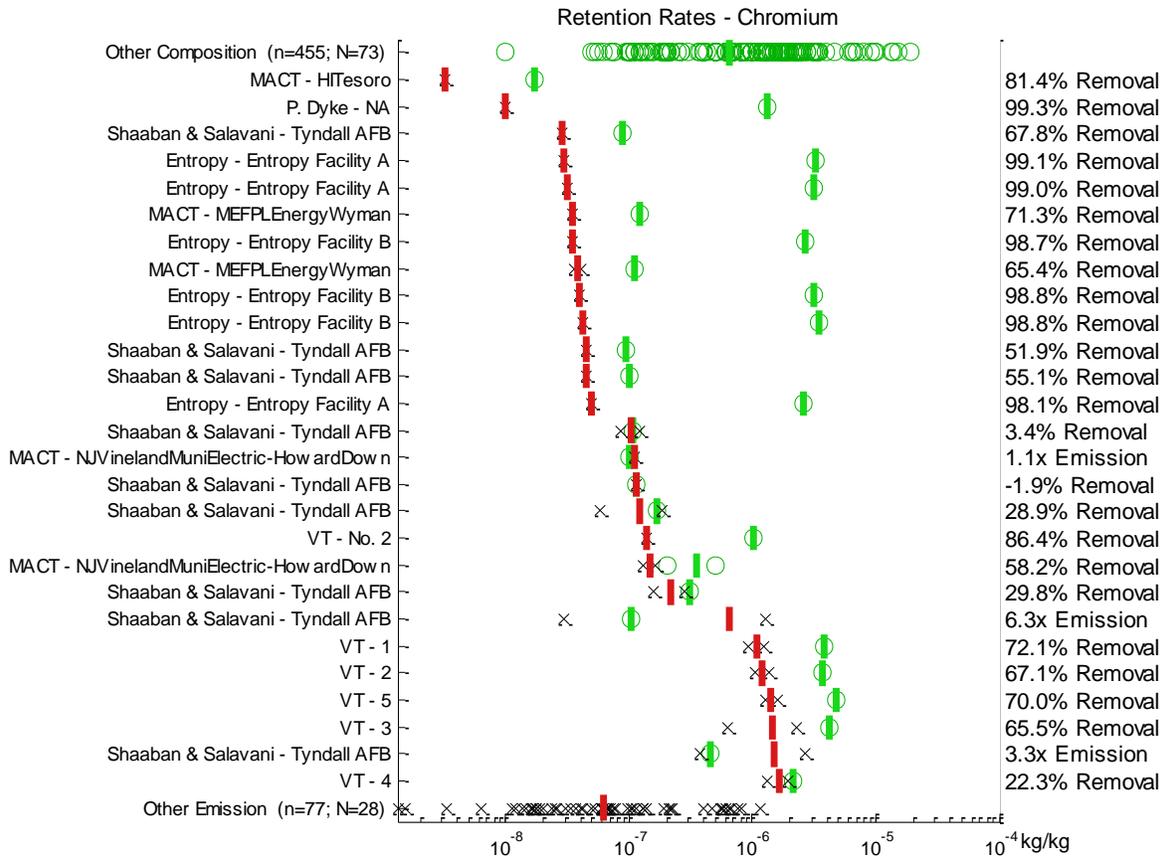


(a) Lead retention rates by facility.



(b) Mercury retention rates by facility.





(e) Chromium retention rates by facility.
 Figure 72 (a)-(e): Retention rates for selected metals.

NONMETALS

Data on nonmetals were much more sparse. Halogens appeared to be not well controlled, though the set of facilities with data was limited. Selenium was grouped with metals, following U.S. EPA practices (e.g. Boiler MACT rule). Boron had no impact characterization and was therefore excluded from analysis. Phosphorus appeared in be retained by vaporizing heaters (Dyke) but emitted elsewhere.

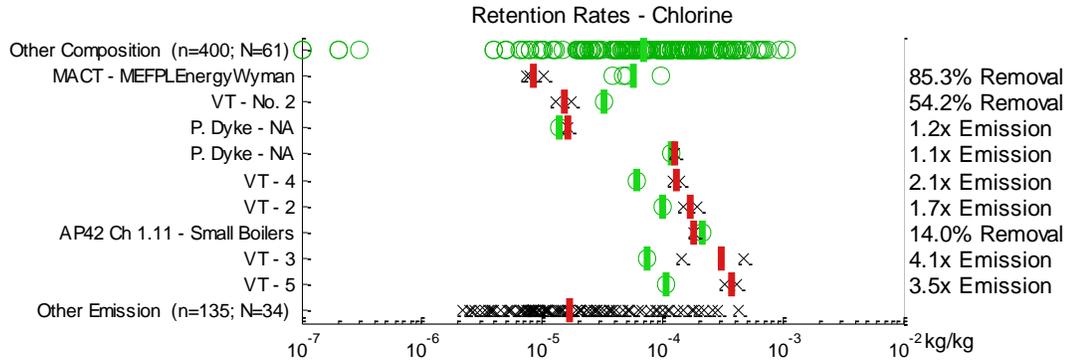


Figure 73: Chlorine retention rates by facility.

The remaining flows were modeled using retention rates for halogens (emitted as acids) and for phosphorus, shown in Table 157. Selected values are ad hoc. Phosphorus is an influential eutrophication pollutant and so the ultimate behavior of phosphorus in combustion may be of environmental relevance.

Table 157: Retention rates for halogens and phosphorus.

Nonmetals Retention	Halogens			Phosphorus		
	low	default	high	low	default	high
Boiler	0	0.1	0.5	0	0.5	0.99
Atomizing Heater	0	0.1	0.2	0	0.5	0.99
Vaporizing Heater	0	0.1	0.2	0	0.99	0.999
Baghouse	0	0.2	0.7	0	0.5	0.99
Marine	0	0.1	0.2	0	0	0.2

11 Appendix C: Informal Management

Three informal management fates of used oil were considered in the model: On-site combustion, landfill, and dumping (the latter two collectively known as “improper disposal”).

Among the informal disposition routes, the quantity of used oil deposited in landfill is most accurately known. The most recent California waste management study involving extraction and analysis of 751 samples of municipal solid waste in landfills estimated the quantity of used oil deposited in landfills at approximately 4,000 metric tons per year (including oil in filters, estimated using 25 percent of the total mass of oil filters in landfill) (Adams et al., 2009). All recoverable used oil that is generated in California in any given year and that is neither collected by authorized used oil haulers nor landfilled is assumed to either be combusted directly at the site of generation or dumped. Therefore the quantity of used oil modeled in on-site combustion and dumping is inferred rather than calculated directly. There is not sufficient data available to estimate the actual split between on-site combustion and dumping; therefore, a bias-free assumption of 50 percent to each route was used.

Thus, of the ~112,000 metric tons of uncollected recoverable used oil generated in the 2010 base year, 4,000 metric tons were landfilled, and on-site combustion and dumping each received 50 percent of the remainder (54,000 metric tons).

On-site combustion was modeled identically to recycled fuel oil combustion in space heaters and small boilers with no control technology (see Appendix B for details on combustion modeling). The following sections describe the modeling approach of dumped used oil.

11.1 Dumped used oil

Aside from being landfilled or burned on-site, used oil that is not properly managed can be disposed of in two principal ways: it can be dumped to storm drains and sewers that eventually drain to fresh and sea water, or it can be dumped on different types of soils. Each of these transport pathways leads to different eventual environmental releases and associated impacts.

There is very little literature on the fate of dumped oil. One study provides a very rough estimate of 6.1 million gallons (Mgal) of used oil discharged to water bodies in California, but the authors warn that this figure accounts primarily for drips and spills rather than intentional dumping, and also that the relationship between this figure and the total amount of used oil improperly disposed to waterways is not established (Mazur, Milanes, Randles, & Salocks, 2006). The quantity of California used oil deposited to different types of waterways and to soil is currently unknown.

Part of the reason that no estimates exist for the relative magnitudes of the dumping pathways is that they are nearly impossible to measure empirically. Generation of used oil is highly dispersed, and disposal is handled by an extremely large number of individuals operating under little to no regulatory oversight. Measuring the number of people who dump their automotive oil in the nearest storm drain or on a patch of empty land is likely to be prohibitively resource-intensive and unlikely to yield honest or meaningful results. Behavioral surveys may uncover some information, but responses are likely to be biased as improper disposal of hazardous waste is a criminal offense. Additionally, some oil is burned in use, and some is dripped from crankcases and machinery during use; these losses make it difficult to isolate dumped oil in empirical measurements of streamflow and soil samples.

Based on the lack of data on flow sizes and the large uncertainty in transport pathways, a probabilistic approach was employed that models the transport and fate of an average quantity of improperly disposed oil, shown in Figure 74. Improperly disposed oil was modeled in three primary routes:

- W: waterway (dumping/dripping down a storm drain)
- L: landfill (disposing of containers of used oil in municipal solid waste)
- S: soil (dumping/dripping on land)

Each route leads to a variety of transport pathways and eventual environmental emission fates. Oil destined for waterways drains to or is placed directly into storm drains or sewer pipes. Oil in sewer water is routed through a wastewater treatment plant. Oil dumped or dripped in storm drains can flow through either a filtered or an unfiltered storm drain, or in rarer cases it can be routed through a wastewater treatment plant in dry weather conditions. Oils, metals, and particulates are removed from filtered storm drains and treatment plants and either landfilled, incinerated, or used as fertilizer on agricultural land. The remaining effluent is emitted to either fresh or sea water.

Used oil disposed at curbside collection waste bins is transported to local municipal solid waste facilities. Although some of this oil may leach into groundwater, the extent to which this occurs is unknown and likely to be small in a modern landfill, and is thus excluded from this study. Some portion of the municipal solid waste (and therefore the used oil) is incinerated for electricity generation, emitting some portion of its constituents as particulates to air. Used oil deposited to soil is the simplest fate route—it is either deposited on agricultural soil or industrial soil.

Probabilities used in the model were based on literature, calculations using proxy measurements such as population, and where no data was available, 50/50 zero-bias assumptions. The model produces quantities of oil (including both the hydrocarbon portion and other constituents) released to fresh water, sea water, agricultural soil, industrial soil, and air. Transfers between environmental media (air, soil, and water) after the point of release into the environment, as well as impacts from these releases are handled by the TRACI 2.0 impact characterization model.

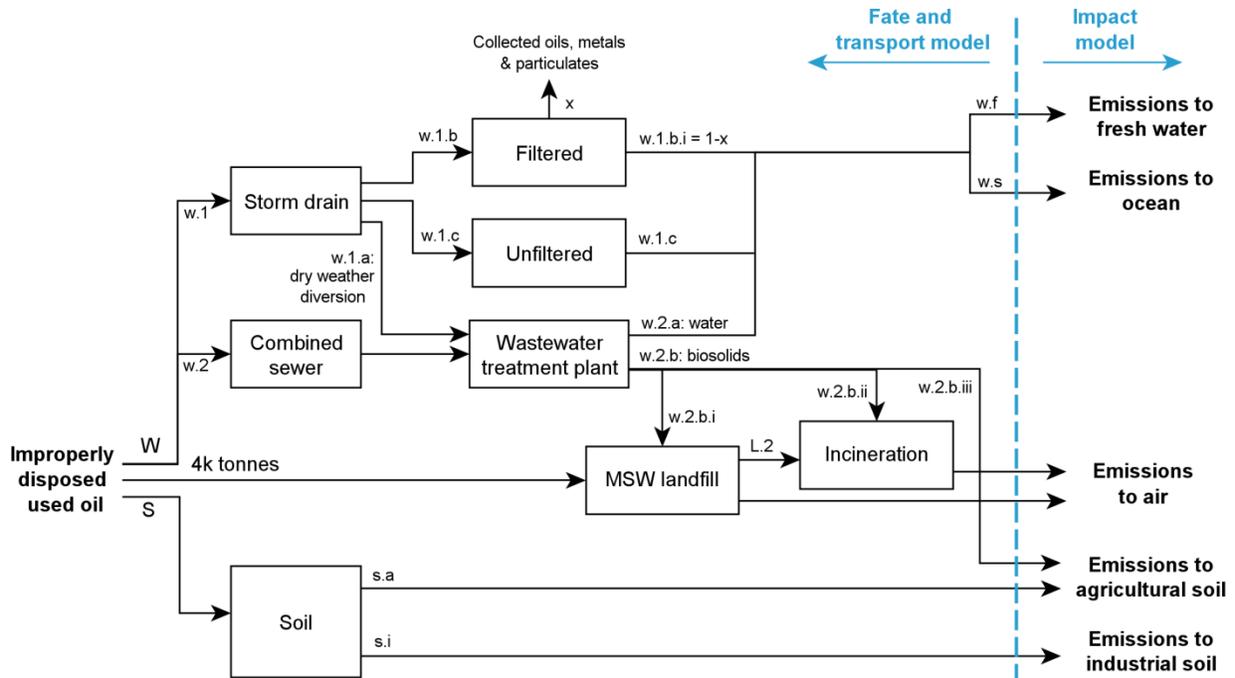


Figure 74: Fate and transport model for improperly disposed used oil.

Each sub-route split was assigned a parameter, and a percentage was assigned to each parameter to reflect the relative probabilities of oil passing through the respective sub-route. Thus, taken as a whole the model describes the fate and transport of an average volume of oil improperly disposed in California. Transfer between environmental compartments (air, land, water) is handled by impact assessment modeling. To avoid double modeling such transfers, the scope of the probabilistic fate and transport model ends and the impact model begins when used oil is first released as a flow directly to the environment.

11.2 Parameter estimates

The ability of a parametric model to produce accurate results rests with the accuracy of the parameters. Since no data on these parameters exist (aside from the absolute quantity of landfilled used oil discussed earlier), we used a variety of methods to estimate likely values. This section details the methodology behind each parameter estimate.

11.2.1 Primary dumping route (W , S)

There was extremely little guidance in the literature on how to select the primary pathway parameters; there are no reliable estimates for quantities of oil deposited to soil or water. Therefore to avoid introducing bias, water (W) and soil (S) were split evenly. This even split is not meant to suggest anything substantive about the actual relative quantities disposed to soil and water, but rather to make transparent our lack of data in this area, and to facilitate unbiased comparisons between the two pathways by weighting them equally.

11.2.2 Sewers vs. storm drains (w.1, w.2)

It is important to distinguish between oil dumped in a dedicated storm drain system and oil dumped in a combined sewer system that handles both sewer waste and storm water because combined sewers treat water in treatment plants, which filter a large portion of pollutants (discussed further in section 11.3). Combined sewers are prone to flooding during periods of high precipitation, and have been phased out in favor of split storm/sewer systems. Combined sewers only remain in only two cities in California: San Francisco and Old Town Sacramento (Oakland Museum of California, n.d.). Because humans are responsible for dumping oil, a larger population leads to more chances for improperly disposed oil; thus, the probability of used oil being dumped in a combined sewer was estimated based on the populations of San Francisco and Old Town Sacramento as compared to the total California population. The population of Old Town Sacramento was not directly available, but was estimated at 5 percent of the total Sacramento population. The combined San Francisco and Old Town Sacramento population is approximately 840,000, compared to 38 million total California population (U.S. Census, 2010), leading to values for *w. 1* and *w. 2* of 98 percent and 2 percent, respectively.

11.2.3 Dry-weather diversions and storm drain filters (w.1.a, w.1.b, w.1.c)

Dry-weather diversions (DWD) are systems whereby storm water can be diverted from a storm drain system through a wastewater treatment plant to filter pollutants during dry weather periods with the goal of reducing non-point pollution. The diversions have been installed in several California coastal water districts. A list of current and proposed dry-weather diversions affecting coastal runoffs is provided by Surfrider Foundation (2012), citing State Water Resources Control Board (2012). Because modeling the hydrology of every coastal watershed in California was well outside the scope of this study, a simplifying assumption was made that a dry-weather diversion diverts all the storm drain runoff in its vicinity. Thus, to estimate the likelihood of improperly disposed oil being routed through a dry-weather diversion, the length of dry-weather diverted coastline (i.e. coastline with a diversion project in the area) was compared to the total length of coastline in each county with diversion programs. This was accomplished by approximating the length of coastline of beaches with diversion projects (Surfrider Foundation, 2012) using an on-line mapping service (Google Maps, 2012), and dividing that number for each county by the published total length of coastline in the county (Los Angeles County, 2012; Monterey Convention and Visitors Bureau, 2012; Orangecounty.net, 2012; Pacific Union International, 2012; San Diego Tourism Authority, 2012; Santa Cruz County Conference and Visitors Council, 2012; VenturaCountyInfo.com, 2012).

This figure gives a rough estimate for the probability of oil disposed in a storm drain in a county with diversion systems being treated in a wastewater plant. For example, if used oil is dumped in Monterey County, which has diversions on 14 of its 99 total miles of coastline, that oil has a 14 of 99 (or 14.1 percent) chance of flowing through a diverted storm drain. For each county, this probability was multiplied by the ratio of the county population to the total coastal California population. The total coastal population (defined below) is 30.2 million (U.S. Census, 2010; U.S. National Oceanic and Atmospheric Administration, 2012). A summary of the information used is provided in Table 158.

To summarize, to estimate the final probability of used oil dumped in a storm drain being diverted to a wastewater treatment plant, the probability of oil being dumped in each county with a diversion system ($P(\text{divcounty}_i)$) was multiplied by the probability of oil in such a county

actually being diverted ($P(\text{diverted}|\text{divcounty}_i)$) and summed over all counties with diversions:

$$P(\text{diverted}_{tot}) = \sum_i [(P(\text{divcounty}_i) * P(\text{diverted}|\text{divcounty}_i))]$$

for each diversion county i , where $P(X|Y)$ indicates the conditional probability of event X given event Y has occurred

County	Diverted coast miles	Total coast miles	Percent diverted	Population	Population percent
San Mateo	2	90	2.2	718,451	2.4
Santa Cruz	3	29	10.3	262,382	0.8
Monterey	14	99	14.1	415,057	1.4
Ventura	4	43	9.3	823,318	2.7
Los Angeles	18.5	75	24.7	9,889,056	32.7
Orange	22	42	52.4	3,010,232	10.0
San Diego	21.5	70	30.7	3,095,313	10.3

Table 158: Populations of counties with dry-weather diversions and percentage of coastline diverted (Los Angeles County, 2012; Monterey Convention and Visitors Bureau, 2012; San Diego Tourism Authority, 2012; Santa Cruz County Conference and Visitors Council, 2012; Surfrider Foundation, 2012; VenturaCountyInfo.com, 2012).

Thus calculated, $P(\text{diverted}_{tot}) = 17$ percent. This may be an overestimate based on the fact that dry weather diversions were assumed to affect entire beach areas whereas in reality they affect only select watersheds. Additionally, diversions only operate during dry weather conditions, and more used oil may be washed down storm drains during rainy conditions. On the other hand, the fact that population density in different areas of county coastline is ignored (and that dry-weather diversions are usually installed in areas with high density) means that the probability may be underestimated. Regardless, it is a very rough estimate and was rounded to a single significant digit (20 percent) to reflect the lack of confidence in the figure.

Another alternative to filtering storm water is to install in-situ filtration systems at the inlets to storm drains. These filters can take many forms, from simple metals grates to carbon filters or advanced manufactured systems. Storm drain filtrations systems have been installed in many water management districts. To estimate the percentage of storms drains in the state that are filtered, our approach was to sample individual cities and scale that adoption rate to the entire state based on population. For this purpose, cities can be divided by their regulatory status under the Federal Clean Water Act: Cities with population larger than 100,000 are required to obtain a National Pollutant Discharge Elimination System (NPDES) permit for storm water discharges (U.S. EPA, 2012a), and are thus more likely to have storm water filtration systems in place than cities with under 100,000 residents. Records of filtered and unfiltered storm drain inlets were obtained from officials in San Diego and Redding, representing large and small cities, respectively. According to city officials, 2,666 of San Diego’s 23,400 storm drain inlets (11 percent) have a filter of some kind in place (Hook, 2012). Redding, however, has filters on only 3 of its 10,454 (0 percent) storm drain inlets (Stacher, 2012) (Table 159).

City	Population class	Inlets	Filtered inlets	Filtered %
San Diego	>100,000	23,400	2666	11%
Redding	<100,000	10,454	3	0%

Table 159: Storm drain filter statistics for two classes of cities (Hook, 2012; Stacher, 2012).

These proportions were scaled up to the entire state as follows: There are 66 California cities with populations above 100,000, representing 57.85 percent of the total California population (U.S. Census, 2010). Continuing with the assumption that population is correlated with improper oil disposed, oil dumped in a random storm drain in California has a 58 percent chance of being dumped in a city with a population greater than 100,000. Within such a city, it has an 11 percent chance of being dumped in a filtered storm drain inlet. Therefore, the probability of oil dumped in any storm drain being filtered is the probability of it being dumped in a large city multiplied by the conditional probability of it being dumped in a filtered inlet given a large city:

$$P(\text{filtered}_{tot}) = P(\text{largecity}) * P(\text{filtered}|\text{largecity})$$

$$= 58\% * 11\% = 7\%$$

Therefore, of the dumped or runoff used oil in storm drains, 20 percent (*w. a. 1*) is diverted to wastewater treatment plants and 7 percent (*w. 1. b*) of the remainder passes through a storm drain filter, leaving 73 percent (*w. 1. c*) in unfiltered storm drains.

11.2.4 Pollutant removal efficiencies (*x*, *w.2.a*, *w.2.b*)

Pollutant removal efficiencies for storm drain filters were obtained from lab and field testing performed and published by Stormceptor, a manufacturer of storm drain filtration systems (Stormceptor, 2005). Published removal efficiencies are shown in Table 160.

Material	Removal efficiency
Oil (hydrocarbons)	43 - 98%
Total suspended solids	52.7 - 83%
Lead (Pb)	51.2%
Copper (Cu)	21.5%
Zinc (Zn)	39.1%
Iron (Fe)	52.7%
Chromium (Cr)	40.7%

Table 160: Substance removal rate in storm drain filters (Stormceptor, 2005).

The removed portion of the listed substances was subtracted from the overall mass, and the composition was changed accordingly. The removed materials are assumed to be landfilled.

Pollutant removal efficiencies for wastewater facilities were obtained from published data from the U.S. EPA Risk Reduction Engineering Laboratory Treatability Database (U.S. EPA Risk Reduction Engineering Laboratory, 2004) and the U.S. EPA Estimation Programs Interface (EPI) v5.0 (U.S. EPA, 2011). Collectively, these databases contain removal efficiencies for all constituents found in used oil, and values were used in the model exactly as they are published, shown in Table 161. Unfortunately, only point estimates were available, with no indication of

uncertainty. The removed portion of the materials are either landfilled (*w. 2. b. i*), incinerated (*w. 2. b. ii*) or applied to agricultural soil (*w. 2. b. iii*). The wastewater treatment plant model is discussed further in Section 11.3.

Substance	Removal rate	Source	Substance	Removal rate	Source
Aluminum	66%	RREL	Mercury	68%	RREL
Antimony	31%	RREL	Molybdenum	76%	EPI
Arsenic	48%	RREL	Nickel	38%	RREL
Barium	69%	RREL	Nitrogen	88%	EPI
Beryllium	37%	RREL	Org. Halogens	87%	EPI
Boron	96%	EPI	PAH	94%	RREL
Cadmium	68%	RREL	PCB	98%	RREL
Calcium	90%	EPI	Phenanthrene	94%	RREL
Chlorine	90%	EPI	Phosphorus	59%	RREL
Chromium	76%	RREL	Sediment	ND	—
Cobalt	32%	RREL	Selenium	43%	RREL
Copper	72%	RREL	Silicon	95%	EPI
Fluorine	90%	EPI	Silver	66%	RREL
Glycols	92%	RREL	Sodium	90%	EPI
Halogens	87%	RREL	Sulfur	77%	EPI
Hydrocarbons	99%	RREL	Thallium	53%	RREL
Iron	90%	EPI	Tin	90%	EPI
Lead	63%	RREL	Titanium	90%	EPI
Magnesium	90%	EPI	Vanadium	31%	RREL
Manganese	38%	RREL	Zinc	66%	RREL

Table 161: Substance removal rate at wastewater treatment plant (U.S. EPA Risk Reduction Engineering Laboratory, 2004; U.S. EPA, 2011).

11.2.5 Release to fresh water vs. sea water (*w.f, w.s*)

The effluent from storm drains and wastewater treatment plants is released to either fresh or sea water. The split between drain pipes draining to ocean vs fresh water was estimated based on relative populations in coastal areas vs inland (except in the case of storm water routed through dry-weather diversions, which flows only to sea water). The National Ocean and Atmospheric Administration’s (NOAA) National Ocean Service publishes a list of 28 California counties that are considered “coastal counties.”

According to NOAA, these are defined as meeting one of the following criteria: 1) at least 15 percent of a county’s total land area is located within the nation’s coastal watershed; or 2) a portion of or an entire county accounts for at least 15 percent of a coastal cataloging unit” (U.S. National Oceanic and Atmospheric Administration, 2012). The population of those 28 counties (30 million) was divided by the total California population (38 million) to derive the seawater/freshwater split of 81 percent and 19 percent, respectively (U.S. Census 2010). Although some of this coastal water may in fact be deposited to freshwater systems for a short time before reaching the ocean, this quantity is unknowable without involved hydrologic modeling (and in many of the heavily populated areas of California will travel through a concrete-paved drainage river to the ocean).

11.2.6 Wastewater sewage sludge disposal (w.2.b.i, w.2.b.ii, w.2.b.iii)

A 2004 study commissioned by the California Water Resources Control Board reported on wastewater sewage sludge disposal methods employed in California (California State Water Resources Control Board, 2004). The study used historical survey data as well as estimates based on data reported to the U.S. EPA to estimate relative volumes of biosolid disposal. The California Association of Sanitation Agencies (CASA) published relative volumes for biosolid disposal methods for 2011 (California Association of Sanitation Agencies, 2012). The combined data is shown in Table 162.

Disposal method	1988	1991	1998	2001	2011
Landfill*	60.2%	43.3%	9.1%	18.0%	34.0%
Agriculture**	25.5%	40.4%	78.4%	48.0%	57.0%
Incineration	4.7%	7.0%	5.6%	2.4%	3.0%
Onsite storage	9.5%	7.2%	6.9%	1.0%	—
Other	—	—	—	—	6.0%

* Combines burial, surface disposal, and daily cover

** Combines land application and compost

Table 162: Fate of wastewater treatment plant sewage sludge (California Association of Sanitation Agencies, 2012; California State Water Resources Control Board, 2004).

Based on the historical trend and information from CASA, 2011 data were believed to be most representative of biosolids disposal in the future, and were used as the basis for the landfill/incineration/agriculture split. “Other” was combined with landfill to form the final breakdown of 40 percent, 3 percent, and 57 percent for landfill, incineration, and agriculture, respectively.

11.2.7 Used oil incinerated in MSW (L.2)

The amount of incinerated municipal solid waste (MSW) was estimated based on data from a 2010 California Energy Commission on waste-to-energy (Orta & Zhang, 2010). According to this report, waste-to-energy plants routinely collect municipal solid waste that is currently in place in landfills and incinerate it for energy recovery. There are currently three municipal solid waste incinerators in operation in California: Commerce, Southeast Resource Recovery Facility, and Stanislaus. All are mass burn, stoker-fired incinerators with acid gas treatment consisting of dry scrubbers. Emissions modeling is discussed further in Appendix B.

The information in the Energy Commission study was used to estimate the fraction of municipal solid waste that is removed from landfills and incinerated. In 2008, California waste-to-energy facilities had 943 MW of built bioenergy capacity, 4 percent of which (38 MW) came from municipal solid waste directly collected from landfills (Orta and Zhang 2010). Based on 20 percent conversion efficiency (Ecoinvent 2012) and an average energy density of municipal solid waste of 6500 Btu/lb (Levie et al. 1994) this equates to 419 k BDT (bone-dry tons) of municipal solid waste incinerated. The total amount of municipal solid waste in California in 2008 was 19.2 million BDT (Orta and Zhang 2010); the incinerated portion was therefore 2.2 percent (see eq. C.1) Thus, based on the authors’ understanding that all waste in landfills has an equal probability

of being collected for incineration, the probability of used oil in landfills being incinerated is also 2.2 percent. It should be noted that this assumes that no significant quantity of municipal solid waste collected from landfills is exported from California to be burned elsewhere. Additionally, this estimation ignores any municipal solid waste that is collected but diverted to incineration before being deposited in a landfill. This flow is omitted based on a lack of reliable information on the quantity of pre-landfill municipal solid waste incineration.

$$\begin{aligned}
 &943 \text{ MW (2008)} \times 0.04 \text{ from MSW}^a = 38 \text{ MW} \\
 &38 \text{ MW} \times 8400 \text{ h/yr}^b = 319,200 \text{ MWh} \\
 &1 \text{ MWh} = 3412142 \text{ Btu} \\
 &319,200 \text{ MWh} \times 3412142 = 1089155726400 \text{ Btu} \\
 &6500 \text{ Btu/lb MSW energy density}^a \\
 &20\% \text{ conversion efficiency}^c \tag{C.1} \\
 &1089155726400 \text{ Btu} / 6500 / 0.2 = 418906 \text{ BDT MSW} \\
 &\text{Total MSW in CA in 2008} = 19.2 \text{ M BDT}^a \\
 &0.418906 / 19.2 = 0.0218 \\
 &L.2 = 2.2\%
 \end{aligned}$$

^a Orta and Zhang (2010)

^b Activity level assumption

^c Ecoinvent (2012)

11.2.8 Agricultural vs. industrial soil (s.a, s.i)

It was not readily apparent how best to model the split between oil deposited on agricultural and industrial soil. Using population density would unrealistically weight industrial soil, while using surface area would unrealistically weight agricultural soil. Fortunately, initial sensitivity analysis showed that this is a fairly unimportant distinction; for most materials, the impact models used do not characterize emissions to the two soil types differently. Since there is no data or apparent estimation methodology available for this parameter, a 50/50 split was used to avoid any bias.

11.3 Modeled processes

The inventories of three processes in the improper disposal system were explicitly modeled: wastewater treatment, used oil in landfill, and used oil in municipal solid waste incineration. In the wastewater treatment model, energy and ancillary inputs were taken from the European wastewater treatment process in the PE Professional database (PE International, 2012). This process models an average wastewater treatment plant using a chemical reduction/oxidation process. Inputs to the process are shown in Table 163. Using the standard life cycle assessment assumption of linearity, the process inputs were assumed not to change as a result of used oil in wastewater; rather, the presence of 1kg of used oil in wastewater simply increases the mass flow through the treatment plant by 1kg. Effluent and sludge outputs were calculated using the average composition of used oil used throughout this report and the removal efficiencies for each

constituent as discussed earlier. Upstream inputs were modeled using the PE Professional and Ecoinvent databases (PE 2012, Ecoinvent 2012).

Inputs	Quantity	Unit	DB
Electricity	0.0028572	MJ	USLCI
Steam	0.10213	MJ	PE Professional*
Hydrated lime dry slaked	0.0011429	kg	PE Professional
Iron chloride	0.00057086	kg	Ecoinvent
Phosphoric acid	6.258E-8	kg	Ecoinvent

* US Process steam from natural gas

Table 163: Process inventory for treatment of 1 kg used oil in wastewater.

The used oil in landfill process consists of solid waste collection and landfill air emissions from decomposition. Leachate emissions to water are tightly monitored and controlled, and are therefore likely to be too small to include in the study. Municipal solid waste collection was modeled as 10km delivery by 22 t truck. Landfilling was modeled by modifying a European landfill process from the PE Professional database. Of particular concern were the methane and carbon dioxide emissions from biodegradation. Prior research has shown that lubricants are capable of being biodegraded via both aerobic and anaerobic processes (O. P. Abioye, Agamuthu, & Abdul Aziz, 2012; P. O. Abioye, Abdul Aziz, & Agamuthu, 2009; Berdugo-Clavijo, Dong, Soh, Sensen, & Gieg, 2012; Haritash & Kaushik, 2009; Lapinskiene & Martinkus, 2007; Siddique, Penner, Klassen, Nesbø, & Foght, 2012), but conditions in the vast majority of U.S. landfills allow only for anaerobic degradation. Anaerobic degradation produces methane and carbon dioxide emissions (Haritash & Kaushik, 2009) at roughly 45 percent CH₄, though this split depends on composition of organic material, temperature, moisture, and other conditions (Scheutz et al., 2009).

The vast majority of U.S. landfills are sealed from air and water to prevent rainwater runoff and odor, and consequently have low levels of overall biodegradation (Borglin, Hazen, Oldenburg, & Zawislanski, 2004). It is somewhat unclear whether the used oil will completely or only partially biodegrade in either condition (and in what time frame), as certain classes of hydrocarbons such as complex polycyclic aromatic hydrocarbons (PAHs) are recalcitrant to biodegradation even in ideal conditions (Haritash & Kaushik, 2009). Ultimately, the gasses that do result from biodegradation will largely be captured before they are emitted to air: As of 2013, all active and inactive California landfills with methane generation greater than 3.0 MMBtu/hr or 450k metric tons of waste-in-place are statutorily required to capture and eliminate methane emissions (California Code of Regulations 2010), and as a result will also capture CO₂ emissions. However, some used oil may be deposited in smaller exempt landfills. The emissions from the landfill process were parameterized based on stoichiometric relationships using the carbon content of used oil to allow for a range of biodegradation levels and emission capture levels at any CH₄/CO₂ split. The baseline values chosen were 50 percent CH₄/ 50 percent CO₂, with 10 percent organic material degradation and 25 percent emission capture, with the latter value increasing over the 20-year projected period.

Incineration of used oil in municipal solid waste was modeled using thermal and electric energy input levels from a PE Professional database waste incineration process. No information on

combustion emissions removal efficiencies from the three municipal solid waste incineration facilities operating in California was available. However, municipal solid waste incineration facilities are highly regulated (Federal Code of Regulations, 2007) and utilize a variety of state-of-the-art pollution controls including NO_x, SO_x, mercury and dioxin removal, particulate baghouse filtration, and flue gas testing. According to EPA publications, more than 99 percent of particulates are removed in the filtration process (U.S. EPA, 2012b). Therefore, the hydrocarbon portion of the used oil (~95 percent) was assumed to be completely combusted, creating stoichiometrically-calculated CO₂ emissions, and 1 percent of the non-hydrocarbon materials (using the average used oil composition) were emitted to air. Using the methodology discussed above, during the 2010 base year 4,000 metric tons of used oil were landfilled, 88 metric tons of which were collected from landfill and incinerated. In addition, 3 percent of biosolid output from wastewater treatment is incinerated, totalling 175 metric tons. In sum, 263 metric tons of used oil is incinerated, generating 2026 GJ of energy. Accordingly, avoided burden credits for 2026 GJ of displaced primary electricity production were modeled.

Omitted systems include sewer and storm drain infrastructure, treatment plant production, and manufacturing and installation and maintenance of storm drain filters, which were deemed to be outside the scope of the study.

11.4 Summary of informal management

A summary of the dumping model parameter names, estimates for probability values, and brief justifications is provided in Table 164. The fate and transport diagram is repeated complete with estimated parameters in Figure 75. Based on a total of ~112,000 metric tons uncollected recoverable used oil in the 2010 base year, the informal management model result in the following fates:

- 54,000 metric tons to on-site combustion
- 3,690 metric tons to fresh water
- 15,800 metric tons to sea water
- 16,840 metric tons to agricultural soil
- 13,510 metric ton to industrial soil
- 5,840 metric tons through wastewater treatment
- 7,550 metric tons to municipal solid waste landfill (direct flow plus filtered contaminants)
- 263 metric tons to incineration (extracted from municipal solid waste flow plus 3 percent of wastewater treatment biosolids)

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Parameter	Value	Justification
W	50%	50/50 split for unbiased model
w.1	98%	Population of cities with separate vs. combined storm water systems
w.1.a	20%	Population of coastal counties with DWD and portion of coastline diverted
w.1.b	7%	Population in large vs small cities and percentage of filtered drains in large cities
x	varies	Removal efficiencies for three classes of materials from filter mfg testing
w.1.c	73%	1 - w.1.a - w.1.b
w.2	2%	Population of cities with combined vs. separate storm water systems
w.2.a	varies	Removal efficiencies for each used oil constituent from two EPA sources
w.2.b	varies	Removal efficiencies for each used oil constituent from two EPA sources
w.2.b.i	40%	California Water Board and California Association of Sanitation Agencies
w.2.b.ii	3%	California Water Board and California Association of Sanitation Agencies
w.2.b.iii	57%	California Water Board and California Association of Sanitation Agencies
w.f	19%	Population of coastal vs. inland counties, as defined by NOAA
w.s	81%	Population of coastal vs. inland counties, as defined by NOAA
L	3k t	Matching absolute flow size reported in waste characterization studies
L.1	97.8%	1 - L.2
L.2	2.2%	Calculation based on California Energy Commission study on bioenergy
y	varies	Used oil combustion emissions and MSW incineration emissions controls
S	50%	50/50 split for unbiased model
s.a	50%	50/50 split for unbiased model
s.i	50%	50/50 split for unbiased model

Table 164: Probability parameter estimates and brief justifications.

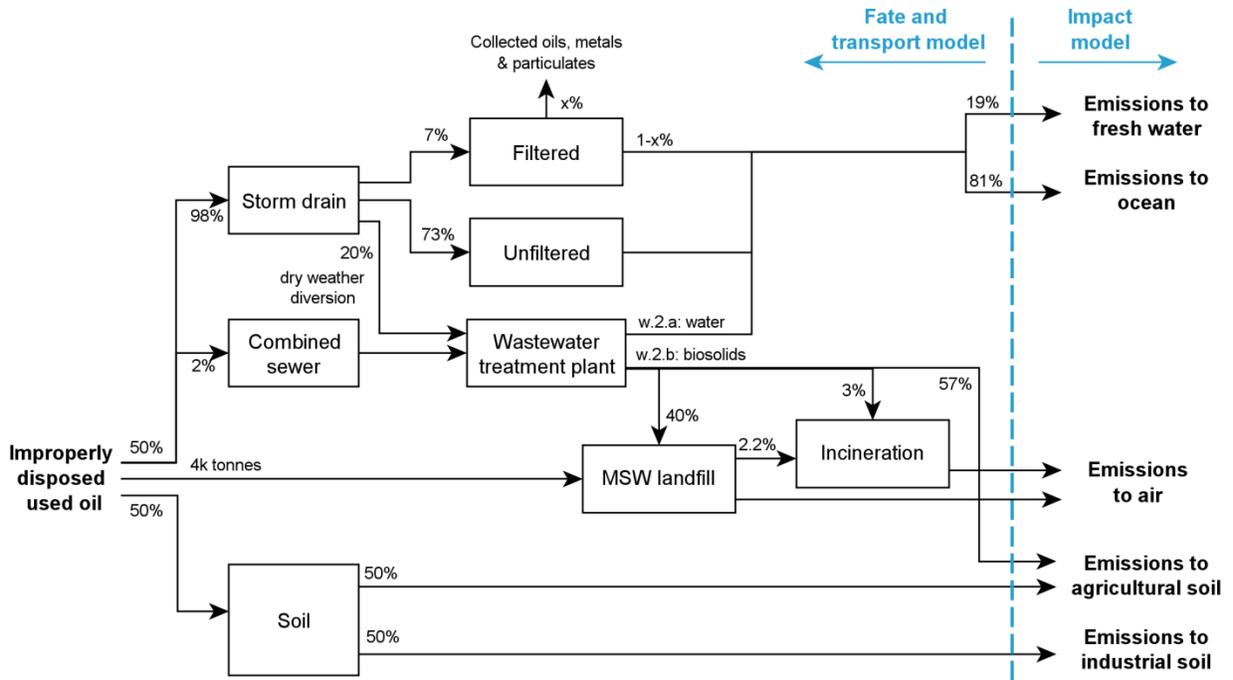


Figure 75: Fate and transport model with estimated probability parameters shown.

12 Appendix D: Displacement Modeling

As stated in ISO 14041, “wherever possible, allocation should be avoided by: ... expanding the product system to include the additional functions related to the co-products” (ISO, 1998). The method of system expansion was employed in this study whenever possible to preclude the need for allocation. The methodology was also consequential in nature, meaning that the system is modeled so as to account for the market-level consequences that would result from changes to the status quo. In other words, the model attempts to avoid the need for allocation of inputs, outputs, and environmental impacts by attempting to reflect the big picture impacts to the market as a whole.

Consequential system expansion therefore requires that the study account for the primary products that would be produced and consumed if the used oil management system were not in place. The first step in system expansion is to identify the primary products that used oil management system products compete with in the marketplace. These products would be considered substitutes since a consumer could potentially choose between them in order to achieve the same function. In most cases, this choice will be a balance between the functionality of the substitutes and their relative prices. If two products are perfect substitutes, it means there is no functional difference between the primary and the secondary product and they can be substituted for one another at a ratio of 1:1. If they are not perfect substitutes, it means that a consumer may have to use more or less of a certain product to achieve the same function as they would with the product’s substitute.

Technical considerations and price are the two main factors that determine the most likely substitutes for any given product, and the same is true for the used oil product system. In the case of petroleum fuel products, technical considerations may include energy content, viscosity, sulfur content, and a fuel’s appropriateness given the operating requirements of the machinery in which a product is going to be combusted. When trading off between different fuels, the energy density of the fuel, i.e. the Btu/kg fuel ratio, must be considered in the substitution ratio. A consumer will need to burn more of a fuel that has a lower energy density in order to achieve the same heating functionality. All fuel displacement ratios are thus based on a per MJ basis. However, most combustion devices are designed for only a certain range of fuels. It is not possible, for instance, to burn residual oil in a space heater, so in this context, residual oil and recycled fuel oil would not be considered substitutes. Viscosity is a key technical consideration in determining displacement ratios for lubricants since it is a major factor in their functionality. Price is important for both because if a consumer has a choice between a number of similar products, they are likely to choose the least expensive.

Once the correct substitutes have been identified, the rate of actual market displacement must be determined. This can range from 0 (no displacement) to 1 (100 percent displacement per unit energy or mass, depending on the product.) In a consequential life cycle assessment, it is assumed that the benefits of recycling will result from secondary products displacing primary products that otherwise would have been produced. In other words, the secondary product results in an overall reduction in primary production. A displacement rate of less than 1 implies that primary production has not been completely avoided by the secondary product and overall production for the market has increased. The impacts of this avoided primary production, or “avoided burden,” can be subtracted from those of the recycling system to determine the overall environmental

impact of the system. If in any impact category the impacts of primary production are lower than those of the recycling system, then there is no recycling benefit for that impact category.

12.1 Determination of Displaced Products

All of the saleable products that result from the management of used oil in California have the potential to displace primary products. Products were considered from both a technical and an economic perspective to determine the most likely displacement relationships. It is the nature of petroleum-based fuels that they may fall along a broad spectrum in terms of density, heating value, viscosity, sulfur content, flash point, and many other composition specifications. The fuels most relevant to the study of the used oil management system are those that are produced by the processors of California's used oil and their substitutes. Primary data providers and industry stakeholders were consulted regarding the characteristics of these secondary products.

Given their secondary nature, most are not identical in composition to any of the primary products that come from a large refinery. Therefore, displacement relationships were determined mainly based on expert industry knowledge about the products that secondary products compete with in the marketplace. Both the producers and the consumers of these secondary products were questioned regarding what products would be used if the secondary products were not available, and these responses were given a large amount of weight. Technical considerations were also taken into account regarding boiling range, heating value, sulfur content, and viscosity in order to establish the full range of technically possible substitutes and as a quality assurance check.

While different producers make have different names for their co-products, they were grouped together for modeling purposes based on information about their technical specifications and functions. The product groups and their specifications are detailed below in Table 165 follows on the next page.

Table 165.

Displacement modeling requires comparable and complete life cycle inventory data regarding the production and use of all secondary and competing primary products within the scope of the life cycle assessment. The inventory data for the production of secondary products was provided by the participating re-processors of used oil. Primary refinery production was modeled using the PE International U.S. refinery model that was developed for this project. Natural gas production was modeled using a PE International process as well. While inventory data about the use phase of some products were available from existing data sources, for others, no acceptable inventory data were available. Good and consistent data were particularly lacking with regards to the modeling of the combustion of the various in-scope fuels in particular combustion technologies. The potential exists for fuel products to have significantly different environmental impacts based on differences in composition and the specific circumstances under which they are burned. This meant that the combustion model had to be sensitive to these factors, and also reflect the particular technologies in which secondary products of the used oil system are likely to be combusted. In order to meet this inventory data need, an empirical combustion model was developed based on composition and emission data taken from a range of primary and secondary sources. This combustion model was used to model the use phase of all fuels. A detailed description of the proprietary used oil combustion model methodology and results can be found in Appendix Q. Table 165 follows on the next page.

Table 165: Used Oil Secondary Product Descriptions



Secondary Product	Description	Boiling Point (°C)	Sulfur Content (%)	Process Derived From	RRBO	MDO	RFO	Usage
Base Oil	Primarily Group II, a few producers make Group I.	130-315	Unknown	Vacuum distillation and hydrotreating.	X			Blended into finished motor oil or industrial oil by lubricant blenders.
Light Ends	Naphtha or gasoline-like flammable liquids. High levels of Cl and S.	<200	Unknown	Atmospheric distillation column.	X	X		Pulp paper, cement, & steel industries use to power kilns. Some re-processors burn onsite.
Light Distillate Fuels	Like diesel fuel. Significant Cl levels.	90-315	<0.3	Vacuum distillation, atmospheric column if sufficiently hot.	X	X		Blended into No. 2 distillate or HFO.
Middle Distillate Fuels	Hydrotreated light fuel oil. Very similar to home heating fuel or No. 2 distillate.	130-400	<0.05	Vacuum distillation then hydrotreater. Some hydrocracking occurs.	X			Industrial boilers or off-road diesel vehicles/equipment. Some processors burn onsite.
Marine Distillate Oil	Characteristics similar to No. 2 distillate.	215-530	<0.2	Vacuum distillation column.		X		Blended with HFO in marine engines.
Recycled Fuel Oil	Non-distilled, filtered and de-watered used oil burned without any further treatment.	90-600	≈ 0.4	N/A	X	X	X	Used as cutter stock or burned directly in commercial/industrial kilns or boilers.
Asphalt Flux/Extender	Characteristics vary depending on production process & yields, but flux is like a very heavy gas oil or hydrolene.	250-700	Unknown	Vacuum distillation column bottoms.	X	X		Used as an additive to asphalt. Improves expansion properties. Primarily used on roads, also in shingles and mop-on roofs. 7-15% asphalt flux mixed with 0-Pen asphalt.
Ethylene Glycol	Waste antifreeze that ends up in used oil stream due to mixing.	N/A	N/A	Unknown	X	X		Input to finished anti-freeze.

Non-combustion use phase processes theoretically need to be modeled as well. However, in cases in which the use phase of the secondary product is understood to be identical to the use phase of the primary product, their environmental impacts are also identical and therefore cancel out. Use of secondary Group II base oil in a lubricating capacity is no different from that of primary base oil. The same is true for ethylene glycol and asphalt flux's primary and secondary products. Therefore, the use phase for these three product categories was not modeled. It is important to note that the contents of the asphalt flux secondary product are somewhat different from those of primary lubricating road oil because the wear metals and chemical lubricant additives that are in used oil primarily end up being concentrated in the asphalt flux co-product, meaning asphalt flux has a higher concentration of these constituents than an alternative primary product would. If these contaminants were not securely bound in the asphalt, the environmental impacts of the two products might be quite different. However, numerous studies have failed to detect significant leaching of contaminants from asphalt (c.f. Legret, Odie, Demare, & Jullien, 2005), and the U.S. EPA states in its used oil management standard, Chapter 40 of the Code of Federal Regulations Section 279, that distillation bottoms, such as asphalt flux, are conditionally exempt from the standard because "data submitted to EPA showed that distillation bottoms from re-refining processes do not exhibit the toxicity characteristic for hazardous waste." Therefore, the use phase of the asphalt flux co-product is assumed not to be significantly different in impact from that of a primary asphalt modifier product.

The baseline model includes both refinery products and natural gas in its displacement model. While the increase in shale gas fracturing and resulting natural gas boom has caused natural gas prices to drop in recent years, natural gas was more expensive in the base year of 2010 than recycled fuel oil. Natural gas is currently far less expensive than comparable petroleum products, meaning that at this point, if a facility has the technical capacity to use natural gas they will do so. However, in future years the prices of both natural gas and recycled fuel oil may vary, meaning recycled fuel oil could potentially displace natural gas once again.

Unless otherwise indicated, a 1:1 technical displacement rate is assumed in the used oil life cycle assessment model. In instances where a product has the potential to displace several primary products, an equal split between the primary products is assumed. Technical displacement rates vary based on the critical properties of the primary and secondary products. In the case of lubricating base oils, the technical substitution rate is assumed to be 1kg:1kg because secondary Group II base oil and primary Group II base oil are understood to be equally good at achieving their function on a per mass basis. In the case of fuel products, the substitution rate is assumed to be 1MJ:1MJ, i.e. the displacement is based on the relative energy content per unit mass, since the function of a fuel is to heat and heating values may vary between interchangeable fuels.



13 Appendix E: Closed-Loop Versus Open-Loop Recycling

Closed-loop recycling is usually regarded as environmentally superior to open-loop recycling, which is frequently suspected as being down-cycling, i.e. generating secondary materials of ‘lower quality’ as the original primary material. However, in order to substantiate the claim of environmental superiority it is necessary to show that closed-loop recycling generates more environmental benefits than open-loop recycling. The objective of this appendix is therefore to provide a rigorous quantitative comparison of the environmental benefits of closed-loop and open-loop recycling.

Without loss of generality, let’s consider the following material production and consumption scenario: A material commodity, e.g. a polymer, a metal, etc., has two market applications, A and B, which have both a constant annual demand, X and Y. Only the material from application A is being collected and recycled with a constant recycling rate R, which accounts for collection and reprocessing losses. The cycling time of material application A, i.e. the time between two subsequent uses of the same batch of material, is constant and one year. Material application B, on the other hand, is single use, i.e. all material used in application B is disposed of after use.

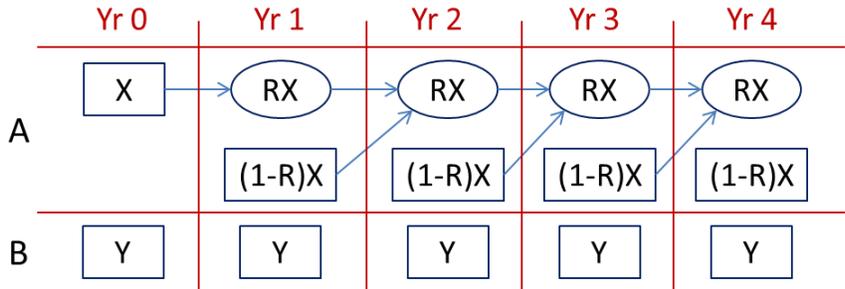


Figure 76: System CL – Closed-loop recycling of material application A over four years (boxes indicate primary material, ovals secondary material).

Figure 76 depicts closed-loop (CL) recycling of the material from application A over a period of four years. It can be seen that years two to four are just repeats of year one. Every year the amount X is consumed in material application A. After the first year the amount RX is being recycled annually from the material produced and consumed in the previous year. This reduces the need of primary material for application A to (1-R) X per year. All material from application B is discarded after its use, which means that every year Y primary material needs to be produced for application B.

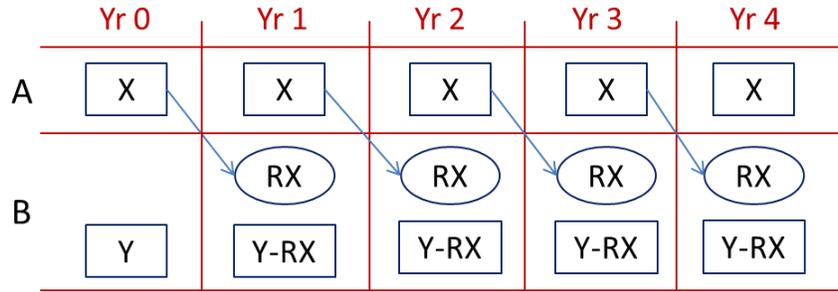


Figure 77: System OL – Open-loop recycling of material application A into application B over four years (boxes indicate primary material, ovals secondary material).

Figure 77 shows open-loop (OL) recycling of the material from application A into application B over a period of four years. Again, years two to four are just repeats of year one. Every year the amount RX is collected from application A and recycled into application B. This reduces the need of primary material for application B to $Y - RX$ per year. Application A does not use any secondary material as input, which means that every year X primary material needs to be produced for application A.

Note that the only difference between the material production and consumption systems closed-loop and open-loop is that in closed-loop the material from application A is recycled back into application A (closed-loop), while in system open-loop the material from application A is recycled into application B (open-loop). The only implied assumptions are that in system closed-loop the material can be recycled multiple times back into application A, and that in system open-loop $RX < Y$, otherwise application B does not have enough demand to consume all secondary material recycled from application A.

Let E_i denote an environmental impact indicator of process i measured in units of environmental impact indicator per kg of material output. The cradle-to-gate environmental impact of primary production of A is E_{prim_A} and of primary production of B is E_{prim_B} . The scrap-to-gate environmental impact of closed-loop recycling of A into A is $E_{repro_{AA}}$ and of open-loop recycling of A into B is $E_{repro_{AB}}$. We can now calculate the environmental benefits of open- and closed-loop recycling. The total annual environmental impact of the system CL is then

$$(1 - R)X \cdot E_{prim_A} + RX \cdot E_{repro_{AA}} + Y \cdot E_{prim_B} = X \cdot E_{prim_A} + Y \cdot E_{prim_B} - RX(E_{prim_A} - E_{repro_{AA}}).$$

Closed-loop recycling as described in Figure 76 reduces environmental impact, i.e. generates environmental benefit, when $E_{prim_A} - E_{repro_{AA}} > 0$. On the other hand, the total annual environmental impact of the system OL is

$$X \cdot E_{prim_A} + (Y - RX) \cdot E_{prim_B} + RX \cdot E_{repro_{AB}} = X \cdot E_{prim_A} + Y \cdot E_{prim_B} - RX(E_{prim_B} - E_{repro_{AB}})$$

Open-loop recycling as described in Figure 77 generates environmental benefit if $E_{prim_B} - E_{repro_{AB}} > 0$. It follows that the closed-loop system has higher environmental benefits than the open-loop system if and only if

$$(E_{prim_A} - E_{repro_{AA}}) - (E_{prim_B} - E_{repro_{AB}}) > 0,$$

i.e. the difference between primary and secondary production of application A is larger than the difference between primary and secondary production of application B. This condition is not related to the issue of closed-loop vs. open-loop recycling. Instead, it is a purely function of the two specific applications A and B of the material. In other words, our analysis has not provided any evidence that closed-loop recycling has intrinsic environmental advantages over open-loop recycling.

This general point can be illustrated with two different examples.

The first is the recycling of PET bottles back into PET bottles or into apparel fiber. In this example, primary production and recycling processes can be divided into primary production of PET granulate, E_{PET} , conversion of primary or recycled PET granulate into bottles, E_{bottle} , conversion of primary or recycled PET granulate into clamshells, $E_{clamshell}$, and recycling of PET bottles into secondary PET granulate (RPET), E_{RPET} . In other words, bottles are stretch-blow-molded and clamshells are thermoformed from the same PET granulate, and there is no environmental difference between using PET or RPET granulate for blow-molding or thermoforming.

Using the generic notation this means that $E_{prim_A} = E_{PET} + E_{bottle}$, $E_{repro_{AA}} = E_{RPET} + E_{bottle}$, $E_{prim_B} = E_{PET} + E_{clamshell}$, and $E_{repro_{AB}} = E_{RPET} + E_{clamshell}$.

The total annual environmental impact of the closed-loop and open-loop systems for PET is thus

$$E_{CL-PET} = X \cdot (E_{PET} + E_{bottle}) + Y \cdot (E_{PET} + E_{clamshell}) - RX \cdot (E_{PET} - E_{RPET}) = E_{OL-PET},$$

i.e. the environmental performances of the closed-loop and open-loop recycling systems are identical.

Applying the analysis to the case of PET therefore provides no evidence that there are additional environmental benefits in bottle-to-bottle recycling relative to the more common open-loop recycling of PET into clamshells, fibers, or other RPET applications, as long as production of PET and RPET granulate is the same in closed- and open-loop recycling.

The second example considers used lubricant oil, which can be re-refined back into secondary lubricant oil. This form of closed-loop recycling is therefore an example of material application A in Figure 76. Used lubricant oil can also be used as a fuel, which is called recycled fuel oil. This form of open-loop recycling is equivalent to material application B in Figure 77. Let's assume for the sake of this example that recycled fuel oil is used to replace fuel oil. In this example the relevant processes are therefore virgin base oil production $E_{prim_{BO}}$, re-refining of used lubricant oil into secondary base oil E_{ReRe} , production and combustion of virgin fuel oil $E_{prim_{FO}}$, and the use of used lubricant oil as recycled fuel oil E_{RFO} . The generic condition for closed-loop recycling to have higher environmental benefits than open-loop recycling is thus

$$(E_{prim_{BO}} - E_{ReRe}) - (E_{prim_{FO}} - E_{RFO}) > 0.$$

Re-refining used lubricant oil into secondary base oil has higher environmental benefits than using used lubricant oil as recycled fuel oil if and only if the difference between primary and

secondary production of base oil is larger than the difference between production and combustion of virgin fuel oil and recycled fuel oil.

Both examples illustrate our general conclusion that closed-loop recycling appears to have no intrinsic environmental advantage over open-loop recycling. Which recycling path has higher environmental benefits depends only on the difference in environmental impacts between the primary and secondary production and use processes.

The two assumptions we had to make to derive the generic equations generate two additional observations. The condition that $RX < Y$ means that closed-loop recycling becomes necessary once more secondary material is generated than can be accommodated in open-loop recycling applications. One example of this is aluminum recycling, where the majority of recycled wrought aluminum is used for castings. Once the castings market can no longer accommodate all recycled wrought aluminum, wrought products will have to be recycled back into wrought products. Again, this is not an issue of open- versus closed-loop recycling, but simply about matching production and consumption of secondary products.

The other assumption was that multiple closed recycling loops are technically and economically feasible. The prevalence of open-loop recycling over closed-loop recycling suggests that there might in fact be technical and economic disadvantages to closed-loop recycling. The good news is that open-loop recycling has the potential to deliver the same environmental benefits than closed loops while potentially posing fewer technical and economic challenges.

One argument that could be made in favor of closed-loop recycling is that more secondary resource S can be generated from a given amount of primary resource P , since the amount of resulting secondary resource S is calculated as $S = P \frac{(1-R^{n+1})}{(1-R)}$, with R being the recycling rate again and n the number of recycling cycles. However, Figure 76 and Figure 77 show that closed- and open-loop recycling lead to the same amount of annual primary resource consumption as long as the demand for the secondary resource equals or exceeds the supply. Again, closed-loop recycling becomes important only once open-loop recycling is no longer able to consume all available recycled material.

In summary, we conclude that closed-loop recycling has no intrinsic higher environmental benefit than open-loop recycling. In both cases the environmental benefits are determined exclusively by the environmental impact difference between primary and secondary production and use processes. As long as $(E_{prim_A} - E_{repro_{AA}}) = (E_{prim_B} - E_{repro_{AB}})$ switching from the open-loop system in Figure 76 to the closed-loop system in Figure 77 will not lead to additional environmental benefits. As long as demand for the secondary resource exceeds supply, the best way to increase the environmental benefits in open-loop and closed-loop systems is to increase collection and recycling of the material coming out of the use phase of applications A and B.

14 Appendix F: Data Map and Quality Assessment

Appendix F contains metadata regarding all the unit processes used in the life cycle assessment (LCA) model and an assessment of their data quality. Table 166 contains a complete summary of all unit process, the life cycle stages in which they are used, the reference year in which the data was collected, the geographic location in which it was collected, the format of the data, and the source from which it was drawn for this project. All source abbreviations are defined in the source key beneath the table.

Table 167 contains an assessment of the data quality of each unit process used in the LCA model. These data quality ratings are based on the rating parameters outlined by Weidema and Wesnaes, as defined in Table 168. Each unit process that is used in the LCA model is assessed for its reliability, completeness, temporal appropriateness, geographic appropriateness, and technological appropriateness to the system under study.

Life cycle phase	Process	Year	Geo	Format	Data Source
<i>Used oil Generation</i>	Lubricant Sales	2010	CA	average data	Kline
	Used Oil MFA	2010	CA	primary data	DTSC/CalRecycle
<i>Collection</i>	LHD2 Diesel truck, 5t capacity	2010	CA	average data	EMFAC
	MHD Diesel Truck Class 6, 11 t capacity	2010	CA	average data	EMFAC
	HHD Diesel Truck Class 8b, 18t capacity	2010	CA	average data	EMFAC
	Diesel Rail	2010	US	average data	GREET
<i>Improper Disposal</i>	Used oil disposed in landfill	2013	CA	average data	Calculation
	Used oil in wastewater filtration	2006	EU	average data	Literature
	Used oil in MSW incinerator	2013	CA	average data	Literature
<i>Energy Inputs</i>	Electricity	2012	US/CA	average data	US LCI/EIA
	Natural gas supply	2001	US	average data	US LCI
	Natural gas combustion	2013	US	average data	UOCM
	Light ends combustion	2013	US	average data	UOCM
	No. 2 distillate production	2009	US	average data	PE Intl.
	No. 2 distillate combustion	2013	US	average data	UOCM
	Gasoline production	2010	US	average data	PE Intl.
	Gasoline combustion	2003	US	average data	USLCI
	LP gas combustion (C-G)	2001	US	average data	USCLI
<i>Chemical Inputs</i>	Process Water	2011	EU	average data	PE Intl.
	Hydrogen production	2011	NL	average data	PE Intl.
	Nitrogen (liquid) production	2011	DE	average data	PE Intl.
	Sodium hydroxide production	2011	DE	average data	PE Intl.
	Hydrochloric acid production	2011	DE	average data	PE Intl.
	Sodium chloride production	1996	EU	average data	PE Intl.
	Sodium hypochlorite production	1997	EU	average data	Ecoinvent
<i>Waste treatment</i>	Hazardous waste incineration	2000	CH	average data	Ecoinvent
	Haz waste to landfill	2000	DE	average data	Ecoinvent
	Landfill of inert waste	2011	EU	average data	PE Intl.
	Waste water treatment	2011	EU	average data	PE Intl.
<i>Recycling</i>	Re-refining	2010	CA/US	primary data	N/A

Life cycle phase	Process	Year	Geo	Format	Data Source
	Distillation	2010	CA	primary data	N/A
	RFO Production	2010	US	primary data	N/A
<i>Secondary Product Use</i>	Light ends combustion	2003	US	average data	USLCI
	No. 2 distillate combustion	2013	US	average data	UOCM
	RFO combustion	2010	US	average data	UOCM
	MDO combustion	2001	US	average data	UOCM
<i>Displaced Processes</i>	Lubricant production	2010	US/CA	average data	PE Intl.
	Bitumen production	2010	US/CA	average data	PE Intl.
	Natural gas supply	2009	US	average data	PE Intl.
	Natural gas combustion	2013	US	average data	UOCM
	No. 2 distillate production	2010	US/CA	average data	PE Intl.
	No. 2 distillate combustion	2013	US	average data	UOCM
	MDO Combustion	2013	US	average data	UOCM
	HFO production	2010	US/CA	average data	PE Intl.
	HFO combustion	2013	US	average data	UOCM
	Ethylene glycol production	2010	DE	average data	PE Intl.

Table 166: Complete process list.

Source Key

UOCM	UCSB used oil combustion model
US LCI	U.S. Life Cycle Inventory Database
PE Intl.	PE International proprietary database
EMFAC	California Air Resources Board Emissions Factor Model, version 2011
GREET	Department of Energy's Greenhouse gases, Regulated Emissions, and Energy Use in Transportation Model
DTSC	Department of Toxic Substances Control
CalRecycle	California Department of Resources Recycling and Recovery
EIA	Energy Information Agency
Kline	Contractor for Used Oil Study
C-G	Indicates cradle to gate

Table 167: Pedigree data quality assessment.



Process	Reliability	Completeness	Temp. Correlation	Geo. Correlation	Tech Correlation
Bitumen production	1	1	1	1	2
Diesel Rail	1	1	1	1	2
Used oil disposed in landfill	4	2	2	1	1
Used oil in wastewater filtration	1	1	3	4	1
Used oil in MSW incinerator	3	1	1	1	1
Used oil distillation	2	2	1	1	1
Electricity	1	1	1	1	1
Ethylene glycol production	1	5	1	3	2
Gasoline combustion	1	5	3	1	2
Gasoline production	1	1	1	1	2
Haz waste to landfill	1	1	4	3	2
Hazardous waste incineration	1	1	4	3	2
HFO combustion	2	2	2	2	2
HFO production	1	1	1	1	2
HHD Diesel Truck Class 8b, 18t capacity	1	1	1	1	1
Hydrochloric acid production	1	1	1	3	2
Hydrogen production	1	1	1	3	2
Landfill of inert waste	1	1	1	3	2
LHD2 Diesel truck, 5t capacity	1	1	1	1	1
Light ends combustion	2	2	2	2	2
LP gas combustion	1	1	4	1	2
Lubricant production	1	1	1	1	1
MDO combustion	2	2	2	2	2
MHD Diesel Truck Class 6, 11 t capacity	1	1	1	1	1
Natural gas combustion	2	2	2	2	2
Natural gas supply	1	1	2	2	2
Nitrogen (liquid) production	1	1	1	3	2
No. 2 distillate combustion	2	2	2	2	2
No. 2 distillate production	1	1	1	1	1
Process Water	1	1	1	3	2
Used oil re-refining	2	2	1	1	1
RFO combustion	2	2	2	2	2
RFO Production	2	2	1	1	1
Sodium chloride production	1	1	1	3	2
Sodium hydroxide production	1	1	1	3	2
Sodium hypochlorite production	1	5	4	3	2
Waste water treatment	1	1	1	3	2

Weidema & Wesnaes (1996) Pedigree matrix

Indicator Score	Reliability	Completeness	Temporal Correlation	Geographical Correlation	Technological Correlation
1	Verified data based on measurements	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Less than three years of difference to year of study	Data from area under study	Data from enterprises, processes and materials under study
2	Verified data partly based on assumptions or non-verified data based on measurements	Representative data from a smaller number of sites but for adequate periods	Less than six years difference	Average data from larger area in which the area under study is included	Data from processes and materials under study but from different enterprises
3	Non-verified data partly based on assumptions	Representative data from an adequate number of sites but from shorter periods	Less than 10 years difference	Data from area with similar production conditions	Data from processes and materials under study but from different technology
4	Qualified estimate (e.g. by industrial expert)	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Less than 15 years difference	Data from area with slightly similar production conditions	Data on related processes or materials but same technology
5	Non-qualified estimate	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods	Age of data unknown or more than 15 years of difference	Data from unknown area or area with very different production conditions	Data on related processes or materials but different technology

Table 168: Data quality pedigree rating matrix.