ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF COMMERCIAL SPACE TRANSPORTATION ACTIVITIES IN THE UNITED STATES

BY

SHELIA SCOTT NEUMANN, P.E.

Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

THE UNIVERSITY OF TEXAS AT ARLINGTON

May 2018

Supervising Committee:

Supervising Professor, Melanie Sattler

Mostafa Ghandehari

Hyeok Choi

Susan Ferreira

Kamesh Subbarao

Acknowledgements

I would like to express my sincere gratitude to my academic advisor and supervising professor, Dr. Melanie Sattler. She was one of the best professors I have had for graduate work who cares about the student and their learning. She was always available to address questions and provided excellent guidance and direction. I truly appreciate her time, expertise, and efforts to make this dissertation successful and worthwhile. Thank you!

I would also like to express my appreciation to my committee members for their willingness to be part of this effort, Dr. Mostafa Ghandehari, Dr. Hyeok Choi, Dr. Susan Ferreira and Dr. Kamesh Subbarao. Their varying experience in both academics and industry contributed to the dissertation topic and its direction. They inspired me in their classes and in our conversations.

For believing in my ability to pursue the Ph.D. with their endorsement and encouragement, I am grateful to Dr. Jill Jermano, Dr. Leigh Abts, and Dr. Michel Johnson.

I would like to also thank everyone who I reached out to for knowledge, information, generosity, and support along the way: Michael Stock; Edgar Zapata; Andrew Wilson; Thibaut Maury; Jakob Huesing; Julian Austin; Colonels Kirk Phillips and Mark Smallwood; Stacey Zee; Shari Miller; Michael Blaylock; Ken Davidian; Lieutenant Colonels Francisco Catala and Steven Lange; John Cirucci; Andrew Rak; Dr. Shannon Lloyd; John Langett; Eduardo Manual Dias Lopes; Jordan Klovstad; Krista Rand; Kelly Busquets; Sam Higuchi; Jeff Haynes; Dr. Andrei Zagrai; Michael Bruckner and others who were willing to speak with me and share their time and information. Thank you all so very much!

I am very grateful to my mother, Mignon, and my father, Shelby, for their love, prayers, and support in every aspect of life. They have always encouraged me to be who God wanted me to be.

I would also like to thank my husband, Scott, for his love, faith and belief in me. He is my most trusted sounding board who offered valuable insights into the Commercial Space industry. I love you!

Finally, my faith in Jesus Christ has given me the courage, discipline, and vision to pursue the dreams He put in my heart. I can do all things through Christ who strengthens me; Philippians 4:13.

Abstract

The Commercial Space Transportation (CST) activities in the United States are increasing and have increased over 50% in the last year. The launches in the United States for commercial purposes are expected to increase another 50% in the next 3-5 years. National Environmental Policy Act (NEPA) environmental assessments do provide the regulatory environmental analysis for launching space vehicles within the United States. However, the environmental impacts from these launches have not been fully characterized. One method to characterize environmental impacts from a system is through conducting a Life Cycle Assessment (LCA) based on an international standard, ISO14040. The results from this environmental LCA will augment the NEPA efforts for launch activities. The European Space Agency uses LCAs to evaluate their environmental impacts or burdens for specific launchers. Instead of evaluating a specific launcher, this study focused on the consumables used for the launch of one space vehicle. Therefore, this study had the overall goal to characterize those environmental burdens and impacts of one space vehicle launch in the United States with emphasis on the Use Phase.

Specific objectives for this environmental life cycle assessment (ELCA) included:

1. To conduct a base-case life cycle environmental inventory and impact assessment of CST activities in the United States based on ISO 14040 and 14044 focused on:
    - Use Phase (launch) with six consumables: reusable and expendable rocket boosters; liquid propellants (liquid oxygen/liquid hydrogen (LOx/LH_2), liquid oxygen/liquefied natural gas (LOx/LNG), liquid oxygen/kerosene (LOX/RP-1)), water, electricity, and chemicals,
    - Use Phase outputs of greenhouse gases, traditional air pollutants (criteria air pollutants), solid and hazardous wastes, water contamination, and noise.
2. To identify a range of impacts due to sensitivity in model inputs (sensitivity analysis).
3. To conduct additional LCAs incorporating “green technologies” to identify strategies for reducing environmental impacts.
4. To operationalize this ELCA and develop an operational tool, space transportation environmental profile for launch (STEP-L) Dashboard.

The research contribution of this study advances knowledge and analytic application of the LCA to U.S. space launch operations. This study is the first ELCA to begin to characterize environmental domain from the launch of one space vehicle. Each of the objectives added new knowledge to identify and illustrate those environmental impacts from CST launch activities in the United States. From the sensitivity analysis, essential data and process information was identified so a U.S. space mission LCA can be more refined for future LCAs and to enhance options for reduced environmental impacts and better decision making in mission profiles and eco-design. Finally, the STEP-Ls generated a quick-look view for operators, environmental professionals, systems engineers, and other decision makers on each of the launch missions evaluated in this study.

SimaPro Software version 8.3.2 and IMPACT2002+ was used to conduct the life cycle inventory and assessment. Data inputs were gathered from public accessible documents, industry websites, technical journals, and textbooks. Each consumable was assessed one-at-a-time (OAT) to determine its environmental impacts per Launch and then all the consumables were analyzed as a whole system per Launch.

The reusable rocket booster impacted the Human health and Resources the most, whereas, the expendable rocket impacted Human health and Climate change damage areas the most. Since the 1st Stage in the reusable rocket was the only element of the rocket that was reused, the mineral extraction was 89% less than the expendable rocket booster.

The propellants, in particular the LOx, and the engine components and their material makeup generate or influence the greatest environmental burden per Launch for a space vehicle launch into orbit. All three propellants impacted Human health and Resources damage areas the most. Comparatively, LH_2 influenced the characterization categories and damage areas the least of the three propellants. This result is primarily due the lower quantity of LH2 modeled in this study.

The various chemicals used and stored at the launch facility can make a difference as to the environmental burden. Hydrazine, diesel and liquid nitrogen had the highest impact for the chemicals considered. The Chemicals consumable impacted Human health and Resources damage areas the most.

Finally, electricity and water are minimal contributors to the environmental burden. However, the diesel-generator was the largest contributor of impact within the electricity consumable. Finding another source of electricity for back-up power and other support equipment rather than using the diesel would decrease the environmental impacts significantly. Transportation was evaluated for consumables traveling to the launch facility from the manufacturing. The west and southeast data for both diesel and gasoline trucks were used in this study. The diesel truck on the west showed higher contributions in both the characterization and the damage areas than the diesel truck in the southeast. This higher contribution might be due to the additives and refining processes used to produce the diesel in the west.

A qualitative input using the Delphi Method was applied to compare the base-case results with the results of a panel of selected experts. An online tool, QUALTRICs© was used to administer the Delphi method surveys. The comparison showed the top two damage areas for Delphi Method and SimaPro results agreement were in: the reusable rocket booster impacted Human health, expendable rocket impacted Climate change, LOx/LH_2 impacted Human Health and Resources, and the other propellants impacted Resources.

Five sensitivity parameters were evaluated: reusable rocket life uses, electricity substitute for diesel, material composition change for engine, test firings propellant quantity, and chemical quantity changes. The highest influencer was the propellant amount used in a test firing as part of the launch campaign. Scenario analysis was performed on the frequency of launches and number of engines. The results of an expendable rocket with three engines would have more impacts than the reusable rocket booster with 27 engines. Reusability is validated as a key way to minimize environmental burdens.

Green technology recommendations included replace diesel with solar for the electricity, replacing titanium process (Kroll) with the Armstrong® process, replacing conventional manufacturing for parts with 3-D additive manufacturing, and replacing kerosene (RP-1) with methane as a fuel. A notional green technology STEP-L was generated with solar replacement for diesel-generated electricity. The comparison of the green STEP-L with the reusable rocket with LOx/RP-1 results showed less impact to the damage areas. Green notional launch campaign reduced damage areas of Resources by 1.6%, reduced Climate change by 2.1%, reduced Ecosystem quality by 1.6% and reduced Human health by 1.3%. Overall, impact change for all damage areas combined is 1.5%. The STEP-L for the notional launch campaign with green technology additions generated slight reductions in impact to all damage areas. Even though the reductions appear small, adding a green technology to a full launch campaign can provide a meaningful decrease in environmental impacts. The framework for inserting the green technology recommendations can be transferred to other similar government operations.

Finally, the STEP-L Dashboard provides a way for operators and planners to determine the environmental damage from the consumables as an operational system. The Dashboard input can be changed according to the operational scenario at the launch operation to allow for quick identification of each consumable’s contribution to damage areas.

Table of Contents

ACKNOWLEDGEMENTS .... **II**

ABSTRACT .... **III**

TABLE OF FIGURES .... **IX**

LIST OF TABLES .... **XIII**

LIST OF ABBREVIATIONS .... **XV**

CHAPTER 1 INTRODUCTION **1**

1.1 Recent Growth in Commercial Space Transportation Activities 1
1.2 Environmental Impacts of Commercial Space Activities 3
1.3 Research Objectives 5
1.4 Dissertation Organization 6

CHAPTER 2 LITERATURE REVIEW **7**

2.1 Overview of Life Cycle Assessment Framework 7
2.2 Overview of Commercial Space Transportation Relevant Literature 12
2.2.1 University of Texas at Arlington (UTA) Electronic Search for Peer-Reviewed Material: *13*
2.2.2 All-Inclusive Literature On-Line Searches: *15*
2.3 Research Objectives 24
2.4 Research Contribution Advances Knowledge and Analytic Application of LCA to U.S. Space Launch Operations 24

CHAPTER 3 METHODOLOGY **26**

3.1 Methodology Applied for Research Objective 1. 26
3.1.1 Goal and Scope Definition *28*
3.1.2 Inventory Analysis *39*
3.1.3 Impact Assessment *71*
3.1.4 Interpretation *79*
3.2 Methodology Applied for Research Objective 2: Conduct a sensitivity analysis to determine range of environmental impacts. 79
3.2.1 Sensitivity Parameters *80*
3.2.2 Scenario Analysis *81*
3.3 Methodology Applied for Research Objective 3: Conduct "green technology" LCA scenarios to identify strategies for reducing environmental impacts. 83
3.3.1 Green Technology Recommendation: Replace Diesel with More Electricity or Solar Power *84*
3.3.2 Process Change Recommendation: Use Armstrong Process Titanium Powder for Titanium instead of Kroll Process *84*
3.3.3 Material Change Recommendation: Additive Manufacturing for Parts *85*
3.3.4 Propellant Change from LOx/RP-1 to LOx/CH_4 (Methane) *85*
3.3.5 Notional Green Technology Launch Campaign *86*
3.4 Methodology Applied for Research Objective 4. Operationalizing the LCA and the STEP-L Dashboard Development. 86

CHAPTER 4 RESULTS AND ANALYSIS **89**

4.1 Results for Objective 1: ELCA Base Case Analysis for CST Activities 89

4.1.1 Inventory Analysis for CST Activities in the United States Base-Case 89
4.1.2 Impact Assessment for CST Activities in the United States Base-Case 128
4.1.3 Comparison of Reusable and Expendable Rocket Booster Per Launch...181
4.1.4 Comparison of Liquid Propellants Per Launch 186
4.1.5 Delphi Method Applied to Rocket Boosters and Propellants Per Launch 193
4.1.6 Space Transportation Environmental Profiles Per Launch Derived From Base-Case..............................195
4.1.7 Summary of Base-Case of CST Activities using LCA Methodology..210
4.2 RESULTS FOR OBJECTIVE 2: RANGE OF ENVIRONMENTAL IMPACT THROUGH SENSITIVITY ANALYSIS AND SCENARIO ANALYSIS215
4.2.1 Sensitivity Analysis of Five Sensitivity Parameters 215
4.2.2 Frequency of Launches Over the Next 10 Years 225
4.2.3 Cumulative Effects from Frequent Launches 225
4.2.4 Scenario Analysis – Frequency of Launches and Number of 1st Stage Engines 226
4.2.5 Monte Carlo Analysis of the Data Quality in SimaPro of Per Launch Consumables 229
4.2.6 Comparison Between Base-Case and TRACI Impact Method 231
4.2.7 Comparison Between Base-Case and ReCiPe Impact Method 233
4.3 RESULTS FOR OBJECTIVE 3: GREEN TECHNOLOGY RECOMMENDATIONS FOR LAUNCH CAMPAIGN 236
4.3.1 Green Technology Scenarios 236
4.3.2 Notional Launch Campaign with Green Technologies...241
4.4 **RESULTS FOR OBJECTIVE 4. OPERATIONALIZING THE LCA AND THE DEVELOPMENT OF THE SPACE TRANSPORTATION ENVIRONMENTAL PROFILES FOR LAUNCH (STEP-L) DASHBOARD** 242
4.5 **ANSWERS TO THE RESEARCH QUESTIONS**..244

CHAPTER 5 CONCLUSIONS, FINDINGS, AND RECOMMENDATIONS FOR FUTURE STUDIES................................. 248

5.1 CONCLUSIONS AND FINDINGS 248
5.2 FUTURE RESEARCH RECOMMENDATIONS 253
5.3 STEP-L DASHBOARD FOR OPERATORS, ENVIRONMENTAL AND OCCUPATIONAL HEALTH PROFESSIONALS, AND DECISION-MAKERS 255

APPENDIX 257

APPENDIX A DELPHI METHOD METHODOLOGY AND SURVEYS 258

APPENDIX B SPACE TRANSPORTATION ENVIRONMENTAL PROFILE FOR LAUNCH (STEP-L) DASHBOARD STEP-BY-STEP DEVELOPMENT PROCEDURES... 283

REFERENCES.. 287

BIOGRAPHICAL INFORMATION 297

Table of Figures

FIGURE 1-1 U.S. SPACE TRANSPORTATION INDUSTRY SITES AND LOCATIONS (FAA, 2014) 3
FIGURE 1-2 EUROPEAN SPACE AGENCY LIFE CYCLE ASSESSMENT (ESA, 2012) 4
FIGURE 2-1 LCA FRAMEWORK (ISO 14040, 2006) 8
FIGURE 2-2 LIFE CYCLE PHASES (EPA, 1993) 9
FIGURE 2-3 LIFE CYCLE IMPACT ASSESSMENT (LCIA) SUB-PHASES (ISO 14040, 2006) 10
FIGURE 2-4 LIFE CYCLE PHASES (ISO 14040, 2006; NASA, 2011; COSE, 2016, CREATED BY NEUMANN) 11
FIGURE 3-1 FALCON 9 ORBITAL COMMUNICATION LAUNCH FACILITY HANGAR (SPACEX, 2014) 27
FIGURE 3-2 LIFE CYCLE ASSESSMENT FRAMEWORK (ISO 14040, 2006) 28
FIGURE 3-3 ELCA FOR CST ACTIVITIES SYSTEM BOUNDARY 34
FIGURE 3-4 ELCA FOR CST ACTIVITIES INPUTS AND OUTPUTS 36
FIGURE 3-5 TROPOSPHERE AND STRATOSPHERE DIMENSIONS (RUSSELL, 2011) 37
FIGURE 3-6 DATA SOURCES FOR ELCA PHASES (DEVELOPED BY NEUMANN USING LUCIDCHART.COM, 2016) 41
FIGURE 3-7 SYSTEMS ENGINEERING BREAKDOWN OF REUSABLE ROCKET BOOSTER 43
FIGURE 3-8 SYSTEMS ENGINEERING BREAKDOWN OF EXPENDABLE ROCKET BOOSTER 44
FIGURE 3-9 OPERATIONAL EXPENDABLE ROCKET BOOSTER, DELTA IV HEAVY, EXPLODED ELEMENTS (DELTA IV LAUNCH SERVICES USERS GUIDE, 2013). 45
FIGURE 3-10 ONE SPACE VEHICLE LAUNCH GENERAL TASKS AND TIMELINE 46
FIGURE 3-11 GENERIC LAUNCH CAMPAIGN ACTIVITIES 46
FIGURE 3-12 REUSABLE ROCKET BOOSTER LANDING (SPACEX-FALCON 9) (FAA COMPENDIUM, 2018) 48
FIGURE 3-13 GENERIC ROCKET BOOSTER DIMENSIONAL ANALYSIS FOR ESTIMATED MASSES (FAA COMPENDIUM, 2018) 53
FIGURE 3-14 REUSABLE AND EXPENDABLE ROCKET BOOSTER MODULES 55
FIGURE 3-15 LIFE CYCLE IMPACT ASSESSMENT (LCIA) SUB-PHASES (ISO 14040, 2006) 71
FIGURE 3-16 INCREASED LAUNCHES FROM 2017-2026 BY 10, 15 AND 20% 82
FIGURE 3-17 NOTIONAL ARMSTRONG PROCESS FOR TITANIUM POWDER 85
FIGURE 4-1 REUSABLE ROCKET NETWORK, SINGLE SCORE, 5% CUTOFF, SIMAPRO VERSION 8.2.3 SOFTWARE 93
FIGURE 4-2 EXPENDABLE ROCKET BOOSTER NETWORK, SINGLE SCORE, AT 5% CUTOFF 97
FIGURE 4- 3 CHEMICALS (GENERIC) NETWORK, DAMAGE ASSESSMENT, SINGLE SCORE (SIMAPRO SOFTWARE) 103
FIGURE 4- 4 ELECTRICITY NETWORK, DAMAGE ASSESSMENT, SINGLE SCORE, 5% CUTOFF (SIMAPRO SOFTWARE) 107
FIGURE 4-5 PROPELLANT – LOX/LNG NETWORK DAMAGE ASSESSMENT – SINGLE SCORE AT 10 % CUTOFF (SIMAPRO SOFTWARE) 122
FIGURE 4-6 REUSABLE ROCKET, CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 130
FIGURE 4-7 REUSABLE ROCKET, DAMAGE ASSESSMENT NORMALIZATION RESULTS 131
FIGURE 4-8 REUSABLE ROCKET, DAMAGE ASSESSMENT SINGLE SCORE RESULTS 132
FIGURE 4-9 REUSABLE ROCKET, 1ST STAGE CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 133
FIGURE 4-10 REUSABLE ROCKET, 1ST STAGE DAMAGE ASSESSMENT NORMALIZATION RESULTS (SIMAPRO SOFTWARE) 134
FIGURE 4-11 REUSABLE ROCKET, 1ST STAGE DAMAGE ASSESSMENT - SINGLE SCORE (SIMAPRO SOFTWARE) 135
FIGURE 4-12 REUSABLE ROCKET, 2ND STAGE CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 136
FIGURE 4-13 REUSABLE ROCKET, 2ND STAGE DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 137
FIGURE 4-14 REUSABLE ROCKET, 2ND STAGE DAMAGE ASSESSMENT SINGLE SCORE 138
FIGURE 4-15 REUSABLE ROCKET, FAIRING CHARACTERIZATION AREAS (SIMAPRO SOFTWARE) 142
FIGURE 4-16 REUSABLE ROCKET, FAIRING DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 143
FIGURE 4-17 REUSABLE ROCKET, FAIRING NETWORK – SINGLE SCORE (SIMAPRO SOFTWARE) 144
FIGURE 4-18 EXPENDABLE ROCKET BOOSTER CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 145

FIGURE 4-19 EXPENDABLE ROCKET BOOSTER DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 146
FIGURE 4-20 EXPENDABLE ROCKET BOOSTER DAMAGE ASSESSMENT SINGLE SCORE 147
FIGURE 4-21 EXPENDABLE ROCKET NORMALIZATION – HUMAN HEALTH, CONSTITUENTS IN PROCESSES AT 10% CUTOFF (SIMAPRO SOFTWARE) 148
FIGURE 4-22 EXPENDABLE ROCKET 1ST STAGE CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 149
FIGURE 4-23 EXPENDABLE ROCKET 1ST STAGE DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 150
FIGURE 4-24 EXPENDABLE ROCKET, 1ST STAGE ENGINES DAMAGE ASSESSMENT – NORMALIZATION, HUMAN HEALTH CONSTITUENTS AT 10% CUTOFF (SIMAPRO SOFTWARE) 151
FIGURE 4-25 EXPENDABLE ROCKET, 1ST STAGE ENGINES DAMAGE ASSESSMENT – NORMALIZATION, CLIMATE CHANGE CONSTITUENTS AT 10% CUTOFF (SIMAPRO SOFTWARE) 152
FIGURE 4-26 EXPENDABLE ROCKET, 2ND STAGE CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 153
FIGURE 4-27 EXPENDABLE ROCKET, 2ND STAGE DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 154
FIGURE 4-28 EXPENDABLE ROCKET, FAIRING CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 155
FIGURE 4-29 EXPENDABLE ROCKET, FAIRING DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 156
FIGURE 4-30 CHEMICALS (GENERIC) CHARACTERIZATION PER LAUNCH 158
FIGURE 4-31 CHEMICALS DAMAGE ASSESSMENT NORMALIZATION PER LAUNCH 159
FIGURE 4-32 CHEMICALS NETWORK DAMAGE ASSESSMENT NORMALIZATION CLIMATE CHANGE AT 10% CUTOFF PER LAUNCH (SIMAPRO SOFTWARE) 160
FIGURE 4-33 WATER CHARACTERIZATION CATEGORIES PER LAUNCH 162
FIGURE 4-34 WATER DAMAGE ASSESSMENT NORMALIZATION PER LAUNCH 163
FIGURE 4-35 ELECTRICITY CHARACTERIZATION CATEGORIES PER LAUNCH 164
FIGURE 4-36 ELECTRICITY DAMAGE ASSESSMENT NORMALIZATION PER LAUNCH (SIMAPRO SOFTWARE) 165
FIGURE 4-37 ELECTRICITY – DIESEL DAMAGE ASSESSMENT NORMALIZATION - CLIMATE CHANGE PER LAUNCH (SIMAPRO SOFTWARE) 166
FIGURE 4-38 PROPELLANT LOX/LH_2 CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 170
FIGURE 4-39 PROPELLANT LOX/LH_2 DAMAGE ASSESSMENT (SIMAPRO SOFTWARE) 171
FIGURE 4-40 PROPELLANT (LOX/LH_2) NETWORK DAMAGE ASSESSMENT NORMALIZATION - HUMAN HEALTH AT 10% CUTOFF PER LAUNCH (SIMAPRO SOFTWARE) 172
FIGURE 4-41 PROPELLANT (LOX/LH_2) DAMAGE ASSESSMENT SINGLE SCORE (SIMAPRO SOFTWARE) 173
FIGURE 4-42 PROPELLANT LOX/LNG CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 174
FIGURE 4-43 PROPELLANT LOX/LNG DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 175
FIGURE 4-44 PROPELLANT LOX/RP-1 CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 176
FIGURE 4-45 PROPELLANT LOX/RP-1 DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 177
FIGURE 4-46 TRANSPORTATION CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 178
FIGURE 4-47 TRANSPORTATION DAMAGE ASSESSMENT NORMALIZATION (SIMAPRO SOFTWARE) 179
FIGURE 4-48 TRANSPORTATION DAMAGE ASSESSMENT SINGLE SCORE PER LAUNCH 180
FIGURE 4-49 REUSABLE ROCKET BOOSTER WITH LIQUID PROPELLANTS COMPARISON CHARACTERIZATION CATEGORIES 182
FIGURE 4-50 REUSABLE ROCKET BOOSTER WITH LIQUID PROPELLANTS COMPARISON DAMAGE ASSESSMENT, NORMALIZATION 183
FIGURE 4-51 EXPENDABLE ROCKET BOOSTER WITH PROPELLANTS COMPARISON, CHARACTERIZATION CATEGORIES 184
FIGURE 4-52 EXPENDABLE ROCKET BOOSTER WITH PROPELLANT COMPARISON DAMAGE ASSESSMENT NORMALIZATION 185

FIGURE 4-53 COMPARISON OF REUSABLE VERSUS EXPENDABLE ROCKET BOOSTER IN CHARACTERIZATION IMPACTS 189
FIGURE 4-54 COMPARISON OF REUSABLE AND EXPENDABLE ROCKET BOOSTERS DAMAGE ASSESSMENT NORMALIZATION....190
FIGURE 4-55 COMPARISON OF LIQUID PROPELLANTS CHARACTERIZATION IMPACT CATEGORIES 191
FIGURE 4-56 COMPARISON OF LIQUID PROPELLANTS DAMAGE ASSESSMENT NORMALIZATION....192
FIGURE 4-57 DELPHI METHOD PARTICIPANT RESULTS 194
FIGURE 4-58 SIMAPRO RESULTS FOR FIVE CONSUMABLES....195
FIGURE 4-59 STEP- L FOR REUSABLE ROCKET BOOSTER WITH LOX/LH_2 CHARACTERIZATION CATEGORIES 198
FIGURE 4-60 STEP- L FOR REUSABLE ROCKET BOOSTER WITH PROPELLANT LOX/LH_2 DAMAGE ASSESSMENT NORMALIZATION....199
FIGURE 4-61 STEP- L FOR REUSABLE ROCKET BOOSTER WITH PROPELLANT LOX/LNG CHARACTERIZATION CATEGORIES....200
FIGURE 4-62 STEP- L FOR REUSABLE ROCKET BOOSTER WITH PROPELLANT LOX/LNG DAMAGE ASSESSMENT NORMALIZATION....201
FIGURE 4-63 STEP- L FOR REUSABLE ROCKET WITH PROPELLANT LOX/RP-1 CHARACTERIZATION CATEGORIES..202
FIGURE 4-64 STEP- L FOR REUSABLE ROCKET WITH PROPELLANT LOX/RP-1 DAMAGE ASSESSMENT NORMALIZATION....203
FIGURE 4-65 STEP- L FOR EXPENDABLE ROCKET BOOSTER WITH PROPELLANT LOX/LH_2 CHARACTERIZATION CATEGORIES....204
FIGURE 4-66 STEP- L FOR EXPENDABLE ROCKET BOOSTER WITH PROPELLANT LOX/LH_2 DAMAGE ASSESSMENT NORMALIZATION....205
FIGURE 4-67 STEP- L FOR EXPENDABLE ROCKET BOOSTER WITH PROPELLANT LOX/LNG CHARACTERIZATION CATEGORIES....206
FIGURE 4-68 STEP- L FOR EXPENDABLE ROCKET BOOSTER WITH PROPELLANT LOX/LNG DAMAGE ASSESSMENT NORMALIZATION....207
FIGURE 4-69 STEP- L FOR EXPENDABLE ROCKET BOOSTER WITH PROPELLANT LOX/RP-1 CHARACTERIZATION CATEGORIES....208
FIGURE 4-70 STEP - L FOR EXPENDABLE ROCKET BOOSTER WITH PROPELLANT LOX/RP-1 DAMAGE ASSESSMENT NORMALIZATION....209
FIGURE 4-71 ALL CONSUMABLES PER LAUNCH CHARACTERIZATION RESULTS 212
FIGURE 4–72 ALL CONSUMABLES PER LAUNCH DAMAGE ASSESSMENT NORMALIZATION 213
FIGURE 4-73 ALL CONSUMABLES PER LAUNCH DAMAGE ASSESSMENT SINGLE SCORE 214
FIGURE 4-74 REUSABLE ROCKET BOOSTER USE LIFE COMPARISON CHARACTERIZATION RESULTS....216
FIGURE 4-75 REUSABLE ROCKET BOOSTER USE LIFE COMPARISON DAMAGE ASSESSMENT RESULTS....217
FIGURE 4-76 SENSITIVITY – MATERIAL COMPOSITION OF ENGINE COMPONENTS....218
FIGURE 4-77 ELECTRICITY DIESEL HOURS SENSITIVITY COMPARISON CHARACTERIZATION RESULTS....219
FIGURE 4-78 ELECTRICITY DIESEL HOURS SENSITIVITY COMPARISON DAMAGE ASSESSMENT NORMALIZATION RESULTS 220
FIGURE 4-79 TEST FIRINGS QUANTITY SENSITIVITY COMPARISON CHARACTERIZATION RESULTS 221
FIGURE 4-80 TEST FIRINGS QUANTITY CHANGE SENSITIVITY COMPARISON DAMAGE ASSESSMENT NORMALIZATION RESULTS....222
FIGURE 4-81 CHEMICAL QUANTITIES CHANGE SENSITIVITY COMPARISON CHARACTERIZATION RESULTS....223
FIGURE 4-82 CHEMICAL QUANTITIES CHANGE SENSITIVITY COMPARISON DAMAGE ASSESSMENT NORMALIZATION RESULTS....224
FIGURE 4-83 SCENARIO ANALYSIS OF REUSABLE AND EXPENDABLE ROCKET BOOSTERS COMPARISON CHARACTERIZATION 227

FIGURE 4-84 SCENARIO ANALYSIS OF REUSABLE AND EXPENDABLE ROCKET BOOSTER COMPARISON DAMAGE ASSESSMENT NORMALIZATION 228
FIGURE 4- 85 MONTE CARLO ANALYSIS ON ALL CONSUMABLES PER LAUNCH CHARACTERIZATION CATEGORIES (SIMAPRO SOFTWARE) 230
FIGURE 4-86 MONTE CARLO ANALYSIS ON ALL CONSUMABLES PER LAUNCH DAMAGE ASSESSMENT WEIGHTING (SIMAPRO SOFTWARE) 231
FIGURE 4-87 TRACI IMPACT METHOD CHARACTERIZATION RESULTS FOR BASE-CASE ALL CONSUMABLES 232
FIGURE 4-88 TRACI IMPACT METHOD DAMAGE ASSESSMENT RESULTS FOR BASE-CASE ALL CONSUMABLES 233
FIGURE 4-89 RECIPE WORLD V1.2 CHARACTERIZATION RESULTS FOR BASE-CASE ALL CONSUMABLES 234
FIGURE 4-90 RECIPE WORLD V1.2 IMPACT METHOD DAMAGE ASSESSMENT RESULTS FOR BASE-CASE ALL CONSUMABLES 235
FIGURE 4-91 RECIPE WORLD V1.2 IMPACT METHOD SINGLE SCORE RESULTS FOR BASE-CASE ALL CONSUMABLES 236
FIGURE 4-92 GREEN TECHNOLOGY CHANGE WITH DIESEL COMPARISON DAMAGE ASSESSMENT NORMALIZATION 237
FIGURE 4-93 GREEN TECHNOLOGY ARMSTRONG PROCESS TITANIUM SUBSTITUTION DAMAGE ASSESSMENT NORMALIZATION 239
FIGURE 4-94 GREEN TECHNOLOGY FUEL CHANGE TO METHANE FROM RP-1 ALTERNATIVE DAMAGE ASSESSMENT NORMALIZATION 241
FIGURE 4-95 NOTIONAL LAUNCH CAMPAIGN WITH GREEN TECHNOLOGIES 242
FIGURE 4-96 SPACE TRANSPORTATION ENVIRONMENTAL PROFILE FOR LAUNCH (STEP-L) 244

List of Tables

TABLE 2-1 JOURNAL ARTICLES ON ENVIRONMENTAL IMPACTS FROM ROCKET PROPULSION EMISSIONS 14
TABLE 2-2 NATIONAL LEGISLATION AND POLICY FOR COMMERCIAL SPACE TRANSPORTATION 16
TABLE 3-1 CONSUMABLES' CONSTITUENTS PER LAUNCH 48
TABLE 3-2 TRANSPORTATION FOR CONSUMABLES TO LAUNCH FACILITY 50
TABLE 3-3 ENGINES 1ST AND 2 STAGE MATERIAL COMPOSITION – REUSABLE/EXPENDABLE ROCKETS SIMAPRO DATA 55
TABLE 3-4 1ST STAGE EXTERNAL CASING, PROPELLANT/OTHER GAS TANKS – REUSABLE/EXPENDABLE ROCKETS SIMAPRO DATA 56
TABLE 3-5 1ST STAGE REUSABLE – GRID FINS, LANDING LEGS AND LANDING PROPELLANT SIMAPRO DATA 56
TABLE 3-6 2ND STAGE REUSABLE/EXPENDABLE ROCKET SIMAPRO DATA 57
TABLE 3-7 FAIRING REUSABLE/EXPENDABLE ROCKET SIMAPRO DATA 57
TABLE 3-8 ELECTRICITY, WATER AND CHEMICALS AT USE PHASE SIMAPRO DATA 58
TABLE 3-9 LIQUID HYDROGEN AND LIQUID OXYGEN PROPELLANT SIMAPRO DATA 64
TABLE 3-10 RP-1 AND LIQUID OXYGEN PROPELLANT SIMAPRO DATA 64
TABLE 3-11 LNG AND LOX PROPELLANT SIMAPRO DATA 64
TABLE 3-12 END-OF-LIFE PROCESSES FOR CONSUMABLES 66
TABLE 3-13 IMPACT2002+MID-POINTS AND END-POINTS (JOLIET ET.AL, 2003) 72
TABLE 3-14 FORUM FOR DELPHI METHOD AUTHORITATIVE EXPERTS 77
TABLE 3-15 INCREASE LAUNCH FREQUENCY ESTIMATES FROM 2017-2026 82
TABLE 4-1 REUSABLE ROCKET BOOSTER AIR POLLUTANTS 90
TABLE 4-2 REUSABLE ROCKET BOOSTER SOIL POLLUTANTS 90
TABLE 4-3 REUSABLE ROCKET BOOSTER WATER POLLUTANTS 91
TABLE 4-4 EXPENDABLE ROCKET BOOSTER AIR EMISSION RESULTS 95
TABLE 4-5 EXPENDABLE ROCKET BOOSTER SOIL EMISSION RESULTS 96
TABLE 4-6 EXPENDABLE ROCKET BOOSTER WATER EMISSION RESULTS 96
TABLE 4-7 CHEMICALS (GENERIC) AIR EMISSION RESULTS PER LAUNCH 99
TABLE 4-8 CHEMICALS (GENERIC) SOIL EMISSION RESULTS PER LAUNCH 100
TABLE 4-9 CHEMICALS (GENERIC) WATER EMISSION PER LAUNCH 101
TABLE 4-10 ELECTRICITY AIR EMISSIONS PER LAUNCH 104
TABLE 4-11 ELECTRICITY SOIL EMISSIONS PER LAUNCH 105
TABLE 4-12 ELECTRICITY WATER EMISSIONS PER LAUNCH 105
TABLE 4-13 WATER AIR EMISSIONS PER LAUNCH 109
TABLE 4-14 WATER SOIL EMISSIONS PER LAUNCH 110
TABLE 4-15 WATER WATER EMISSIONS PER LAUNCH 110
TABLE 4-16 PROPELLANT – LOX/LH_2 AIR EMISSIONS PER LAUNCH 114
TABLE 4-17 PROPELLANT – LOX/LH_2 SOIL EMISSIONS PER LAUNCH 115
TABLE 4-18 PROPELLANT - LOX/LH_2 WATER EMISSIONS PER LAUNCH 116
TABLE 4-19 PROPELLANT – LOX/RP-1 AIR EMISSIONS PER LAUNCH 117
TABLE 4-20 PROPELLANT – LOX/RP-1 SOIL EMISSIONS PER LAUNCH 118
TABLE 4-21 PROPELLANT – LOX/RP-1 WATER EMISSIONS PER LAUNCH 118
TABLE 4-22 PROPELLANT – LOX/LNG AIR EMISSIONS PER LAUNCH 119
TABLE 4-23 PROPELLANT – LOX/LNG SOIL EMISSIONS PER LAUNCH 120
TABLE 4-24 PROPELLANT – LOX/LNG WATER EMISSIONS PER LAUNCH 121
TABLE 4-25 NOISE LEVELS FOR PER LAUNCH 125
TABLE 4-26 ALL CONSUMABLES WITHOUT EXPENDABLE ROCKET BOOSTER AIR EMISSIONS RESULTS PER LAUNCH 126
TABLE 4-27 ALL CONSUMABLES WITHOUT EXPENDABLE ROCKET BOOSTER SOIL EMISSIONS 126

TABLE 4-28 ALL CONSUMABLES WITHOUT EXPENDABLE ROCKET BOOSTER WATER EMISSIONS 127
TABLE 4-29 COMPARISON OF DELPHI RESULTS AND SIMAPRO RESULTS.. 194
TABLE 4-30 SENSITIVITY PARAMETER RANKING.. 224

List of Abbreviations

AFB Air Force Base

AFCEC Air Force Civil Engineering Center

CCAFS Cape Canaveral Air Force Station

CFC Chlorofluorohydrocarbons

CST Commercial Space Transportation

DALY Disability Adjusted Life Years

DoD Department of Defense

DoT Department of Transportation

EA Environmental Assessment

ELCA Environmental Life Cycle Assessment

ESA European Space Agency

EIS Environmental Impact Assessment

ESOH Environmental Safety and Occupational Health

FAA Federal Aviation Administration

FAA AST Federal Aviation Administration Office of Commercial Space

FOIA Freedom of Information Act

GAO Government Accountability Office

GHG Greenhouse Gases

GIS Geospatial Information Systems

GLO Global

GTO Geostationary Transfer Orbit

GWP Global Warming Potential

H2 Liquid Hydrogen

HFC Hydrofluorocarbon

HMMP Hazardous Material Management Plan

IMPACT2002+ IMPact Assessment of Chemical Toxics 2002+

IRP Installation Restoration Program

ISO International Organization for Standardization

ITAR International Traffic and Arms Regulations

KSC Kennedy Space Center

LCA Life Cycle Assessment

LCIA Life Cycle Impact Assessment

LEO Low Earth Orbit

LNG Liquefied Natural Gas

LOx Liquid Oxygen

MAPTIS Materials and Processes Technology Information System

NASA National Aeronautics and Space Administration

NEPA National Environmental Policy Act

NPDES National Pollutant Discharge Elimination System

NTRS Nasa Technical Reports Server

O_3 Ozone

ROW Rest of the World

SE Systems Engineering

STEP-L Space Transportation Environmental Profile for Launch

SysML Systems Modeling Language

TRACI Tool for the Reduction and Assessment of Chemical and other environmental Impacts

USAF United States Air Force

USEPA United States Environmental Protection Agency

VAFB Vandenberg Air Force Base

WTP Water Treatment Plant

WWTP Wastewater Treatment Plant

Chapter 1

INTRODUCTION

“Where there is no vision, the people perish.” Proverbs 29:18

1.1 Recent Growth in Commercial Space Transportation Activities

The United States’ and international commercial space transportation (CST) activities will become more routine and accessible to the general public over the next 10-20 years. The resurgence of space entrepreneurialism built on the nation’s vision for space exploration established in January 2004 is also reigniting and inspiring other space-related industries (NASA, 2004). Currently, both the United States and other countries conduct CST activities with success, using approved launch sites and spaceports primarily for communications commerce.

The Federal Aviation Administration (FAA) Office of Commercial Space Transportation (AST) 2016 and 2018 Annual Compendium of Commercial Space Transportation describes the number of space launches in the United States as remaining fairly constant since 2004 but anticipates increased commercial cargo and crew launches in the next two years (FAA, 2016 and 2018). The Government Accountability Office (GAO) report of testimony to the House of Representatives in June 2016 (GAO, 2016) stated that the commercial space launches increased from zero launches in 2011 to eight launches in 2015. The report also stated, “In January 2016, NASA announced its selections for companies to conduct Commercial Resupply Services (CRS2) to the ISS. SpaceX and Orbital ATK were selected again, and Sierra Nevada Corporation was added as a new participant. According to NASA, these awards require a minimum of six missions to the ISS from each participant between 2019 and 2024. In addition to fulfilling government contracts, these companies also conduct launches for other customers, including international customers.” These CST activities will help advance the United States both technically and economically over the next decade.

Multiple organizations within the United States are part of CST activities. NASA collaborates with United Launch Alliance (ULA), ATK Space Systems, SPACEX, and Final Frontier Design to increase capabilities in orbital and suborbital environments (NASA, 2014). Other private sector industries such as Blue Origin are also launching and landing rocket propulsion systems to support sub-orbital spaceflight and rocket engine manufacturing (Blue Origin, 2016; Aviation Week, 2016). For space tourism, Virgin Galactic with The Spaceship Company seeks to be the space line for the Earth using WhiteKnightTwo and SpaceShipTwo (AOPA, 2016; Virgin Galactic, 2015). The US Air Force (USAF) is bolstering its capabilities through partnerships with commercial industry for launch vehicles and other related products (Executive Biz Daily, 2016).

All CST launches and reentries must occur on preapproved launch facilities or locations such as Spaceports or military facilities at Cape Canaveral Air Force Station in Florida. The FAA AST administers and grants these approvals. One key action that FAA AST uses to make licensing determinations for CST activities is the National Environmental Policy Act (NEPA) process for activities such as launch, reentry, and experimental flights; it will be discussed in a later section. The AST also issues licenses for the operations of non-federal launch sites, or "commercial spaceports," as shown in Figure 1-1 (FAA, 2014). Also, NASA generates NEPA documents in support of CST activities using its launch facilities. When the U.S. Air Force lease launch facilities to CST activities, a NEPA document is generated in collaboration with the CST industry using the leased facility.

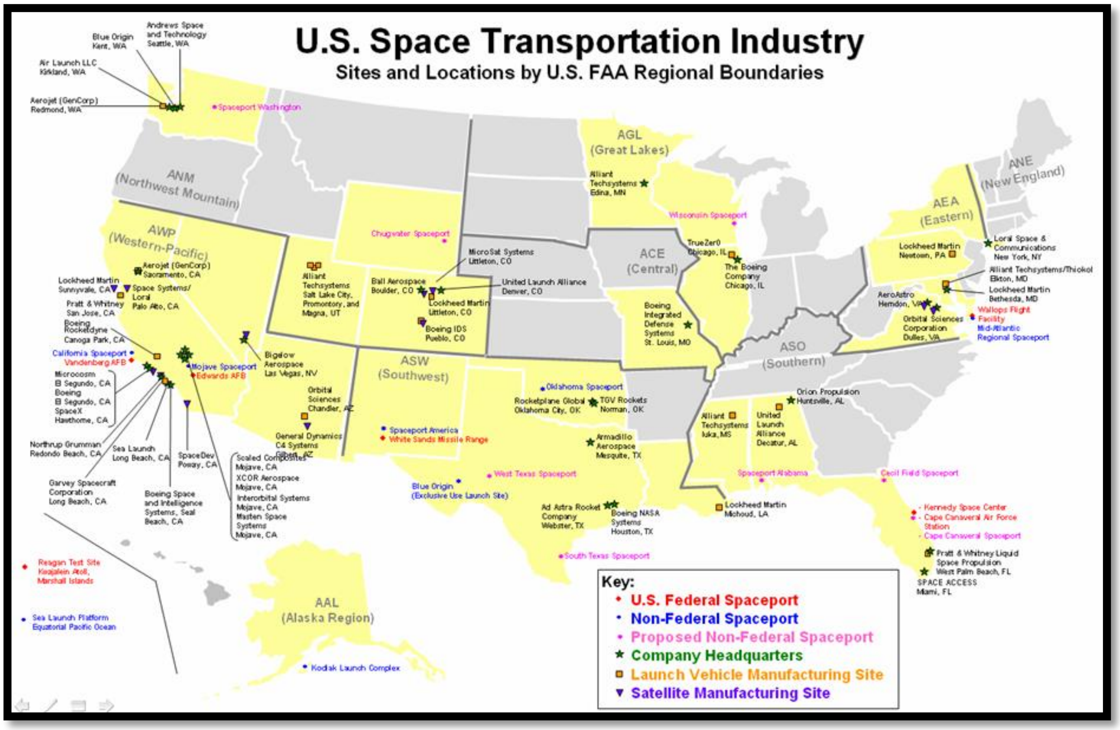


Figure 1-1 U.S. Space Transportation Industry Sites and Locations (FAA, 2014)

1.2 Environmental Impacts of Commercial Space Activities

Evaluating resulting environmental impacts or risks from this nascent industry — and if necessary, mitigating the impacts — will be essential for long-term sustainable operation (White House, 2013; 51 US Code 509, 2015; Darrieu and Nelson, 2013). One study (Murray, Bekki, et.al., 2013) states that the conventional wisdom within the rocket and atmospheric communities is that due to the low frequency of launches worldwide, rocket emissions do not have a significant impact on the global environment. However, this study also indicates that quantifying the actual emission impact per launch is still needed. Potential environmental impacts of increased CST are unknown currently because no comprehensive study has been conducted.

NASA is considering green technologies in some aspects of CST activities. For example, NASA developed and is using tools such as Materials and Processes Technology Information System (MAPTIS) and expanding partnerships with industry to integrate green technologies (NASA MAPTIS, 2016; NASA

HQ discussions). One example of eco-design, “designing with the end in mind,” is seen at NASA through its Green Propellant Infusion Mission project, with a goal to reduce costs and toxic handling concerns with hydrazine (Leonard, 2013; NASA, 2013).

MAPTIS and the Green Propellant Infusion project are making certain aspects of CST more environmentally friendly; however, they do not fully address environmental impacts of CST. Evaluating and mitigating environmental impacts of CST activities throughout their life cycle — from raw material acquisition and processing to production to operation to final disposition (end of life) — will require comprehensive models and frameworks for decision-making. The most commonly used tool to identify and quantify environmental impacts is the Life Cycle Assessment (LCA). The European Space Agency (ESA) has been using the LCA methodology as shown in Figure 1-2 over the past several years for their Clean Space initiative. NASA discussed in a conference paper that the LCA was a means to inform decision makers about inputs into the broader strategic planning process for better risk-informed decisions and mission success (Chytka, Brown, et al., 2006). However, no LCA has been conducted for CST activities in the United States.

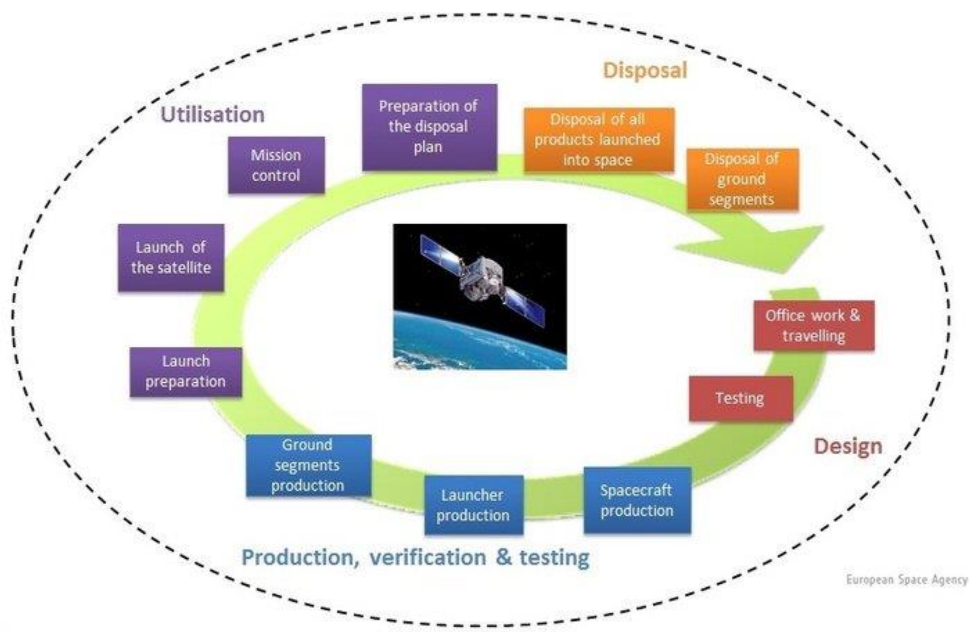


Figure 1-2 European Space Agency Life Cycle Assessment (ESA, 2012)

1.3 Research Objectives

Motivations for this study: The environmental burdens and life cycle implications for launch activities in the United States have not been assessed to date. Therefore, this study will provide a baseline for these activities focused on launch activities. The contribution of this dissertation research is to lay a foundation of knowledge through application of the LCA methodology to CST activities in the United States. This study will be the first LCA focused on U.S. CST activities in an effort to identify those potential environmental consequences, burdens or opportunities for reducing environmental impacts. This study will also provide an operational tool, space transportation environmental profiles for launch (STEP-L) framework, for space mission activities at the launch site and can be transferred to non-commercial or governmental launch activities.

As mentioned, potential environmental impacts of increased CST are unknown currently because no comprehensive study has been conducted. The research will seek to fill this knowledge void by applying an **environmental LCA framework for generic launchers in the CST activities in the United States** (ISO 14040, 2006). This environmental LCA focused on launch operations and the launch campaign to identify and evaluate environmental impacts on the earth and its atmosphere from current level of launches and increased launches expected today and within the next five to ten years.

Specific objectives are:

1) to conduct a base-case LCA environmental inventory and impact assessment of U.S. CST activities based on ISO 14040 and 14044;
2) to identify a range of impacts due to sensitivity in model inputs;
3) to conduct additional screening LCAs incorporating “green technologies” to identify strategies for reducing environmental impacts; and
4) to operationalize the base-case LCA for environmental professionals and other decision makers, by developing a tool to predict Space Transportation Environmental Profiles for Launch (STEP-L).

1.4 Dissertation Organization

The rest of the dissertation is organized as follows: Chapter 2 discusses LCA and CST related literature searches, both peer-reviewed and other relevant literature on space transportation; Chapter 3 discusses the methodology applied and framework used in this environmental LCA; Chapter 4 presents the results of the LCA; and Chapter 5 summarizes conclusions and recommendations for future studies.

Chapter 2

LITERATURE REVIEW

> "Mankind is drawn to the heavens for the same reason we were once drawn into unknown lands and across the open sea. We choose to explore space because doing so improves our lives, and lifts our national spirit. So let us continue the journey." George W. Bush, 2004

2.1 Overview of Life Cycle Assessment Framework

The LCA framework and methodology based on ISO 14040 is recognized and applied in the United States and internationally. LCA is built upon principles of systems thinking, sustainability and life cycle thinking (Rose, 2009). The ISO Standard 14040 has outlined the four LCA framework phases, as shown in Figure 2-1. The general purpose of the LCA (ISO 14040, 2006) is to assist in:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle,
- **informing decision-makers in industry, government or non-government organizations (e.g. for the purpose of strategic planning, priority setting, product or process design or redesign),**
- the selection of relevant indicators of environmental performance, including measurement techniques, and
- marketing (e.g. implementing an eco-labelling scheme, making an environmental claim, or producing an environmental product declaration).

Overall, the LCA framework is a practical approach to determine the environmental impacts of a product or to aid in better informed decision making for future designs. LCA is one of several environmental management techniques (e.g. risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment) and might not be the most appropriate technique to use in all situations (ISO14040, 2006; ISO 14044, 2006). However for this study, the LCA can be applied effectively.

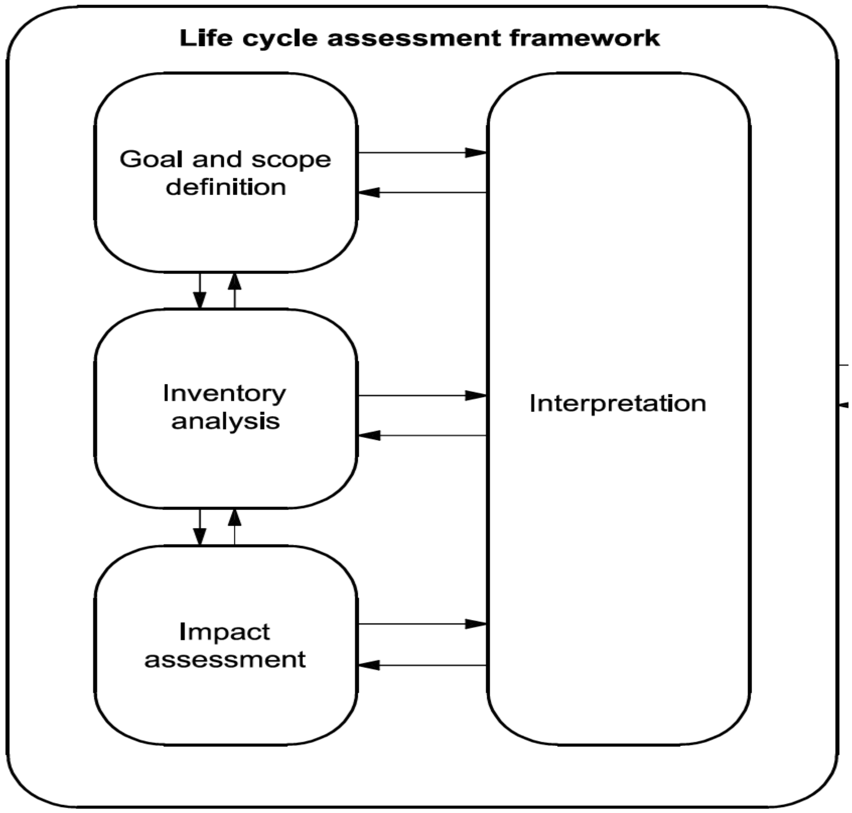


Figure 2-1 LCA Framework (ISO 14040, 2006)

LCA life cycle phases include Raw Materials Acquisition, Material Processing, Production, Use and Maintenance, and End of Life (Curran, 2011). However, another common breakdown of the LCA life cycle phases with inputs and outputs is shown in Figure 2-2 (EPA, 1993).

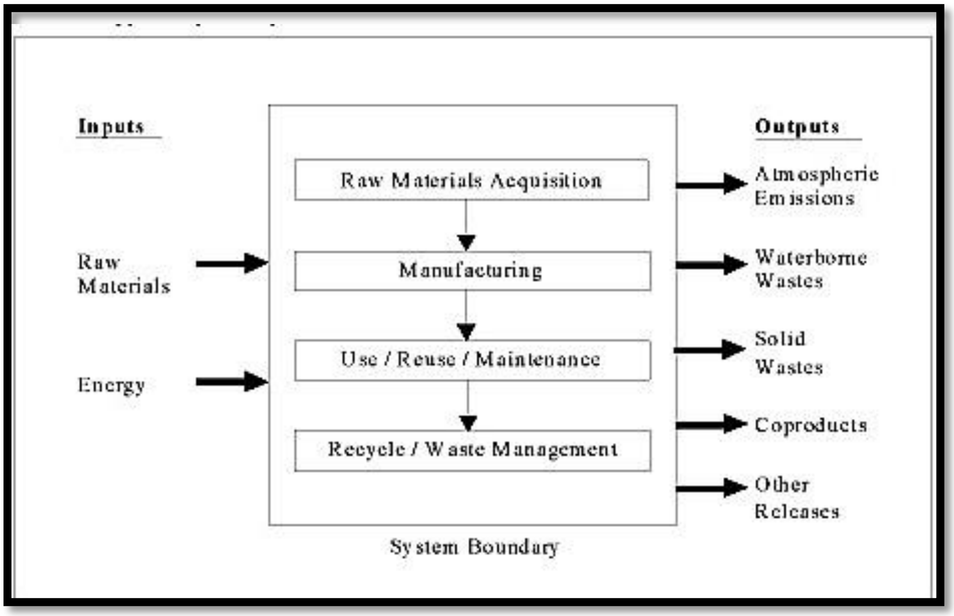


Figure 2-2 Life Cycle Phases (EPA, 1993)

Figure 2-3 shows the sub-phases and those sub-phases that are mandatory for an impact assessment. The mandatory categories are defined as the following (ISO 14040, 2006):

- Impact category definition: Identification and selection of impact categories, models of cause-effect chains and their end-points
- Classification: Assignment of Life Cycle Impact (LCI) result parameters to their respective impact category (ies)
- Characterization: Calculation of the extent of the environmental impact per category

The optional elements are defined as the following:

- Normalization: Relating the characterization results to a reference value such as a regional value versus a local value of pollutants emitted
- Grouping: Sorting and possibly ranking the indicators
- Weighting: Aggregation of characterization results across impact categories
- Data quality analysis: Includes sensitivity analysis among other things to obtain a better understanding of the reliability of the LCIA results.

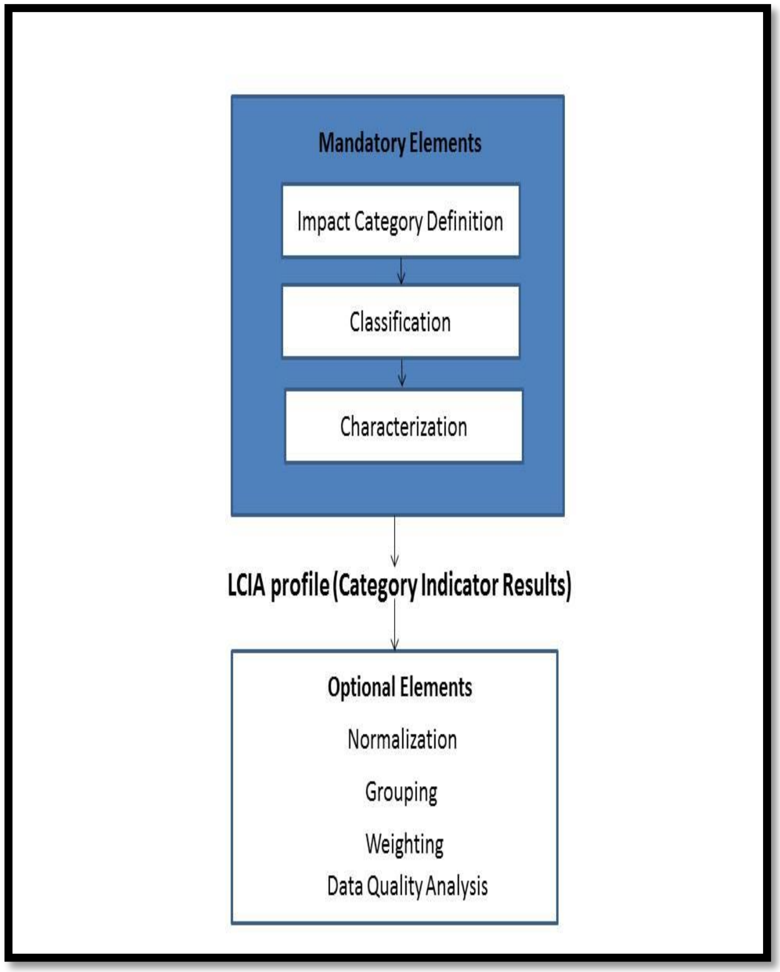


Figure 2-3 Life cycle impact assessment (LCIA) sub-phases (ISO 14040, 2006)

All of the sub-phases shown in Figure 2-3 will be conducted for the ELCA of CST activities.

Figure 2-4 was developed to compare the environmental LCA life cycle phases (Curran, 2011), the generic life cycle phases in systems engineering (INCOSE, 2011), and the NASA systems engineering life cycle phases (NASA, 2007) with this LCA study's CST life cycle phases[1]. These life cycle phases are similar in their view of how development of a product or service, CST activities, are managed and resourced throughout its life cycle. All of these life cycle phases are similar in their elements where specific tasks and actions occur. Therefore, similar terminology can be applied when discussing life cycle

[1] The arrows flowing from one life cycle to another only represent similar phases in each of the life cycles. These life cycle phases are not connected.

phases. This LCA study's CST life cycle phases lexicon also aided in identifying key words used as search terms for the UTA on-line library and other databases.

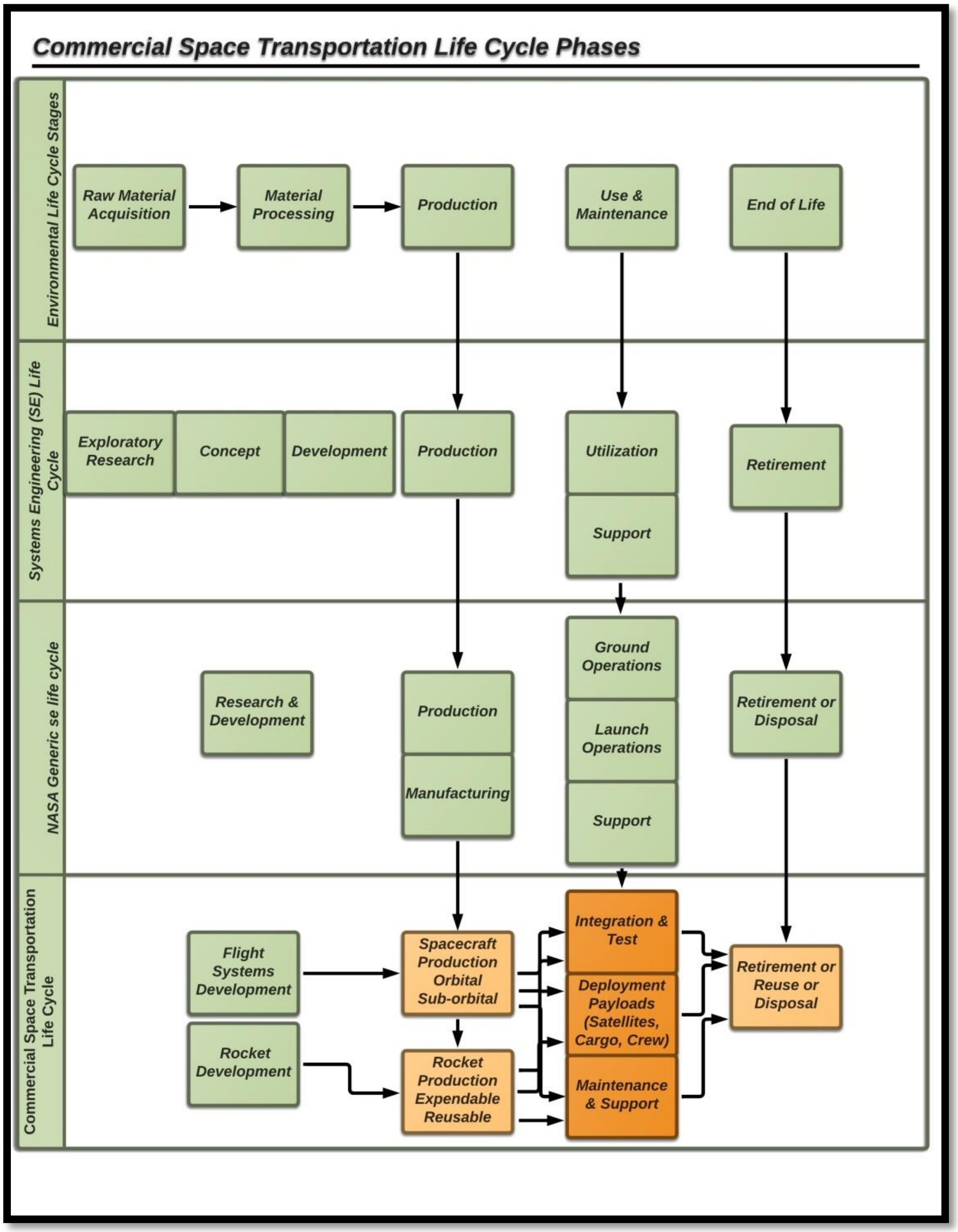


Figure 2-4 Life Cycle Phases (ISO 14040, 2006; NASA, 2011; COSE, 2016, created by Neumann using Lucidchart)

The UTA library on-line search engine was used to identify LCA textbooks, guidance, and datasets. Textbooks on applying the LCA methodology such as *LCA: guide to best practice* (Klopffer, 2015), *LCA Handbook: A Guide for Environmentally Sustainable Products* (Curran, 2012), and *The Hitch Hiker's Guide to LCA* (Baumann and Tillman, 2004) contain useful insight into how to proceed effectively on the LCA. Other textbooks such as *Energy analysis of 108 industrial processes* (Brown, 2008) contained relevant data for process information on CST activities. Relevant LCA data and information was identified through new outreach to professional contacts, academic presentations and government websites (Sattler, 2015). Some of these data and information were located at National Renewable Energy Laboratory (NREL) and National Institute of Standards and Technology (NIST) websites. Other information was found through discussions with LCA practitioners who perform LCAs with industry (Cirucci, 2016) and Department of Defense (Lloyd, 2016). They also provided lessons learned about the use of the LCA methodology.

2.2 Overview of Commercial Space Transportation Relevant Literature

The literature research for the environmental LCA of commercial space transportation (CST) activities in the United States required gathering and reviewing peer-reviewed articles and textbooks, national, state, and organizational standards, policies and regulations, other related technical reports, NEPA documents, state environmental permits, technical publications, news articles and related websites, private industry and government literature, and presentations.

These secondary data sources[2] are typically paper-based or electronic sources. The paper-based sources include: books, journals, periodicals, abstracts, research reports, conference papers, market reports, annual reports, internal records of organizations, newspapers and magazines. The electronic sources include: on-line databases, Internet, videos and broadcasts. These secondary sources were evaluated based on the source of the document, relevant timeframe and context for the dissertation topic, and the credibility of the information in context of other sources.

[2] (https://www.bcps.org/offices/lis/researchcourse/develop_writing_data_secondary.html;accessed 8 Nov 17).

2.2.1 University of Texas at Arlington (UTA) Electronic Search for Peer-Reviewed Material:

Research into the topic of CST activities initially began using the UTA library electronic search engine for peer-reviewed materials in UTA specifically LCAs focused on CST activities. Some of the databases searched included:

- Science Direct
- Geophysical Research Letters
- Journal of Spacecraft and Rockets
- International Journal of Life Cycle Assessment
- EDP Sciences
- Journal of Geophysical Research
- ProQuest
- American Institute of Aeronautics and Astronautics
- American Chemical Society
- International Journal of Life Cycle Assessment
- Journal of Total Environment
- National Academies Press

Searches with the UTA on-line library included added results beyond UTA's holdings, but still no LCA studies were found that had been conducted on CST activities in the United States.

2.2.1.1 Peer-reviewed Journals Articles and Ph.D. Dissertations:

Table 2-1 lists a few of the peer-reviewed journal article that are relevant; however, over 100 journal articles and other peer-reviewed materials were reviewed for content and context on CST activities. Dispersion effects and environmental impacts was one area that provided several articles relevant to this research. These articles listed in the table are focused on the dispersion effects from the propellant used during the launch. Other relevant articles include: solid and liquid propellant environmental issues; launch vehicles and impacts to stratosphere; and space manufacturing. Several of the papers reviewed discussed various modeling techniques and recommended actual data collection to validate models. These papers will be used to estimate values where information is deficient to characterize the system boundary outputs.

Table 2-1 Journal Articles on Environmental impacts from Rocket Propulsion Emissions

Title	Author(s), Year	Relevant Context
"The Effects of Chemical Propulsion on the Environment"	Bennett, Henshaw, and Barnes, 1995	Paper discussed environmental impacts from solid and liquid propellants
"On the Uncertainties in Assessing the Atmospheric Effects of Launchers"	Murray, Bekki, Toumi, and Soares, 2013	Paper discussed areas contributing to uncertainties in modeling effects of launchers on the atmosphere
"Recent Activities and Studies on the Environmental Impacts of Rocket Effluents"	Bennett, McDonald, 1998	Paper provided overview of numerous investigation of environmental impacts of rocket motors effluents over three decades
"Effects of Launch Vehicle Emissions in the Stratosphere"	Brady, Martin, Lang, 1997	Paper discussed dispersion rates for modeled motors resembling a kerosene (RP-1)/liquid oxygen (LOX) propellant and liquid hydrogen/LOX propellant showing that depletion rates using LOX was minimal within 5 minutes of launch

2.2.1.2 Other Related CST Papers:

Other papers discussed the greening of propulsion (Sackheim, Masse, 2014) and limits on space launch activities because of ozone depletion (Ross, M.; Toohey; Peinemann; and Ross, P.; 2009). The papers focused on green technology emphasize propellant alternatives, since this is most likely the biggest cost savings throughout the life cycle. However, the launch operation itself might also be a place to make significant impact in costs and other resources savings. A future scenario might be found where the volume of launches or even the type of propellant used for launches may need to be regulated or controlled due to potential for ozone depletion (Ross, M.; Toohey; Peinemann; and Ross, P.; 2009). If this scenario is reality, then the need for quantifying exactly how many launches, and the contribution of launches to ozone depletion, will possibly become an over-regulation issue and a national security concern. CST activities will not be able to expand and develop if limits are placed on launch payloads or space tourism.

2.2.1.3 Related Ph.D. Dissertations focused on Space Systems**:**

Research into ProQuest dissertation database through the UTA on-line search engine was conducted also to identify other Ph.D. dissertations that may be related to this topic area. Two dissertations were discovered, one on analysis of trade between space launch system operations and acquisition costs (Nix, 2005) and the other on environmental life cycle criteria for decision-making on green and toxic propellants (Johnson, 2012). These dissertations examined space systems using systems engineering, LCA methodology for environmental factors associated with space systems, and environmental cost models. However, since the first focused on costs and the second on environmental impacts of propellants, neither provides a complete ELCA for CST activities.

2.2.2 All-Inclusive Literature On-Line Searches:

The UTA on-line library search engine was then used to include any articles and other information that might be relevant to environmental impacts for rocket systems, and their associated air emissions, environmental contamination, propulsion, environmental assessments, explosions, etc., to discover any relevant studies or information associated with CST activities. This search was not necessarily only labeled as peer-reviewed by the UTA library criteria. These overall search results revealed textbooks, conference papers, international journal articles, technical journal articles, and technical reports. Additionally, open source search using Google scholar and other search engines identified some other information for context. The following types of information found are shown below.

2.2.2.1 United States Legislation and Policies Focused on Space Expansion:

The United States was the first country to land on the moon in 1969, based on a national vision and undivided focus and collaboration by the government agencies and other corporations involved. The resurgence of space exploration in 2004 was reenergized through U.S. Code 509, The Space Act and other governing legislation, Congressional funding, civil and private collaborations, and entrepreneurship of private corporations. The following table identifies these legislation and policies relevant to the space industry in the United States within the last 15 years but is not all inclusive. The FAA AST website has a more comprehensive list of these legislation and policies.

Table 2-2 National Legislation and Policy for Commercial Space Transportation

National Legislation/Policy	Date	Relevance
Commercial Space Launch Act, 51 U.S.C., Ch. 509, Sec.50901-23	2011	(1) to promote economic growth and entrepreneurial activity through use of the space environment for peaceful purposes; (2) to encourage the United States private sector to provide launch vehicles, reentry vehicles, and associated services by— (A) simplifying and expediting the issuance and transfer of commercial licenses; (B) facilitating and encouraging the use of Government-developed space technology; and (C) promoting the continuous improvement of the safety of launch vehicles designed to carry humans, including through the issuance of regulations, to the extent permitted by this chapter; (3) to provide that the Secretary of Transportation is to oversee and coordinate the conduct of commercial launch and reentry operations, issue permits and commercial licenses and transfer commercial licenses authorizing those operations, and protect the public health and safety, safety of property, and national security and foreign policy interests of the United States; and (4) to facilitate the strengthening and expansion of the United States space transportation infrastructure, including the enhancement of United States launch sites and launch-site support facilities, and development of reentry sites, with Government, State, and private sector involvement, to support the full range of United States space-related activities.
U.S. Commercial Space Launch Competitiveness Act	2015	To facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions, and for other purposes.
Commercial Space Launch Amendments Act of 2004	2004	Provides for experimental permits, restrictions on reusable rockets.
National Space Transportation Policy	2013	The overarching goal of this policy is for the United States to have assured access to diverse regions of space, from suborbital to Earth's orbit and deep space, in support of civil and national security missions
U.S. Space Transportation Policy, NSPD 40	2004	This directive establishes national policy, guidelines, and implementation actions for United States space transportation programs and activities to ensure the Nation's ability to maintain access to and use space for U.S. national and homeland security, and civil, scientific, and commercial purposes.
Public Law 108-428	2004	To extend the liability indemnification regime for the commercial space transportation industry

2.2.2.2 Other National and State Regulations Relevant to Space Operations:

U.S. Code of Federal Regulations which include Department of Transportation (DOT) and the U.S. EPA regulations apply to CST activities at the manufacturing phase, transportation to the launch facility, at the launch facility for the use and maintenance phases, and disposal or end-of-life phase. Since the CST companies are operating in different regions, they must comply with state regulatory requirements also. Through conversations with a representative from one of the rocket propulsion systems manufacturing firms, data and information to some extent might be found on state environmental regulatory websites. The information may have limited use in an LCA include the permits for Title V emissions, hazardous waste, solid waste, and National Pollutant Discharge Elimination System (NPDES) for the manufacturing sites. However, some of these manufacturing facilities produce more than one product for multiple customers and allocation of resources is not evident in these permits. So, this information provided limited insight into the specific fabrication and manufacturing of the expendable and reusable rocket propulsion systems.

2.2.2.3 Commercial Rocket Systems Technical Manuals, Space Systems Textbooks, and CST industry websites:

Relevant literature review included the rocket propulsion and its design and operating parameters in textbooks and specific space propulsion systems identifying the type of propellant, typical launch sites and the required environmental compliance for launching rockets at these facilities (ULA, 2016; SpaceX, 2016). Textbooks focused on space systems included: Safety design for space systems (Musgrove, Larsen, Sgobba, 2009), Space Safety Regulations and Standards (Pelton, Jakhu, 2010), Safety Design for Space Operations: Other Launch Safety Hazards (Allahdadi, 2013), Space Vehicle Design (Griffin, French, 2004) and Rocket Propulsion Elements (Sutton, Biblarz, 2010). Company websites such as SPACEX, Blue Origin, Virgin Galactic and other related private corporations provided information about their space-related operations and activities in space tourism or space launch systems. These data and information will aid in estimating operational parameters as needed when data available is insufficient to determine the mass loadings or values for input and output conditions of the system boundary.

2.2.2.4 NASA Studies and Technical Journals:

NASA LCA efforts were uncovered using the NASA Technical Reports Server (NTRS). The NASA NTRS is an open source repository of NASA's technology, science and research. Space systems and other aspects related to these systems were available (NTRS, 2016). The NASA Space Shuttle program is well documented and numerous studies and reports were found discussing environmental impacts and emissions. These reports and studies included monitoring and surveillance of the launch site specifically for environmental factors. As such, NASA's Space Shuttle program had numerous studies conducted and did include environmental consequences in the emission releases (Jackman, Considine, Fleming, 1996; Brady, Martin, Lang, 1997; Smith, Tevepaugh, Penny, 1975). Specific models for rocket emission dispersion were created to map out where the most likely emissions might generate dispersion emission simulations prior to launches (Bowman et al., 1984). These studies identify some potential impacts after numerous launches and landings of the Space Shuttle. One study focused on the Kennedy Space Center (KSC) launch facility found some deposition of hydrochloric acid (HCl) on vegetation and in soils but assimilated due to low launch and loading rates (Hall, Schmaizer, et al., 2014). Other rocket emission studies apply models to determine the pollutant emissions from the launch of the Ariane 5 rocket after 10 launches per year for 20 years (Jones, Bekki, Pyle, 1995). These studies and research will provide insight into the propellant and environmental consequences from launch where insufficient data might exist with current propulsion systems.

NASA discussed in a conference paper that the LCA was a means to inform decision makers about inputs into the broader strategic planning process for better risk-informed decisions and mission success (Chytka, Brown, et al., 2006). Discussions with the author's office at NASA Systems Analysis and Concepts Directorate, Space Mission Analysis Branch at NASA Langley Research Center also identified that no end-to-end LCA had been done to date for CST activities in the United States (NASA, 2016).

2.2.2.5 National Environmental Policy Act (NEPA) Documents:

The Environmental Protection Agency (EPA) requires a NEPA Environmental Impact Statement (EIS) for each launch facility prior to launch activity and an addendum if the conditions of launch change prior to launch activities. The FAA AST generating the NEPA documents for CST activities such as SPACEX launches, Blue Origin, and experimental launches as part of its environmental policy (FAA, 2011). The FAA AST's environmental policy requires FAA AST to protect and enhance these communities and natural environments affected by these launches and reentries while promoting CST (FAA, 2011). Therefore, FAA AST generates CST NEPA documents in collaboration with the CST industry.

As discussed, various organizations are required to complete a NEPA study prior to launch, landing, and reentry to include United States Air Force (USAF), NASA, and commercial corporations. Discussions with NASA Environmental Specialists (Miller, 2015) led to mining the NASA websites for NEPA documents generated for Wallops Island Space Center and KSC launch facilities. These NEPA documents are for NASA related launches located at NASA launch facilities. So for this environmental LCA, these CST activities conducted by private corporations supporting NASA and independently for commercial efforts will be examined. The NEPA documents provide environmental data and information associated with launches and even the anticipated launches to allow decision makers to understand the environmental factors associated with this effort. However, the NEPA process does not readily adapt to identifying possible cumulative environmental impacts or environmental aspects that might yield better eco-design or system changes to improve environmental burden through the products' life cycle. These CST activities in the United States will be the focus of the literature review and the study; military launch operations will not be included. However, where launch complex operations have shifted from USAF to commercial industry, then the NEPA documents will be considered as information on the baseline of the launch complex prior to CST use.

2.2.2.6 US Air Force Civil Engineering Center (AFCEC) Resource and Conservation Recovery Act (RCRA) or Installation Restoration Program (IRP) Reports:

These AFCEC RCRA Long Term Monitoring (LTM) reports at military installations (Cape Canaveral Air Force Station (AFS), FL, Vandenberg Air Force Base (AFB), CA) were considered as part of the literature search since the launch sites for CST activities are now being leased from the US Air Force. A public website, AFCEC Administrative Record, http://afcec.publicadmin-record.us.af.mil/Search.aspx, was also researched. However, this website has data only from 1996-2011 loaded. SpaceX with Falcon Heavy rocket propulsion system will launch from Vandenberg AFB at Space Launch Complex-4 (SLS-4) (Gruss, 2015). SLC-4 was previously used to launch Atlas Agena and Titan rockets and is an IRP 8 cluster (USAF, 2016). These reports will provide some background information when identifying future launches' environmental releases to determine added contamination. According to discussions with the US Air Force, 45th Space Wing, Civil Engineering Squadron, the lease property management for the corporations monitors these sites to ensure no added contamination (USAF, 2016). Failed launches or test firing might provide additional information into the potential environmental contamination. However, public access to these data is not available.

2.2.2.7 Economic life cycle cost information:

The economic factor of life cycle costs for CST was limited as part of the literature review to determine what information may be available.

NASA has been capturing life cycle costs on launch systems and payloads through their Cost Analysis Division (NASA, 2016). An excellent source of life cycle cost information and analysis for space operations exists at a NASA website and is updated frequently (NASA, 2015; Zapata, 2016). Commercial industry are most likely capturing sustainability and operating costs through their internal processes. However, when they partner with NASA or DoD, then the projected sustainability costs, or life cycle costs, for the operations, maintenance to disposal should be available for public since U.S. tax dollars fund these efforts.

The Department of Defense (DoD) has been capturing life cycle costs for weapon systems sustainability and is using LCA as well (DoD ESOH, 2014). As part of the DoD effort to manage costs and consequences to include environmental impacts is the Air Force Life Cycle Management Center (AFLCMC). The AFLCMC enables the U.S. Air Force's (USAF) military objectives and improves sustainability opportunities from acquisition to operations to disposal (USAF, 2015). The USAF is a contributor to the space launches in the United States. They also generate NEPA documents and are now leveraging commercial industry to enhance their space capabilities. However, this environmental LCA will not include these launches with the exception of a scenario to include all rocket launches within a year or projected years. The military launches are typically not considered CST activity unless the launch is provided as a service by a commercial launch provider. For instance, when the military has operational control and conducts the launch unilaterally then this launch activity is not included in this LCA.

Based on FAA's compiled annual information, the CST industry generates 25.7% of U.S. launch service revenues. The FAA CST Compendium (2016) states:

> The U.S. space industry was approximately $125B in 2014. This includes $87B in revenues generated by satellite services, satellite manufacturing, satellite ground equipment, and launch services as well as $38B spent on space programs by the U.S. government. U.S. launch service providers accounted for about $2.4B in total revenues or 41% of global launch services. FAA AST licensed launches accounted for $617M of the $2.4B.

The economic aspect of this environmental LCA will not be considered in detail but cursorily if data is readily available. For example, costs that might be determined are the propellant used and number of launches, electricity or water consumption, or disposal costs at the launch facility. Information about the costs and profits in the CST industry is not readily available but would allow for a more refined and accurate cost per launch. Cost data from NASA and other industries were researched and informed this ELCA where possible to give a better understanding of the costs associated with CST launches. However, the economic aspect is not an outcome from this ELCA.

2.2.2.8 ESA activities and reports:

The Clean Space Branch at the ESA has initiated several studies focused on CST activities primarily on satellites. Discussions with ESA systems engineers revealed their successes and research in several aspects of CST (Huesing, Austin, 2016). The ESA Clean Space Initiative (CSI) Eco-Design Branch held LCA training sessions in 2015 (ESA, 2015) to aid in eco-design aspects. The ESA CSI Eco-Design Branch is developing methodology with weighting factors to provide guidance for material selection for satellite launches and has conducted two pilot LCAs for an environmental impact analysis on two space missions to define a suitable model and hotspots (ESA, 2015). During the 64th International Astronautical Federation Congress, ESA CSI Eco-Design Branch presented their paper (Huesing, 2013) about the LCA efforts with space systems to identify environmental impacts. In June 2015, an interim environmental impact analysis note discussed a key finding where the launch-related activities were the main contributor to the environmental impacts (ESA, 2015).

The ESA has made impressive progress in developing comprehensive strategies for evaluating environmental impacts of CST activities. ESA started using environmental Life Cycle Assessment (LCA) framework in 2013 to study environmental impacts of a whole mission, from early research stages to the mission end-of-life (ESA, 2015; ESA Discussions, 2016). Specific methodologies and practices are being developed so LCA can encompass the particular aspects of space missions, such as intensive preliminary research and development activities, the use of advanced materials and processes, very low production runs and space propellants (ESA, 2015).

Two pilot LCAs were carried out on two space missions in 2015: one Earth observation (EO) mission and one communication mission. These two pilot LCAs were conducted in an iterative way: environmental hotspots and data quality analysis carried out at each of the three iterations allowed prioritizing the need for additional data collection and further refinement of the LCA model. An important data collection process allowed establishing environmental data over the whole life cycle of space missions (ESA, 2015). The environmental LCA in this dissertation will focus on generic per launch of the launch activity as the functional unit and not a specific launcher, whereas the ESA LCAs did focus on two of the European launchers. This ELCA will use the data from various liquid propellant U.S. launchers.

In addition, the ESA CSI Eco-Design Branch is providing tools and has conducted several studies of specific space activities, including launchers and space missions, and ongoing studies of materials, processes and propellants (ESA, 2015). They plan to establish a common framework to be used by European space agencies and industry when performing spacecraft design, including dedicated databases and tools for space activities. This framework will also allow the quantification of potential benefits of new technologies (ESA, 2015).These ESA LCAs will provide good comparative analysis and methodology insight but will not have a direct application to CST activities in the United States since these LCAs will use different propellant types and launchers data.

2.2.2.9 Literature review summary:

A number of journal articles have focused on the dispersion effects from the propellant used during the launch, as well as methods of greening propellants. Emissions from Space Shuttle launches have been well-documented. FAA AST has generated CST NEPA documents in collaboration with the CST industry. These NEPA documents, however, are limited because they do not provide a cumulative impact assessment and are not specifically focused on the launcher and operations contributing to the total environmental burden.

The European Space Agency (ESA) has made significant progress in developing comprehensive strategies for evaluating environmental impacts of CST activities. European evaluations of CST activities would not necessarily apply in the United States, because commercial space activities refer to primarily to satellites and its activities (ESA, 2016), whereas CST activities in the United States refer to launchers with payloads and its activities. The NASA LCA efforts in the NASA Systems Analysis and Concepts Directorate, Space Mission Analysis Branch used LCA costing analysis for decision making for better risk-informed decisions. Discussions with the Branch leads from this office at NASA Langley Research Center (NASA, 2016) identified that no end-to-end LCA has been done to date for CST activities in the United States.

2.3 Research Objectives

The literature search and discussions with organizations involved in CST activities in the United States revealed no comprehensive environmental LCA exists specifically for CST activities in the United States. As discussed, environmental impact studies and research in related areas exist but did not apply the ISO 14040 and ISO 14044 framework directly to space operations in the United States.

ISO 14040 and ISO 14044 described the principles and framework for life cycle assessment (LCA) including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, the relationship between the LCA phases, and conditions for use of value choices and optional elements (ISO 14040; ISO 14044). Figures 2-1 and 2-2 illustrate these frameworks.

This research applied ISO14040 and ISO14044 standards and framework to CST activities to determine environmental impacts from launch operations. The current ISO14040 is 2006 version and no updated versions are anticipated at the time of this study. However, recent task force efforts are considering revisions in late 2018 (ACLCA, 2018). This environmental LCA has three research objectives:

1. to conduct a base-case LCA environmental inventory and impact assessment of US CST activities based on ISO 14040 and 14044;
2. to identify a range of impacts due to sensitivity in model inputs; and
3. to conduct additional LCAs incorporating “green technologies” to identify strategies for reducing environmental impacts.
4. to operationalize the base-case LCA for environmental professionals and other decision makers, by developing a tool to predict Space Transportation Environmental Profiles for Launch (STEP-L).

2.4 Research Contribution Advances Knowledge and Analytic Application of LCA to U.S. Space Launch Operations

Based on the previous discussion or related LCAs and studies, no other study has evaluated the application of the LCA methodology to the space launch operations in the United States as comprehensively as this study. Each objective provides new knowledge to identify and characterize environmental impacts from CST launch activities in the United States. From the sensitivity analysis, essential data and process information is identified so a U.S. space mission LCA can be more refined for future LCAs and to enhance options for reduced environmental impacts and better decision making into mission profiles and eco-design. The results from the framework and methodology used to operationalize this LCA can be applied to non-commercial and government space vehicles for the launch activities and expanded to other life cycle phases as well.

Chapter 3

METHODOLOGY

"We choose to go to the moon in this decade and do the other things, not because they are easy, but because they are hard. "

[Address at Rice University, September 12 1962]" **John F. Kennedy**

3.1 Methodology Applied for Research Objective 1.

Base-case environmental Life Cycle Assessment (LCA) for commercial space transportation (CST) activities in the United States.

An environmental LCA (ELCA) of the CST activities in the United States will be conducted on space rocket launch operations in the United States. Definitions vary on what is "commercial space" or what activities are included in CST activities (Spacepolicyonline, 2016). For the purposes of this research, CST activities include commercial industry supporting NASA space efforts, and private sector endeavors such as SpaceX. The military collaboration with private industry for classified space launch activities will not be evaluated in this ELCA but will be considered as part of the sensitivity analysis for increased frequency of launches. Data to assess these launches was difficult to access due to possible national security issues. Currently, the CST industry is acting as a surrogate in support of US Air Force space operations and NASA by supplying the launchers to carry payloads into space. Knowledge and maturity for launch systems will be gained with these partnership endeavors between U.S. Air Force, NASA, and private industry.

The main focus of this ELCA was the launch operations for rocket launchers with payloads going to Low Earth Orbit (LEO) and Geostationary Transfer Orbit (GTO). Environmental impacts for space rocket launch operations may comprise a significant portion of the environmental burden of the CST activities and once identified through the ELCA may inform the eco-design or environmental mission planning decisions for space launches.

Figure 3-1 of the SpaceX Falcon 9 rocket system represents a current view of typical launch operations for space rocket systems. To better understand the influence and environmental consequences from the launch operations or the Use and Maintenance Phase, six consumables were evaluated applying the LCA methodology, International Organization for Standardization (ISO) Standard 14040 and 14044 (2006).

Figure 3-1 Falcon 9 Orbital Communication Launch Facility Hangar (SpaceX, 2014)

This ELCA was a cradle to grave (Raw Material Acquisition to End-of-Life) analysis and examined launch operations of all of the consumables: water, electricity, chemicals, liquid propellants, and the expendable and reusable rocket boosters. Due to the proprietary nature of the information related to real world launchers' specific manufacturing and fabrication processes, only the materials used to construct the rocket boosters will be provided and the associated manufacturing processes for these materials.

The LCA framework shown in Figure 3-2 is the framework applied to identify and quantify environmental impacts of a product or a system. These four phases are: Goal and Scope; Inventory Analysis; Impact Analysis; and Interpretation as identified in ISO 14040 (2006)[3].

The 2006 version of ISO Standard 14040 is the most current version and reconfirmed in 2016. However, a Task Group began in late 2017 to update and revise this standard and is expected to be completed by end of 2018 (ACLCA webinar, 2018).

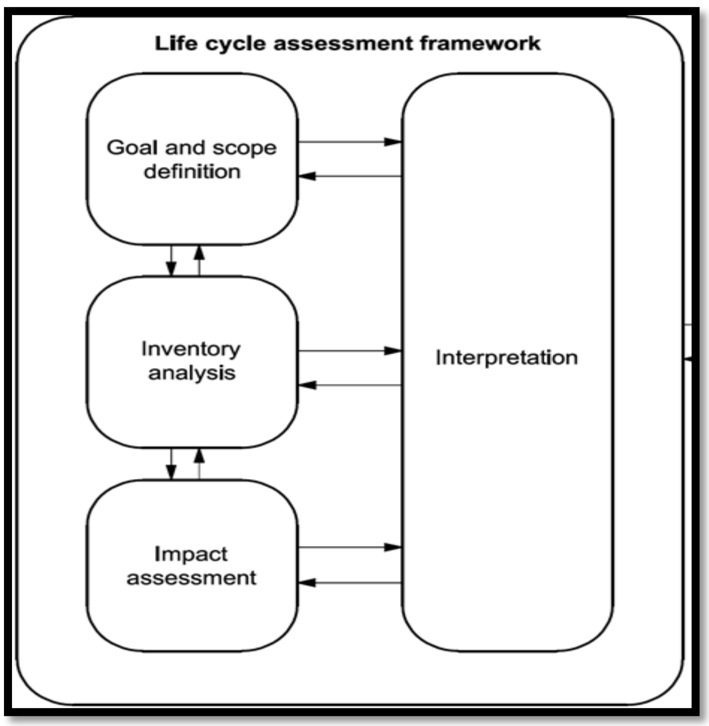


Figure 3-2 Life Cycle Assessment Framework (ISO 14040, 2006)

3.1.1 Goal and Scope Definition

3.1.1.1 Goal

The goal of this ELCA was to generate a base-case analysis applying ISO 14040 and ISO 14044 principles and framework to CST activities in the United States. Since no comprehensive ELCA currently

[3] ISO 14040 and 14044 standards are anticipated to be updated by late 2018 or early 2019 through a Joint Task Force assembled in October 2017 based on webinar presentation in January 2018 hosted by American Center for Life Cycle Assessment (ACLCA).

exists for CST activities in the United States, this base-case will serve as a one key building block for systematic analysis of environmental impacts of these U.S. CST activities.

This ELCA would inform decision-makers in industry and government organizations of the environmental burdens of current and increased launches for compliance and sustainability in the United States. Additionally, this ELCA may also augment current studies performed in the ESA and other space mission operations researchers and manufacturers and augment the NEPA process. The Pre' Sustainability software, SimaPro, is used to calculate the relative environmental impacts from the consumables. This information was developed so decision-makers will know which consumables to target for the largest reductions in environmental impacts. In addition, this ELCA expanded knowledge for potential eco-design strategies and identify relevant indicators of environmental performance for potential measurement.

The main question being addressed in this ELCA is:

As U.S. commercial space transportation activities expand, how are these activities impacting the environment today and within the next five to ten years?

Other relevant questions include:

- What environmental damage impact categories (Human Health, Climate Change, Ecosystem Quality, and Resources) are generated from launch operations using space rocket propulsion liquid propellants (liquid oxygen (LOx)/Liquid Hydrogen (LH_2), LOx/Rocket Propellant (RP-1), LOx/Liquefied Natural Gas (LNG))?
- What environmental damage impact categories (Human Health, Climate Change, Ecosystem Quality, and Resources) are generated from launch operations using either a reusable or expendable rocket booster?
- Which consumable(s) used in launching one space vehicle contributes the greatest environmental impacts and how would this consumable(s) impact the environment?
- How would an increased launch rate of space vehicles impact the environment over the next 10 years?

- What green technologies might aid to minimize environmental impacts during the launch operation?
- What would a general space transportation environmental profile (STEP) be for a reusable launch vehicle with the three types of propellant and the expendable launch vehicle with the three types of propellants?

This ELCA analyses would benefit the environmental planning for space operations as one of the first LCA-related analyses. The ELCA also provided quantitative information augmenting the NEPA process with relative emission values for air, soil and water for a launch and multiple launches and identifies potential damage areas from these launches. Performing a comprehensive LCA on space operations is complex but this ELCA created a reproducible model for performing systematic analyses.

This ELCA created a model for future studies in evaluating the whole system life cycle of space operations modeled at the Use and Maintenance Phases. Also, future spaceports or launch sites might be identified from applying the ELCA in combination with other required operating parameters such as cost, performance, environmental regulations, etc. However, this study will not be determining these launch site parameters. Since this is the first LCA study on space mission launch operations in the United States, it should provide quantitative and characterization information on environmental impacts generated from the launch campaign and the consumables evaluated in this study for the launch.

3.1.1.2 Scope

The space launch vehicle in the United States with payload was the system assessed and the function is launch of payload (satellites, commercial cargo, and commercial crew) to Low Earth Orbit (LEO) and Geostationary Transfer Orbit (GTO). Two comparisons were also evaluated: liquid propellants (LOx/RP-1; LOx/LNG; LOx/LH_2) and reusable and expendable rocket boosters with focus on differences. The timeline for evaluating the space launch of one vehicle included the pre-launch, launch, and post-launch use of the consumables related to one launch. Test firings were also part of the pre-launch activities and will use the consumables of electricity, propellant, water, chemicals and the expendable or reusable rocket booster. These overall launch activities were called the launch campaign (14-days) and considered the Use and Maintenance Phase of the ELCA.

On occasion, the space launch may be delayed due to weather or other engineering or operational holds. These delays that use additional consumables were not examined in this study. Launch failures were not assessed separately in this study but were considered as using all of the consumables needed for a completed launch.

3.1.1.2.1. Functional Unit

The end result from CST activities is the launch of the payload into atmosphere, suborbital and orbital. The functional unit for this study was one launch of space vehicle carrying a payload into LEO or GTO or one launch every two weeks. This launching of one space vehicle with payload going into LEO or GTO was measured for the amount of environmental impacts from use of liquid propellant, chemicals, water, electricity, and reusable and expendable rockets. Environmental impacts were assessed by examining the entire system of launching a space vehicle into the atmosphere – one launch completion.

3.1.1.2.2 System Boundary

The system boundary is shown in Figure 3-3. The system boundary for this ELCA included the five consumables needed for the launch of one space vehicle. However, the expendable booster will also be evaluated as part of this system boundary so six total consumables. These consumables evaluated for environmental impacts for one launch were:

- Reusable rocket booster or expendable rocket booster
- Electricity
- Water
- Chemicals (typically found on launch pad, not all inclusive)
- Propellants (LOx as oxidizer and LH_2; RP-1; LNG)

The environmental outputs from one launch are: greenhouse gases, traditional air pollutants or criteria air pollutants (CAP); water contamination, solid and hazardous wastes and noise, as shown in Figure 3-4.

A typical launch campaign would include the following resources at a minimum:

1) Rocket propulsion system; payload into LEO or GTO[4]

2) Operations facility (electricity and water)

3) Specialized equipment (electricity and chemicals)

4) Launch pad (not assessed in the LCA)

5) Chemical storage with bulk chemicals

6) Transportation from manufacturing facilities

7) Integration facility (electricity, water and chemicals)

8) Water tower

9) Transportation of reusable rocket to refurbishment facility

10) Personnel (electricity and water)

Note: Not all of these resources were evaluated as consumables in this ELCA but may affect the requirements for the consumables which were evaluated.

This ELCA had a system boundary focused on the launch operations (Use & Maintenance), while examining the propellants (fuel and oxidizer), electricity, water, and launch operation chemicals from the raw materials acquisition phase to end-of-life phase. The propellant amounts were determined based on real world launchers using those liquid propellants where data is available. SimaPro software provided the raw materials to manufacturing/production phases to include transportation, electricity and other related processes based on input of the Use phase information of materials and mass.

The reusable and expendable rocket boosters were examined similarly to the other consumables in their life cycle phases and applying SimaPro software. However, due to proprietary nature and International Traffic and Arms Regulation (ITAR) restrictions on available data for the specific rocket engine and other related processes the materials and mass data for the engines, external casings, etc., data was derived from similar rocket launchers and related textbooks. Only the materials are modeled in SimaPro and not the specific space systems manufacturing processes. For the materials modelled in

[4] The payload orbit was not considered and assumed the 2nd Stage propellant was at full capacity.

SimaPro, the raw materials, manufacturing and transportation of these materials are accounted for in this ELCA. These representative rocket launchers are Delta IV Heavy, Falcon Heavy and New Glenn.

This ELCA inventory calculation did not include the raw materials, materials processing, manufacturing and production of expendable and reusable rocket boosters and payloads, or construction of the launch pad and infrastructure at the launch operations site. However, the materials identified and input into SimaPro to develop the rocket boosters at the Use Phase did include the raw materials and its emissions to air, soil and water for representative quantities of basic materials (aluminum, titanium, steel, etc.). Additionally, the buildings' fabrication and manufacturing at the launch site and equipment needed to manufacture and produce the payloads are not included in this LCA.

The major phases within a life cycle, as shown in Chapter 2, include:

a) Raw materials acquisition/Materials processing

b) Manufacturing/Production

c) Use/Maintenance

d) End of Life

e) Transportation throughout the life cycle.

As shown in Figure 3-3, this ELCA did not include environmental impacts of raw material acquisition and production/manufacturing of launch facility infrastructure, expendable and reusable rocket booster manufacturing, and payload (commercial crew, cargo, and satellites), with the exception of representative quantities of basic materials. Similarly, the end-of-life of the launch pad infrastructure and payload while in orbit and its ultimate disposition are outside the scope. The focus of the study was thus the launch of one space vehicle with payload traveling to either LEO or GTO during the use and maintenance life cycle phase. **The payload was not evaluated nor the specific amount of propellant to launch into a specific orbit but assumed the 2nd Stage propellant was at full capacity.**

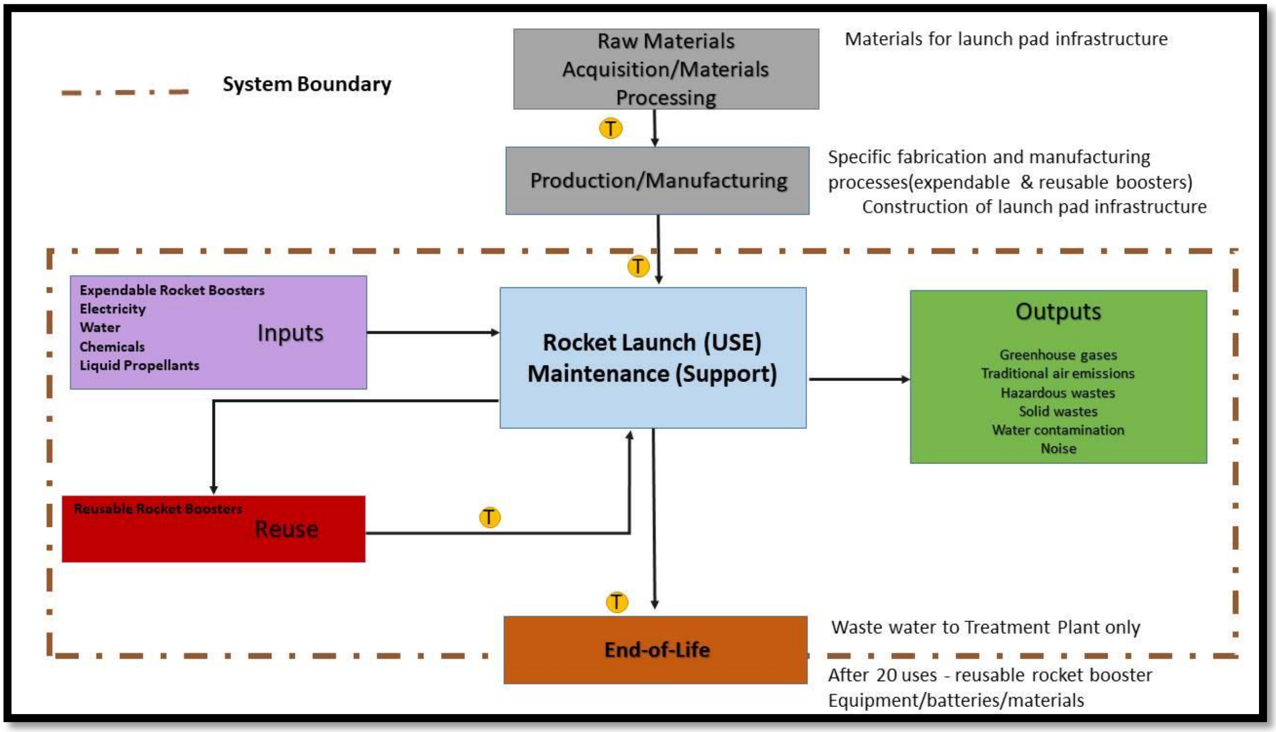


Figure 3-3 ELCA for CST Activities System Boundary

Figure 3-4 shows more detail of the inputs and outputs of the use and maintenance phases. The inventory and impact of one space vehicle launch was evaluated specifically for the following six consumable inputs: water, propellants, electricity, generic launch-operation-relevant chemicals, **generic expendable rocket booster and reusable rocket booster**[5]. For the chemicals, this only includes several key chemicals used frequently at launches but not all inclusive. All propellants (kg) used liquid oxygen (LOx) as the oxidizer and the fuels were liquid hydrogen, RP-1 (kerosene-based), and liquefied natural gas (LNG). Energy was considered as the electricity (kWh) for supporting the launch operations and other equipment at that launch facility. Chemicals (kg) supporting the launch operations was considered to include bulk chemicals stored at the launch facility. Water (kg) was used at the launch

[5] No specific rocket launcher was evaluated. The data from several similar rocket launchers were used for the generic rocket boosters. The propellant amounts were based on the rocket launcher used to meet its performance and thrust requirements.

operations for acoustic energy generated from rocket launch (sound suppression) and the personnel and other general use at the facility.

The expendable rocket booster is used today for launch so this type of booster with liquid propulsion engines was examined. However, reusable rocket boosters are also used today for both operational reasons and for cost savings so reusable rocket boosters were considered as well. The reusable capability of the reusable rocket booster, for this study, was assumed as **20 life uses** with minimal maintenance and refurbishment to launch within days of completing an operation. The re-entry, boost-back[6] and landing of the reusable rocket at the launch pad was assessed for environmental impacts but not the other types of landings to fall back into the water or land on barges.

Figure 3-4 also shows the output from the consumables: greenhouse gases, **traditional or criteria air emissions**, noise, solid waste, hazardous waste, and water contamination. SimaPro Software version 8.2.3 inventory outputs are those air emissions, soil emissions and water emissions of the consumable material inputs used for the CST activities. Noise is not an output from the current SimaPro software. So, this emission was found in the US Air Force and FAA NEPA documents describing the noise around the launch facility during a launch.

It should be noted that space debris is not included in the system boundary. Although space debris is a very critical waste stream from the launching of satellites and other payloads released into orbit, this environmental waste stream **was not** discussed or evaluated in this study, as many agencies and researchers are already exploring the effects of this debris, and ways to capture or mitigate it (NASA, 2012; Wilson, Maury, 2016).

[6] Boost-back is a term used for the re-entry procedure of the Falcon 9 in a NEPA document, Final Supplemental EA for boost-back and landing Boost-Back and Landing of the Falcon 9 Full Thrust First Stage at Iridium Landing Area, Vandenberg Air Force Base, California and Offshore Landing Contingency Option, 20 September 2016

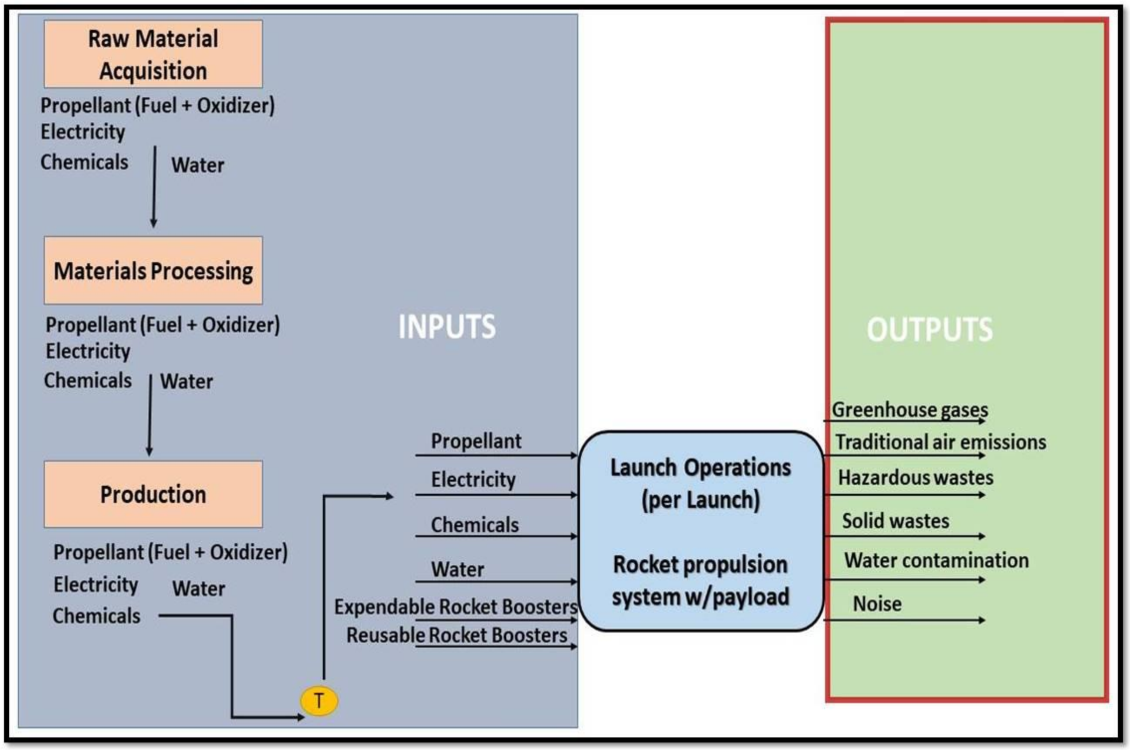


Figure 3-4 ELCA for CST Activities Inputs and Outputs

Geographical boundaries was confined to focusing on the United States; however, lessons learned or other studies such as the ESA informed some of the phases where appropriate.

Atmospheric components examined included the Troposphere[7], the Tropopause (boundary between Troposphere and Stratosphere) and some part of the Stratosphere (maximum 15 miles), shown in Figure 3-5 (Russell, 2011). This ELCA focused in the lower altitudes[8] to examine impacts to human toxicity and natural environment.

---

[7] Ozone is a gas present throughout Earth's atmosphere; 90 percent resides in the stratosphere, the layer of the atmosphere that starts about 6 to 9 miles above the Earth's surface at mid-latitudes, and the rest is located in the troposphere, the atmospheric layer that lies between the stratosphere and the Earth's surface.

[8] In the troposphere, ozone poses both health and ecological risks, but the natural layer of ozone in the stratosphere shields and protects the Earth's surface from the sun's harmful ultraviolet (UV) rays, which can lead to more cases of skin cancer, cataracts, and other health problems (U.S. EPA, 2006).

Greenhouse gas emissions (EPA website, 2017) is defined as: water vapor (H_2O); carbon dioxide (CO_2); methane (CH_4); nitrous oxide (N_2O); ozone (O_3); and fluorinated gases: chlorofluorocarbons (CFCs), hydrofluorocarbons (HFCs), hydrochlorofluorocarbons (HCFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6) are sometimes called high-global warming potential (GWP) gases because, for a given amount of mass, they trap substantially more heat than CO_2.

As stratospheric ozone depleting substances, CFCs, HCFCs, and halons are covered under the Montreal Protocol on Substances that Deplete the Ozone Layer (EPA website, 2017). Also, water vapor is considered a GHG and is found to be negligible effect to climate change. The lifetime of water vapor in the troposphere is on the order of 10 days (EPA website, 2017). Tropospheric ozone is formed from chemical reactions in the atmosphere of precursor pollutants, which include volatile organic compounds (Volatile Organic Compounds, including CH_4) and nitrogen oxides (NOx), in the presence of ultraviolet light (sunlight) (EPA, 2017).

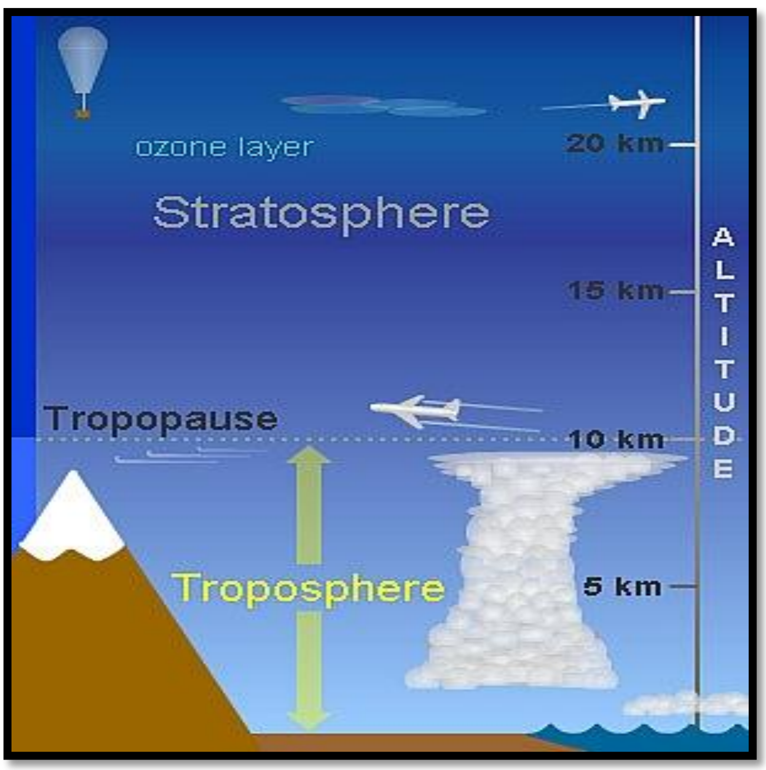


Figure 3-5 Troposphere and Stratosphere Dimensions (Russell, 2011)

3.1.1.2.4 Assumptions and Limitations

Propulsion systems. This ELCA assumed current rocket launch systems will continue to be the primary launch systems for civil, military and private sector commercial space activities for at least 10-15 years. However, in actuality, private sector companies such as Blue Origin and SpaceX will continue to advance and space entrepreneurship will continue to improve using some of the more light-weight propulsion systems from companies such as Virgin Galactic and TheSpaceShip Company. These propulsion systems were not evaluated as part of this study.

For this ELCA of CST activities, the space rocket propulsion systems included rockets that use different liquid propellants with liquid oxygen (LOx) as the oxidizer and liquid hydrogen ($LH_{2)}$, kerosene (RP-1) and LNG as the fuel. These rocket systems are used to send payloads of satellites, cargo and human-rated spaceships into space in support of the International Space Station (ISS) and other paid for service efforts currently. These systems may be used to send missions in deep space such as Mars or the Moon. Solid rocket propulsions systems or emerging technology systems such as ion propulsion were not considered in this study.

Rocket boosters. Expendable rocket boosters are one time use and **will not** be evaluated for reuse or recycling for end-of-life because this ELCA assumed these boosters fall into the ocean. The reusable rocket casings and boosters and other components and equipment will be assumed to have an expected use life of 20 uses. For the first 19 uses, the reusable rocket, evaluated in this study, will land back and then be transported to the refurbishment facility via truck, and then transported back to the launch facility via truck. Other typical ways for the rocket booster to return back to earth is to land on a barge or drop into the ocean. End-of-life for the reusable rocket booster was the 20th use and then its components are assumed disposed of as solid waste, reuse or recycle, as appropriate. The reusable booster was assumed to only expend 1/20 of raw materials, production chemicals and manufacturing efforts, and end-of-life requirements per Launch.

The SimaPro database included raw materials acquisition and manufacturing of materials that were identified for the composition of the components for the reusable and expendable rocket boosters.

Processes used to assemble these materials, like welding, were not assessed due to the proprietary nature of the technology, U.S. export controls and International Traffic in Arms Regulations (ITAR) and limited open source information.

Rocket engine exhaust. The rocket engine exhaust amounts such as CO_2 emissions and other characterization of this exhaust **were not** part of this ELCA. Information on the operational performance of rocket boosters and design characteristics of the specific engines were not available. The products of combustion for a specific engine would be necessary to make an accurate model in SimaPro. In addition, no specific engine or launcher was modeled in this ELCA. However, information from NEPA documents was cited.

Availability of processes in SimaPro. SimaPro software has some limitations related to certain processes relevant to launcher manufacturing. For example, friction-stir welding was not available in the library databases so other related processes were applied when needed. Other efforts are underway to build databases relevant to space missions (Wilson, Maury, 2017).

3.1.2 Inventory Analysis

Life Cycle Assessment (LCA) dedicated software, SimaPro version 8.3.2, was used for this study. Key database libraries were applied within SimaPro for this ELCA were Ecoinvent, version 3.3[9], ELCD[10], Industry 2.0[11], USLCI[12] and US-EL2.2[13] allowed for a robust LCA on CST activities. Ecoinvent and the other libraries are global data. However, US-EL2.2 and USLCI are U.S. centric related data libraries. These databases were chosen as the most relevant and appropriate for this study.

The literature research aided in identifying the raw data available needed in determining the environmental impacts when launching one space vehicle. Key primary data needed for the specific space vehicle launchers such as exact material composition was needed to apply the SimaPro software most effectively at each LCA phase. Figure 3-6 shows the types of data sources relevant to each life

[9] Ecoinvent v3.2 data as unit processes, compiled February 2016
[10] European Life Cycle Database v3.1, September 2015
[11] Industry Associations datasets, April 2015, September 2015, and March 2016
[12] U.S. Life Cycle Inventory Database, updated September 2015
[13] DATASMART Life Cycle Inventory Package , Long Trail Sustainability, May 2017

cycle phase for the six consumables supporting the Use and Maintenance phase of launch operations. In those instances where data was unavailable for public access, then estimates using parametric data from similar products were used. These data are identified as estimates.

Raw data gathering methods consisted of using publically available NEPA documents from the FAA, U.S. Air Force, and NASA; environmental permits; and organizational data. Data and information used to evaluate the environmental impact also included technical journals; peer-reviewed articles; environmental regulations; websites with repository holdings of technical information related to space rocket propulsion systems such as NASA studies and U.S. Air Force Installation Restoration Program (IRP) reports where relevant; ISO standards, national and legislation policies such as the NASA Space Act and organizational policies; Department of Defense (DoD) similar data for other aircraft systems; and ESA relevant data and information.

The Pré Sustainability program, SimaPro version 8.3.2 was utilized for other industry-relevant data such as transportation and other data needs for the phases of raw materials acquisition, materials processing, manufacturing and production for chemicals, electricity, propellants and water consumed for launch operations. Several data libraries within SimaPro were applied extensively, as mentioned previously.

Another means of acquiring primary relevant data sources was through discussions or interviews with relevant launch operations personnel such as the US Space Command, 45^{th} Space Wing, Civil Engineering Squadron (Duce, 2016) and Federal Aviation Administration (Zee, 2015). A Freedom of Information Act (FOIA) response provided information about the launch operations water and electricity. This FOIA provided direct readings at the launch facilities and was assumed as valid and credible. These data are measured and recorded through metered systems such as water or power and directly support the launch complex. However, allocation values were necessary since some of the support systems provide water service to multiple customers. This allocation was developed as specifically as possible.

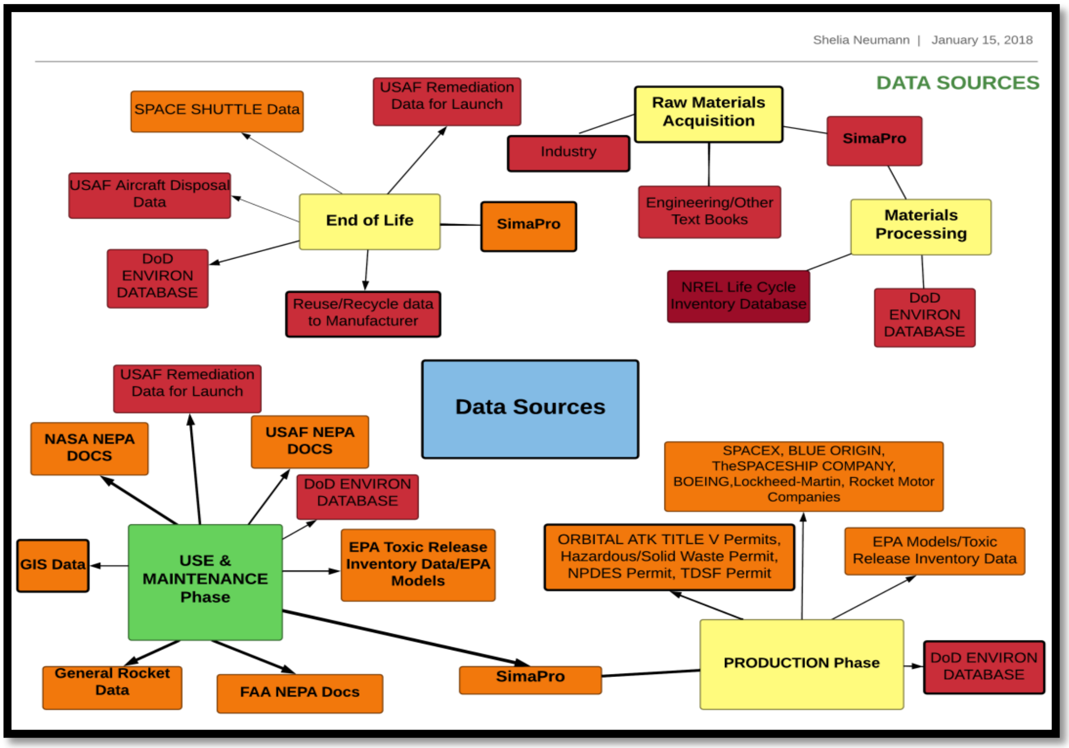


Figure 3-6 Data Sources for ELCA Phases (developed by Neumann using Lucidchart.com, 2016)

Excel spreadsheets or SimaPro Data Collection Workbook was used to capture relevant data with a defined data collection strategy for the unit processes of the six consumables used during the launch operations at each of their life cycle phases. Where data was unavailable, generic or related data to the unit process was applied. Where unique data was required as input into the SimaPro version 8.2.3, then the data sources shown in Fig 3-6 were introduced into the software with an Excel spreadsheet as needed or by building specific processes.

3.1.2.1 Model-Based Systems Engineering Concepts for Rocket Booster Data Collection

Systems engineering principles and concepts were applied to aid in identifying the type of data needed for the rocket boosters. The use of mindmap diagrams and model-based systems engineering (MBSE) was used in part to develop the modules for the reusable and the expendable rocket boosters. The Systems Modeling Language (OMG SysML™) concepts were used for generating block definition diagrams (Friedenthal et al., 2015) and package diagrams. Modeling with SysML concepts allowed a better understanding of how the rocket booster could be deconstructed into modules. The modules built into SimaPro software as product stages were informed using SysML hierarchy and then the block definition diagram methodology. Systems engineering principles provided a roadmap to aid in the datamining of available information and data. This modular approach then informed how to build out the product stages within the SimaPro software.

Figure 3-7 and Figure 3-8 show the modular breakdown structure of the reusable rocket and expendable rocket boosters used in SimaPro. The 1st Stage is used to launch the rocket into earth's atmosphere and imparts the majority of the velocity change to achieve orbit, the 2nd Stage performs the orbital insertion into either LEO or GTO, and the Fairing is used to carry and protect payload during ascent. For this ELCA, **a generic rocket booster** was constructed using three core boosters with nine engines in each booster for the 1st Stage. For the 2nd Stage, only one engine is needed and was used. Figure 3-9 provides an example of these elements of an operational rocket booster (expendable). The differences between the reusable and expendable are the life uses, the use of landing propellant in 1st Stage[14], landing legs and grid fins in the reusable rocket booster. **The 1st Stage in the reusable rocket booster is reused 20 times for this study. The 2nd Stage and the Fairing in both rocket boosters are one-time use.** To increase the robustness of this model, other configurations might be added with more parts within each of the Stages and Fairing to be as complete as possible for future analysis.

[14] The propellant used for landing was modelled in the reusable rocket booster 1st Stage because the intrinsic quality of re-entry of the 1st Stage. Also, combining this added propellant for landing would get overlooked as one of the main differences between reusable 1st Stage and expendable rocket booster.

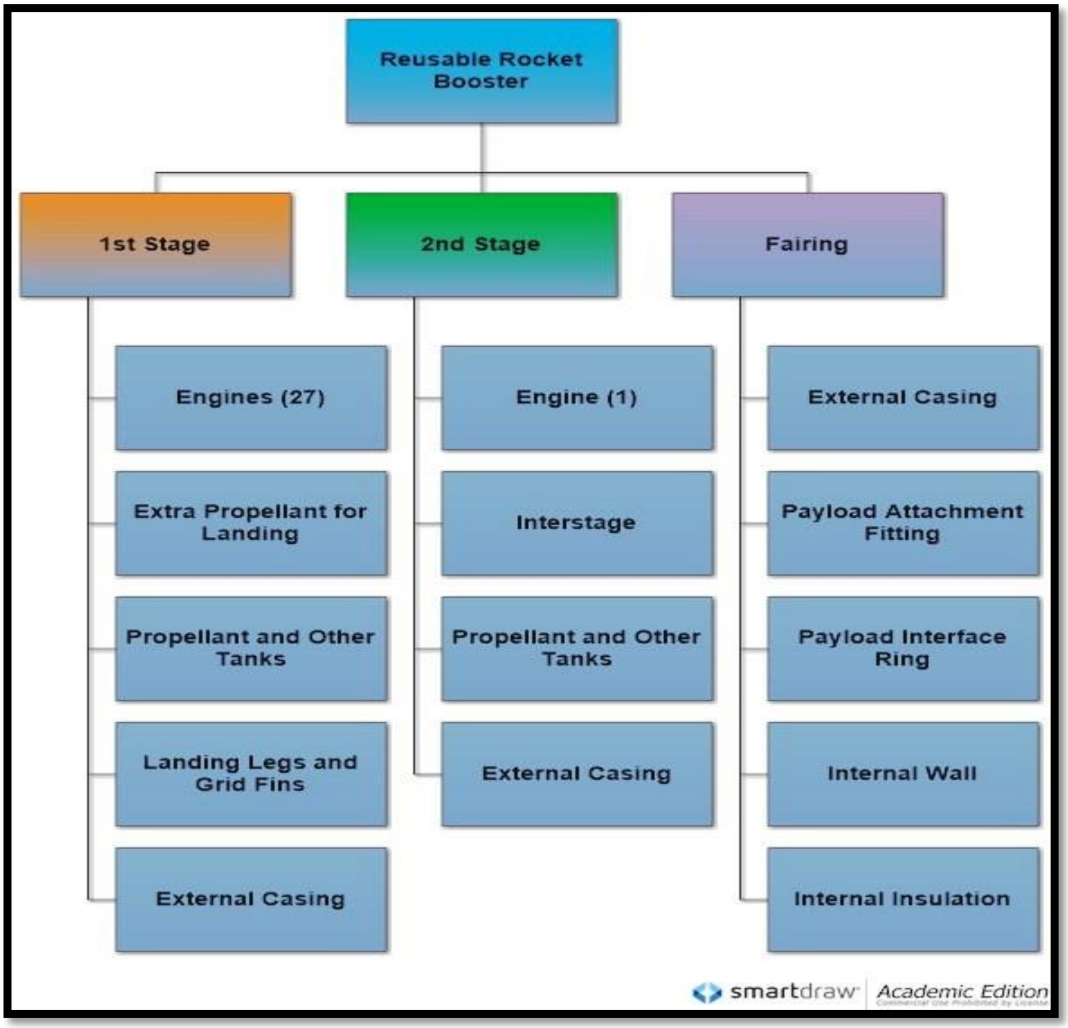


Figure 3-7 Systems Engineering Breakdown of Reusable Rocket Booster (created by Neumann using Smartdraw, Academic Edition, 2017)

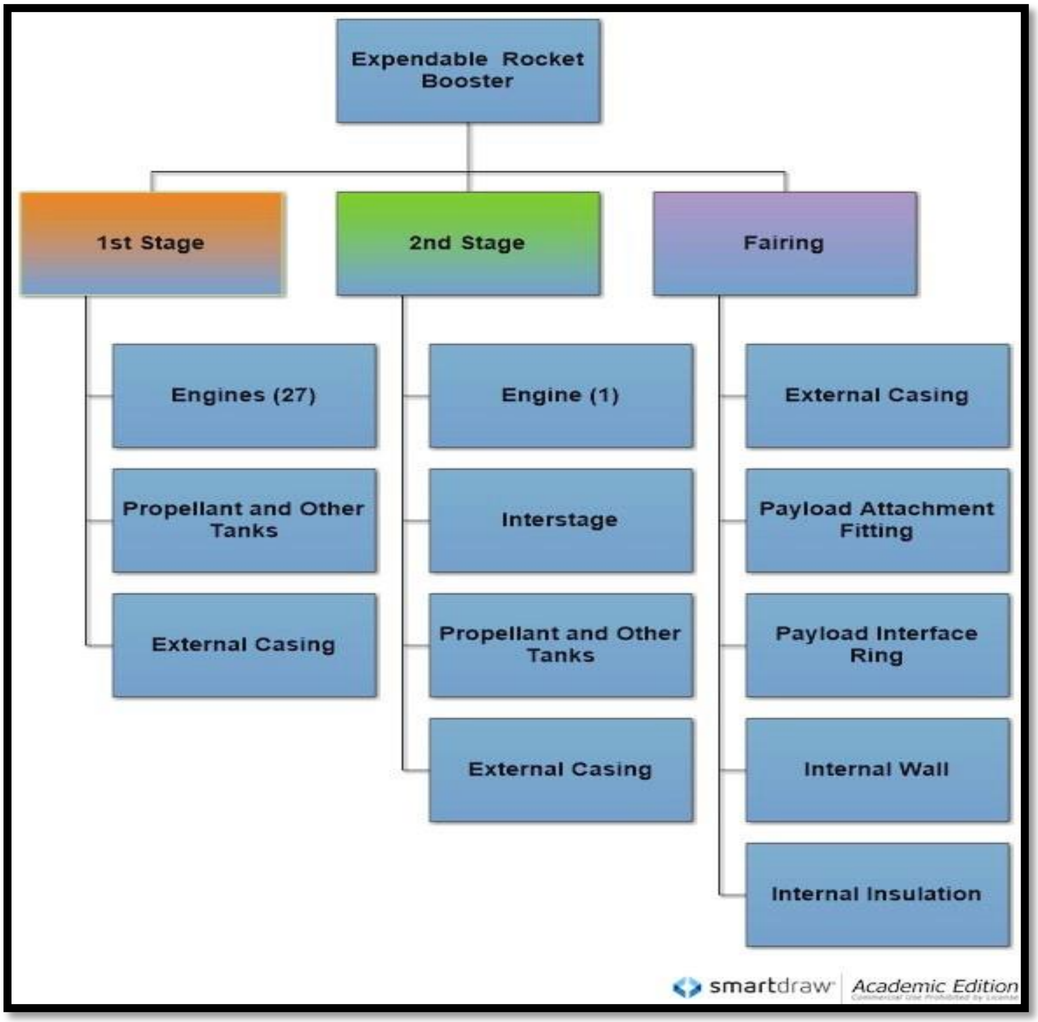


Figure 3-8 Systems Engineering Breakdown of Expendable Rocket Booster (created by Neumann using Smartdraw, academic edition, 2017)

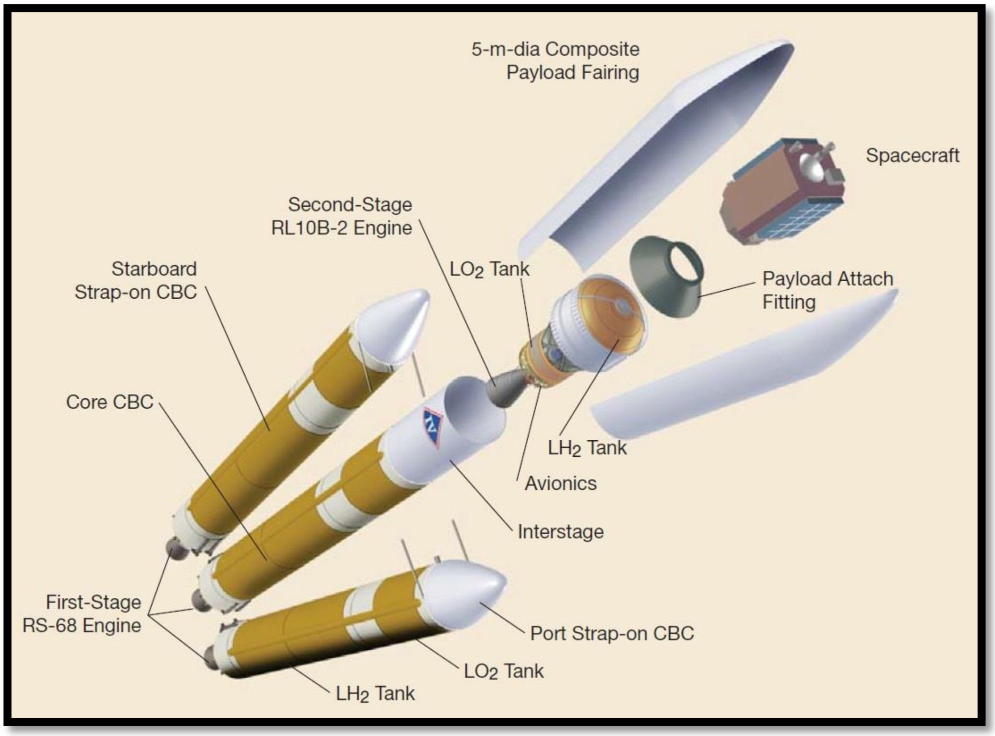


Figure 3-9 Operational Expendable Rocket Booster, Delta IV Heavy, Exploded Elements (Delta IV Launch Services Users Guide, 2013).

3.1.2.2 Launch Campaign Timeline for Launch Use and Maintenance

The timeline for a complete Launch Campaign will be the Test Firings at L-14 days, Launch, and post-launch activity at L+1 days (total of 14 days for a typical baseline Launch Campaign), with the launch considered completed in 14 days, or one launch every two weeks, as shown in Figure 3-10. This figure shows a notional launch campaign timeline of two weeks per launch, with general activities occurring within the timeline. Figure 3-11 illustrates the major tasks needed for the launch campaign; these tasks aided in informing the data collection efforts.

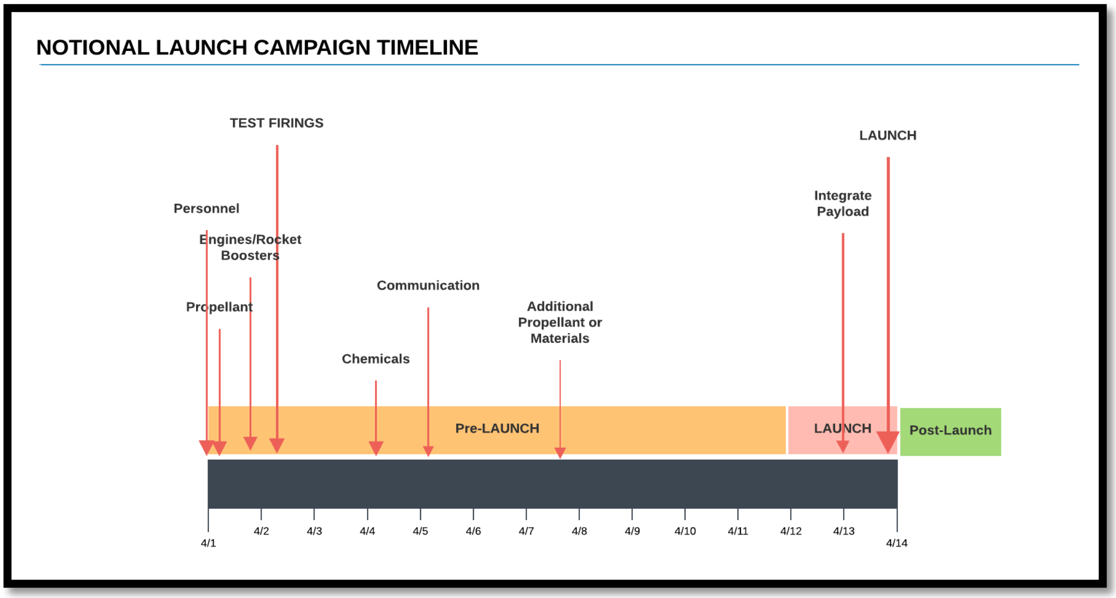


Figure 3-10 One Space Vehicle Launch General Tasks and Timeline (developed by Neumann using Microsoft timeline, 2017)

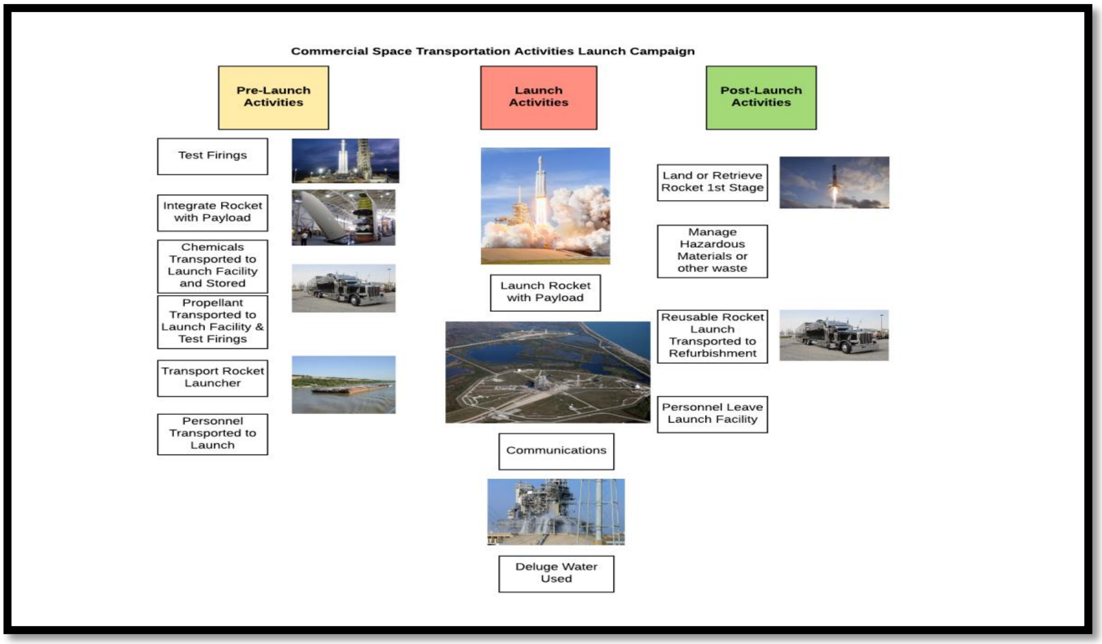


Figure 3-11 Generic Launch Campaign Activities[15]

[15] The images are found in open source images on yahoo and google for barge, payload, trucks, launch facility, and deluge water. Also used FAA 2018 Compendium and NASA.

3.1.2.3 Data for Launching One Space Vehicle at Launch Facility (Use and Maintenance Phase)

The SimaPro software was used to perform the ELCA. The data necessary to build out the inputs for launch operations and launch campaign in the Use and Maintenance Phase was identified by breaking down the space vehicle into major parts (1^{st} stage, 2^{nd} Stage, and Fairing), and the other consumables such as electricity, water, and chemicals, as shown in Table 3-1. Typical tasks shown in Figure 3-10 provided the major activities where available data was collected. For the launch facility, certain infrastructure is standard and necessary, including the fuel storage, mission and launch control centers, and water tank for storage of deluge water. NEPA documents from the FAA and U.S. Air Force supporting launches at Cape Canaveral Air Force Station (AFS) and Vandenberg Air Force Base (AFB) were a significant source of data, as well as other open-source reporting related to launches.

The approach used to determine environmental impacts from one launch of a space vehicle was to identify the amount of electricity consumed, water consumed, chemicals consumed, liquid propellant needed to launch into LEO and GEO, and the expendable and reusable rocket boosters with payloads as whole systems. The overall scope of the Use Phase included a launch campaign of two weeks of the pre-launch and launch and this will be the system boundary timeline. The post launch will not be considered except for the end-of-life activities related to the consumables per Launch. So, the per Launch is considered every two weeks.

Figure 3-12 shows the landing of the reusable rocket, 1^{st} Stage[16], back to the launch facility. Table 3-1 provides the SimaPro module inputs developed for each of the six consumables at the Use and Maintenance Phases. Within the reusable and expendable rocket booster are additional components; these components will be shown in the SimaPro input data.

[16] The 1^{st} Stage in the reusable rocket booster is the only reusable element in the reusable rocket booster.

Figure 3-12 Reusable Rocket Booster Landing (SpaceX-Falcon 9) (FAA Compendium, 2018)

Table 3-1 Consumables' Constituents Per Launch

Consumables	**Constituents**						
Chemicals/Fuels	Liquid Nitrogen	Hydrazine	Diesel	Heavy Fuel Oil	Light Fuel Oil	Unleaded Petrol	Liquefied Helium
Electricity	Medium Voltage	Diesel generator					
Water	Deluge	Personnel					
Propellant (Oxidizer/ Fuels)	Liquid Oxygen	Liquid Hydrogen	Natural Gas, liquid	Kerosene (RP-1)			
Reusable Rocket Booster	Fairing	1st Stage	2nd Stage				
Expendable Rocket Booster	Fairing	1st Stage	2nd Stage				

Primary data sources such as interviews, phone or email surveys and focus groups were used where possible to augment the secondary sources found in the peer-reviewed journals, technical books, rocket manufacturing websites and user's manuals, and other organizational information. Space mission launch is a unique industry even in the manufacturing area, so obtaining specific process and chemical data was challenging due to proprietary and competitive nature of this industry. Emails were sent out to various industries such as SpaceX, Blue Origin, and ULA. ULA did respond to emails; however, they were not able to provide specific rocket manufacturing processes due to proprietary concerns.

Phone interviews with the FAA, U.S. Air Force, Orbital ATK, NASA, ESA, International organizations, Department of Defense (DoD), Aerojet Rocketdyne, ULA, Spaceship Company, and LCA practitioners provided insight into the rocket launch industry, environmental considerations and impacts, and application of the LCA methodology.

3.1.2.3.1 Data for Transportation for Consumables to Launch Facility

Transportation was considered for the consumables in the following ways:

- From manufacturing/production facilities to launch facility
- To refurbishment facilities from launch facility (reusable rocket booster)
- Additional propellant to test firings from production facilities to launch test facility
- From water treatment plant for deluge water (water tower replenishment) to launch facility

For transportation needs of the six consumables, six trucks were used (two with gas engines and four with diesel engines) for chemicals and launch propellant and gases. Additional trucks used for the deluge water (one), test firing propellant and gases, refurbishment for reusable rocket (two trucks) and barge (one) needed for the rocket launchers. The number and types of trucks used to transport materials and fuels were modeled using information found in NEPA documents. Personnel transportation to and from launch facility was not captured in this study.

The transportation phases are shown in Figure 3-3 with a symbol of 

. SimaPro software automatically includes transportation for those consumables from Raw Materials Acquisition Phase to

Manufacturing Phase to Use Phase. Additional transportation is included in the process for all of the consumables as shown in Table 3-2 and provides the distances and the mode of transportation used in SimaPro for the Manufacturing/Production Phase to the Use Phase. The use of the Southeast and the West designation was to provide some comparison if the launches occurred on either the Southeast (Florida) or West (California) to determine if any environmental impacts differences might exist. For the Southeast and West Coasts, the production and manufacturing of the diesel or gasoline may influence these environmental impact differences.

The precise manufacturing or treatment facilities were not available for all consumables so estimated 100 miles to the launch facility for the water trucked in from the water treatment plant, chemicals (multiple) to launch facility, propellants to launch facility, and expendable and reusable rockets to launch facility from manufacturing facility. The East and West Coast Launch Facilities (CCAFS/KSC and VAFB respectively) were considered because CST launches occur on both coasts. NEPA documents provided the truck type used for the consumables. More accurate information on the specific production or manufacturing facility would allow for more precise environmental impacts from the Transportation Phase. SimaPro categories related to the transportation in the coastal regions of Southeast and West are shown in Table 3-2. The difference of transporting consumables from the Southeast or from the West would show differing environmental consequences relevant to typical launch locations and was shown in the Damage Assessment Single Score. All other data related to the study is site-agnostic.

Table 3-2 Transportation for Consumables to Launch Facility

Consumable	From	To	Distance (miles)	Category in SimaPro
Water	Water Treatment Plant	Launch Facility Tower	100	Transport, single unit truck, short-haul, diesel powered/tkm/RNA
Chemicals – varied	Production	Launch Facility Pad	100	Transport, single unit truck, short-haul, diesel powered, Southeast/tkm/RNA Transport, single unit truck, short-haul, diesel powered, West/tkm/RNA Transport, single unit truck, short-

				haul, gasoline powered, Southeast/tkm/RNA Transport, single unit truck, short-haul gasoline powered, West/tkm/RNA
Propellants	Production	Launch Facility Pad	100	Transport, single unit truck, short-haul, diesel powered, Southeast/tkm/RNA Transport, single unit truck, short-haul, diesel powered, West/tkm/RNA
Expendable and Reusable Rocket Boosters	Production	Launch Facility	100	Transport, freight, inland waterways, barge with reefer, cooling {GLO} market for | Allocation Rec, U
Reusable Rocket Booster	Launch Facility	Refurbishment Facility	100	Transport, single unit truck, short-haul, diesel powered, Southeast/tkm/RNA Transport, single unit truck, short-haul, diesel powered, West/tkm/RNA

3.1.2.3.2 SimaPro Material Categories for Consumables

Table 3-3 through Table 3-11 show the consumables, their SimaPro material categories, and the amount of material input used to assess to the environmental impacts from one launch of a space vehicle using liquid propellants for the Use and Maintenance Phase. The material categories used in SimaPro are "{GLO}[17] market for | Allocation Definition where GLO is global, Unit with {RoW} market where RoW is rest of the world" and is also shown in some of the SimaPro material categories. Attributional modeling, recycled content[18], is used for this study at the unit process level. Attributional modeling shows upstream

[17] These codes are the original codes used by Ecoinvent taken from ISO3166. GLO means global and represents activities which are considered to be an average valid for all countries in the world. RoW represents the Rest-of-the-World. In ecoinvent v3.2 (2015) and higher the RoW is generated as an exact copy of the GLO dataset with uncertainty adjusted. The newly generated RoW is then linked with activities of an adequate geographies creating RoW specific supply chain. https://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-do-the-shortcuts-such-as-ch-rer-row-and-glo-mean.html, accessed 3/18.

[18] This cut-off approach means primary production of materials is always allocated to the primary user of a material. If a material is recycled, the primary producer does not receive any credit for any recyclable materials. The consequence is recyclable materials are available burden-free to recycling processes and secondary (recycled) materials bear only the impacts of the recycling processes. Also, producers of

emissions and resource extractions are allocated wherever multi-output processes occur (Pre' Sustainability website, 2018).

3.1.2.3.2.1 Reusable and Expendable Rocket SimaPro Data

The reusable and the expendable rockets are assumed to have the same materials, same size and use the same number of engines for launch. For 1st Stage, 27 engines are used and for 2nd Stage, one engine is used. Specific data on the part dimensions were limited; however, overall mass data for representative launchers was available in the 1st and 2nd stages and the payload load mass capacity. Drawings and photographs of specific space launch systems were used to make estimates of part sizes and mass using dimensional analysis.[19] Figure 3-13 provides some of the dimensional analysis conducted on an operational rocket booster.

---

wastes do not receive any credit for the recycling or re-use of products resulting out of any waste treatment.

[19] For this generic engine, the Merlin 1-D mass was used at 470 kg for one engine and 12690 kg for 27 engines. Source was Quora.com/Is-Spacexs-Merlin-1D-thrust-to-weight-ratio-of-150+-believable/answer/Thomas-Mueller-11, accessed 21 Dec 2017.

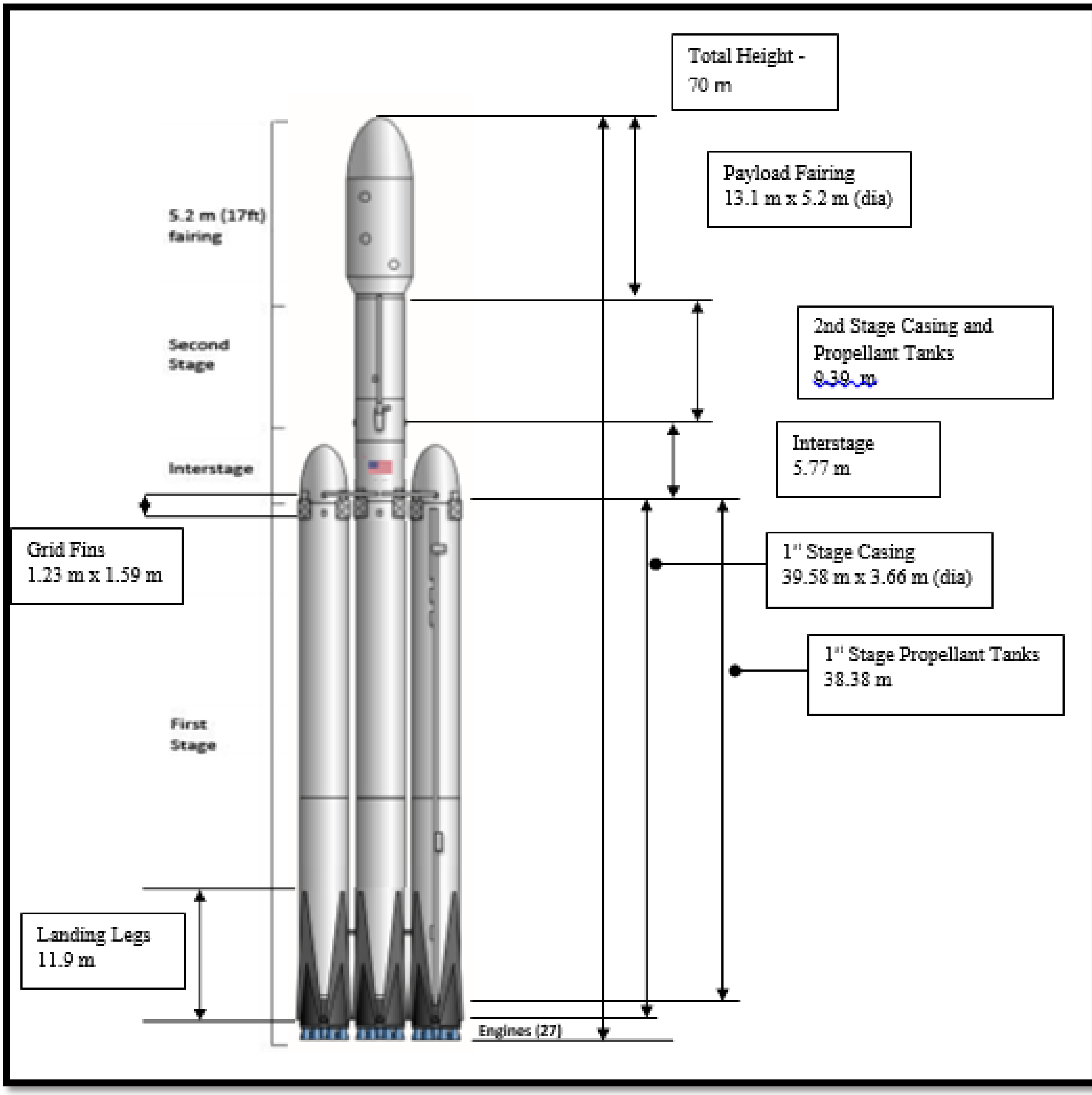


Figure 3-13 Generic Rocket Booster Dimensional Analysis for Estimated Masses (graphic of rocket booster from FAA Compendium, 2018)

The reusable rocket booster has several parts and is modeled in SimaPro software as modules or product stages. Figure 3-14 illustrates the construct with estimated mass and applied for each of the rocket booster components: 1st Stage; 2nd Stage; and the Fairing. For the modules built in SimaPro, the material and the amount used in the processes are shown in Tables 3-4 through 3-8 for both the reusable and expendable rockets. The reusable rocket 1st Stage weighs 6500 kg more than the expendable rocket due to the extra propellant, landing legs and grid fins.

As mentioned, this reusable rocket, 1st Stage only, is 1/20th of the value based on the usability with minimal repair and maintenance so the values reflect this assumption with the exception of the added propellant. The **added landing propellant is included as a component of the 1st Stage element** since it is a critical feature to allow reusability of the 1st Stage booster. Also, this added propellant placement allows for ease of modeling and maintains an accurate comparison of the reusable and expendable booster. **The 2nd Stage and Fairing are one time uses.**

Additional transportation requires using tankers and trucks for the rocket booster so, an additional transportation is included to carry the engines or external casing to the launch facility. This input is accounting for additional transportation using a barge from the manufacturing to launch facility. These transportation methods are based on NEPA documents and other industry websites. So, this is visible in the first use of the reusable rocket as the refurbishment uses other types of transportation. The added propellant is used in whole for each launch. The propellant input consisted of the LOx averaged among the required amount for the three propellants at 2% extra; and 2% extra for LH_2, LNG, and RP-1.

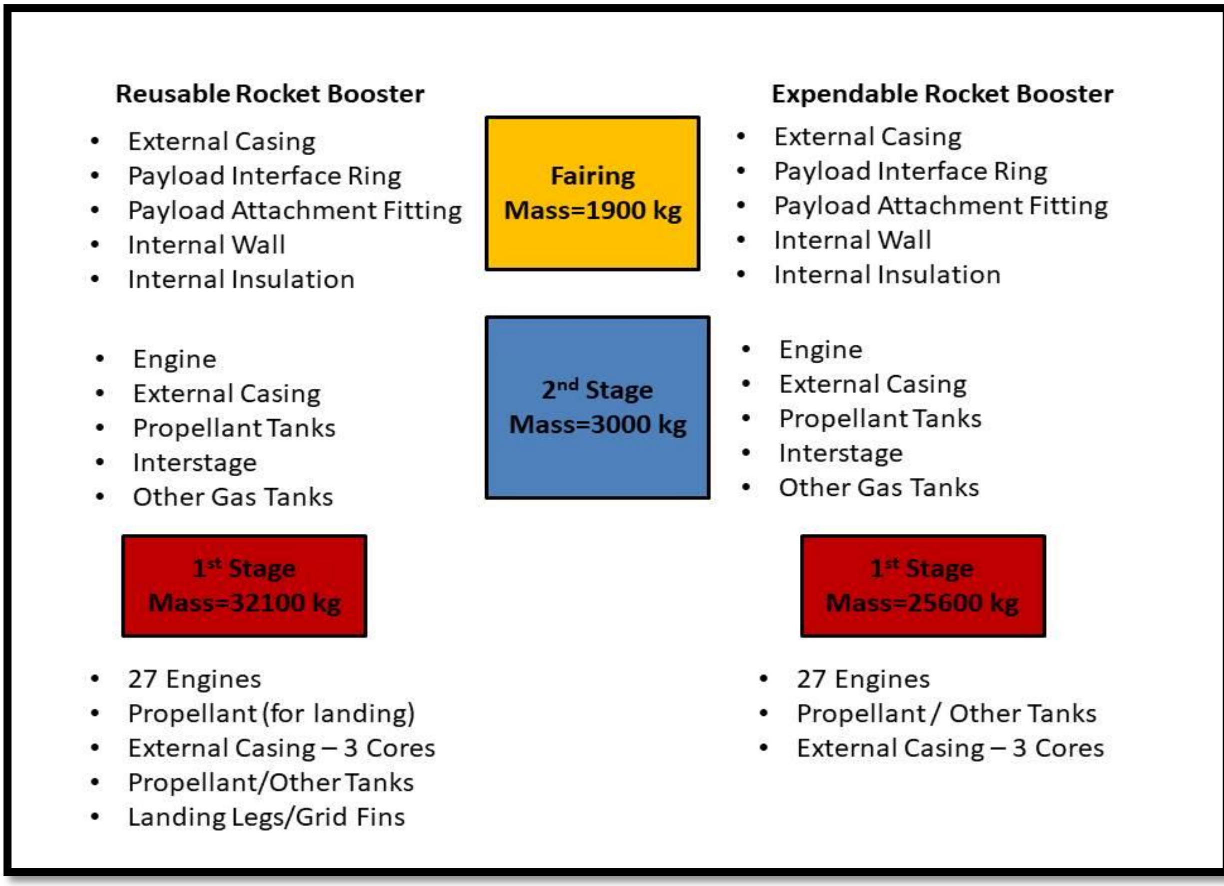


Figure 3-14 Reusable and Expendable Rocket Booster Modules

Table 3-3 Engines 1st and 2 Stage Material Composition – Reusable/Expendable Rockets SimaPro Data

Engine Component[20]	Amount (One Engine) of Material (kg)	Amount (27 Engines) Material (kg)	SimaPro Material Category
Injector Rings (0.5% Mass)	2.35	63.5	Copper {GLO} market for | Alloc Rec, U
Injectors (5% Mass)	23.5	635	Nickel, 99.5% {GLO} market for| Alloc Rec, U
Turbopump (35% Mass)	165	4440	Steel, low-alloyed {GLO} market for | Alloc Rec, U
Pump Housings (5% Mass)	23.5	635	Aluminum alloy, AlMg3 {GLO} market for | Alloc Rec, U

[20] Mass percentages based on images of rocket engine parts and materials generally used estimated from “Materials from Liquid Propulsion Systems Chapter 12, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20160008869.pdf.

Combustion Chamber Insert (1% Mass)	4.7	127	Carbon black {GLO} market for | Alloc Rec, U
Misc. Tubing and Housing (16.5% Mass)	77.5	2090	Steel, billets, at Plant NREL/US U
Gimbel Bearing (5% Mass)	23.5	635	Titanium, primary {GLO} market for | Alloc Rec, U
Nozzle (20% Mass)	94	2540	Steel, chromium steel 18/8
Combustion Chamber (10% Mass)	47	1270	Iron-nickel-chromium alloy {GLO} market for | Alloc Rec, U
Nozzle Inside Shield (2% Mass)	9.4	254	Cobalt {GLO} market for | Alloc Rec, U

Table 3-4 1st Stage External Casing, Propellant/Other Gas Tanks – Reusable/Expendable Rockets SimaPro Data

Component	Amount of Material (kg)	SimaPro Material Category
External Casing	4489	Aluminum alloy, AlLi {GLO} market for | Alloc Rec, U
Propellant Tanks (empty)	4282	Aluminum alloy, AlLi {GLO} market for | Alloc Rec, U
Other Gas Tanks (helium)	461.5	Aluminum alloy, metal matrix composite {GLO} market for | Alloc Rec, U
Insulation around Tanks	188	Polyurethane flexible Foam {GLO} market for | Alloc Rec, U

Table 3-5 1st Stage Reusable – Grid Fins, Landing Legs and Landing Propellant SimaPro Data[21][22]

Component	Amount of Material (kg)	SimaPro Material Category
Grid Fins (12)	64.8	Titanium, primary {GLO} market for | Alloc Rec, U
Grid Fins Actuators	22	Aluminum alloy, AlLi {GLO} market for | Alloc Rec, U
Landing Legs (12)	2390	Aluminum alloy, metal matrix composite{GLO} market for | Alloc Rec, U
Landing Legs (12)	120	Epoxy resin, liquid {GLO} market for | Alloc Rec, U
Liquid Oxygen (LOx) – Landing	12,565	Oxygen, Liquid {ROW} market for | Alloc Rec, U
Liquid Hydrogen (LH_2) - Landing	590	Hydrogen, Liquid {ROW} market for | Alloc Rec, U
Natural Gas, Liquid (LNG) -	522	Natural Gas Liquids {GLO}

[21] Dimensional analysis on SpaceX Gallery of pictures of grid fins, accessed 12/17.
[22] Dimensional analysis on SpaceX actuators and landing legs graphics found in discussions on http://www.spacex.com/news/2013/04/12/falcon-heavy-landing-legs, accessed 12/17.

Landing		{GLO} market for | Alloc Rec, U
Kerosene (RP-1) - Landing	6905	Kerosene {ROW} market for | Alloc Rec, U

Table 3-6 2nd Stage Reusable/Expendable Rocket SimaPro Data[23]

Component	Amount of Material (kg)	SimaPro Material Category
Engine (1)	Same as 1st Stage	Same as 1st Stage
External Casing/Propellant Tank	674	Aluminum alloy, AlLi {GLO} market for | Alloc Rec, U
Interstage	131	Aluminum alloy, metal matrix composite {GLO} market for | Alloc Rec, U
Other Gas Tanks	8	Aluminum alloy, metal matrix composite {GLO} market for | Alloc Rec, U
Explosive for separation	11	Explosive, tovex {GLO} market for | Alloc Rec, U

Table 3-7 Fairing Reusable/Expendable Rocket SimaPro Data[24]

Component[25]	Amount of Material (kg)	SimaPro Material Category
External Casing	457	Aluminum alloy, metal matrix composite {GLO} market for | Alloc Rec, U
Payload Attachment Fitting	250	Aluminum ingot, production mix, at plant NREL/US U
Payload Interface Ring	8.5	Titanium, primary {GLO} market for | Alloc Rec, U
Internal Insulation	1180	Bisphenol A epoxy based vinyl ester resin {GLO} market for | Alloc Rec, U
Internal Insulation	1144	Graphite {GLO} market for | Alloc Rec, U
Internal Wall	1	Cork slab {GLO} market for | Alloc Rec, U
Casing Walls	1180 m^2	Metal composite material (MCM) panel, at plant/m^2/RNA

[23] Dimensional analysis 2nd Stage and other component information from www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf, p. 31.
[24] Dimensional analysis and materials selection from images and www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf, p. 31.
[25] Some information on the type of material and amount found in SpaceX falcon 9 user's manual.

The reusable rocket is modeled with grid fins, landing legs, actuators and 2% more propellant per mass in 1st Stage, and is used 19 more times than the expendable rocket. The mass of the reusable rocket is greater due to the differences mentioned. These components were considered as the only differences between the two boosters based on the best available data found in launchers' users manuals or other open source resources. For the calculations, only **1/20th of the reusable rocket booster** will be compared with one expendable rocket booster.

For the engine, major components were selected and were assigned a mass as a certain percent of the total engine mass. The primary materials used for these parts were assumed as 100% of the mass. Within the 1st and 2nd Stages, several major components such as engine and external casing were included, but avionics, fasteners, and other miscellaneous couplings, clamps, etc., were excluded. So, approximately 10% or less of the mass for each stage was not accounted for because of these minor components.

3.1.2.3.2 Electricity, Water, and Chemicals at Launch SimaPro Data

Table 3-8 provides the electricity, water and chemical SimaPro inputs. These values were estimated from various sources. References and engineering judgment was also used. For instance, in determining the number of generators needed per launch campaign. Also, limited number of generator sizes was available in SimaPro. The number of generators was determined based on the amount of electricity required. Only one type of hydrazine was available in SimaPro so the mass of all three hydrazine types were combined.

Table 3-8 Electricity, Water and Chemicals at Use Phase SimaPro Data

Component	Amount	SimaPro Material Category	Notes	Reference
Electricity for overall Launch facility	42,000 kWh	Electricity, medium voltage {NPCC, US only} market for | Alloc Rec, U	3000 kWh average each day for 14 days	Average based on data from FOIA response, 10/16
Diesel Backup and Operational Generators	224 hrs	Machine operation, diesel, >=74.57 kW, high load factor {GLO} market for | Alloc	Assumed , used resources as guide, used 10 generators operating 22.5 hrs	NASA SL 39 A_B finalMultiuseEA.pdf, p. 70, https://www.faa.gov/about/office_org/headquar

		Rec, U	each during 14-day campaign	ters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf., 2-20
Personnel Drinking Water	429,813 kg	Tap water, at user/US-US-EI U	Average yearly and bi-monthly use at active launch complex	FOIA response, 10/16
Deluge Water	754,552 kg	Tap Water, at user/US-US-EI U	Used 200000 gallons	FOIA response, 10/16
Personnel Wastewater (35% of tap water)	150,435 kg	Wastewater treatment facility, class 1/US*/I US-EI U	Estimated from general experience	
Deluge Wastewater (20% of deluge water)	150,910 kg	Wastewater treatment facility, class 1/US*/I US-EI U	Estimated using the resource	https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf., 4-79-80
Diesel	36,851 kg	Diesel {ROW} market for | Alloc Rec, U	10,000 gal diesel stored at vertical launch area	https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf., p.4-78
Heavy fuel oil	681.4 kg	Heavy fuel oil {RoW} market for | Alloc Rec, U	200 gallons on site	https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf., p. 4-78, http://www.patrick.af.mil/Portals/14/documents/Enviromental%20Docu

				ments/Final%20Environmental%20Assessment%20Blue%20Origin%20Orbtal%20Launch%20Site%20CCAFS.pdf?ver=2017-03-27-090038-627, 327
Helium (2nd Stage or 1st Stage landing legs)	39.2 kg	Helium {GLO} market for | Alloc Rec, U	7750 ft3 stored on-site and used in launcher	https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf, p. 4-78
Hydrazine (2nd Stage or payload & stored on the pad)	13,635 kg	Hydrazine {GLO} market for | Alloc Rec, U	Combined hydrazine, UDMH, and MMH totals	https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf, p.4-78
Light fuel oil	318 kg	Light fuel oil {RoW} market for | Alloc Rec, U	100 gallons	Same as above
Nitrogen, liquid (use at control center)	14,609 kg	Nitrogen, liquid {RoW} | market for |Alloc Rec, U	3000 ft^3 stored at control center	Same as above
Nitrogen, liquid (stored at pad & payload support)	63,305 kg	Nitrogen, liquid {RoW} | market for |Alloc Rec, U	13000 ft^3 stored at pad and payload support	Same as above
Petrol, unleaded	1212 kg	Petrol, unleaded {RoW} | market for |Alloc Rec, U	450 gallons at site	Same as above
Isopropanol (cleaning at Pad)	74.5 kg	Isopropanol {GLO} market for | Alloc Rec, U	100 gallons at site	Same as above

The electricity, water and chemicals are all standard types of launch support needed for both launch operations of space vehicle and personnel.

Electricity: Electricity for typical launch operations (electricity, medium voltage mix in US) where local power plant supplies the daily estimated need for launch campaign was at a rate of 3000 kWh and the diesel generator (s) are used for a total of 224 hours during the launch campaign. The FOIA response provided 2016 monthly and annual amount used at the active launch facility. The amount of launches was estimated at 12 per year in 2016. The data was then divided by 12 to determine a representation of required energy needed per launch. Cost for electricity from the local power plant supplying the launch installations has been shown to cost $0.06 kWh (FOIA, 2016). Electricity acquired from the local power plant and the diesel generators are the only two energy sources evaluated in this study. However in Objective 3, green technology recommendations explored the use of solar to supplement the electricity instead of the diesel generators.

The purchased electricity is at an average of 3000 kWh per day with a total of 42,000 kWh per launch campaign. The 10 diesel generators were assumed to be in use for a total of 224 hours per launch campaign based on the SpaceX Environmental Assessment of the number of generators and the electricity requirement of 3000 kW.

Water: The water used during the launch campaign includes both tap water from a municipal water treatment plant (WTP) for personnel drinking water and miscellaneous use, and deluge water for sound suppression of the rocket launches. Some cost data on water usage at one launch facility was for every 1000 gallon (3785 kg) is $0.06 (FOIA, 2016), but this was cumulative for the entire launch facility. The amount of water was estimated using the data acquired from the FOIA response and averaged for the two-week period for both personnel usage (430,000 kg/launch campaign (14 days)) and the deluge water (754,552 kg) used per launch campaign from tap water. Transportation of large amounts of deluge water for the water tower at the launch facility is by single short-haul truck, diesel powered. Replenishment for this tower is assumed at the end of every launch campaign.

Personnel drinking water also includes any additional water for use around the launch facility during the launch campaign. The water amount per launch was derived from a FOIA response showing the total amount of water used per year at an active launch facility. Typical water uses are drinking, toilets, showering, cooking, pad wash-down and watering grounds. No individual breakdown of specific quantities could be derived from this data. Additional transportation is added for deluge water delivery to the launch facility.

For personnel water, 35% of the incoming water would be sent to the wastewater treatment plant (WWTP) based on engineering experience. For the deluge water, 50% is used in acoustic energy (noise) suppression and the 30% is reused for another launch and 20% is trucked to a WWTP. The estimated 20% was derived from engineering judgment and typical efficiencies found in settling basins and their ability to remove contaminants.

Chemicals: Several chemicals were selected as a model for the launch campaign representing one of the consumable inputs regardless of the type of rocket booster or propellant used. These chemicals were: **diesel (used for ground equipment not for the diesel generators)**[26], heavy fuel oil (used for hydrazine spills), light fuel oil; helium (used in 1st or 2nd Stage), hydrazine (stored at launch facility and used as 2nd Stage) but stored on the launch pad; liquid nitrogen (used for purging lines at launch pad), liquid nitrogen (used as 2nd Stage), petrol, unleaded and isopropanol (cleaning). Hydrazine total is represented as a combination of three hydrazine types: 1, 1 – dimethylhydrazine (UDMH), monomethylhydrazine (MMH) and hydrazine. Hydrazine is stored at the launch pad. The other hydrazine, UDMH and MMH, are being expended in 1st or 2nd stage are not used in process at the launch facility but in 2nd Stage (LEO or GTO) for maneuvering, etc. However, their emissions and raw material acquisition as applicable are accounted for at the launch facility in this study. Two liquid nitrogen amounts are for different purposes so these chemicals were considered as separate.

Chemical quantities are estimated based on NEPA documents or other references shown in Table 3-9. Nitrogen storage capacity was 13,000 ft^3 and 3000 ft^3 used at the launch facility or in the booster. Nitrogen mass was calculated using the ideal gas law at a storage pressure of 2200 psi at 75ºF. Some of the chemicals are stored at the launch facility until loaded onto the space vehicle as part of the

[26] Diesel listed in the chemicals consumable inventory is not used for the diesel generators. The diesel quantity for 75 kW generators operating at 224 hours would require approximately 1367 gallons (full). NEPA documents state that diesel is used for the diesel generators and other ground equipment with a total of approximately 11,000 gallons. The amount of diesel (10,000 gallons) is assumed to support the other ground equipment in this study.

2nd Stage. The chemicals not used at the launch facility for whatever reason may be considered hazardous wastes and must be disposed of as such. That said, the assumption is that 95% of these chemicals would be used either for the launch or in the 2nd Stage with 5% considered disposed of as hazardous waste for end-of-life phase.

3.1.2.3.3 Propellants SimaPro Data

The oxidizer is typically liquid oxygen (LOx) and the three liquid fuels are: liquid hydrogen (LH_2); liquefied natural gas (LNG); and kerosene (RP-1). The liquid propellants examined in this ELCA are shown in Table 3-9 through Table 3-11. These liquid propellants are used to launch payloads into the LEO and GTO and are selected based on the type of engine within the rocket booster. The propellants are captured as the following elements: 1st stage; 2nd stage supporting LEO and GTO payloads; and test firings.

The amounts of LOx and liquid fuel vary based on the mass launched in the lift-off and the type of orbit. For this study, the amount of propellant in the 2nd Stage is modeled as the same for both orbits (this propellant amount is the maximum available in the 2nd Stage). The 2nd Stage propellant needed to travel into LEO and GTO are not fully consumed at the Use and Maintenance Phase. However, these consumables will impact the other life cycle phases of raw materials, materials processing, and manufacturing and are included as part of the requirement for Per Launch functional unit.

The typical launch campaign may consist of the test firings, 1st Stage propellant, and 2nd Stage propellant for payloads to either LEO or GTO. So, the total combined amount of propellant for one test firing, 1st Stage and 2nd Stage will be modeled. In addition, the test firing will include additional transportation for the propellant. (As noted earlier, propellant for landing is included as an integral component of the reusable booster, 1st Stage).

The 1st stage propellant mass is found by using values from the current launchers using these propellants such as Falcon Heavy or Delta Heavy. The 2nd stage propellant sends a payload into either LEO or the GTO. Each launch is usually preceded by a test firing of the 1st Stage engines about 14 days prior and is assumed to expend a full complement of 1st Stage propellant. The reusable rocket is assumed to carry about 2% more propellant for the reentry burn and landing at the launch pad. This additional propellant was accounted for in the 1st Stage reusable rocket inputs in Table 3-5.

Table 3-9 Liquid Hydrogen and Liquid Oxygen Propellant SimaPro Data

Component	Mass Amount (kg)	SimaPro Material Category[27]
Liquid Oxygen – 1st Stage	174,857	Oxygen, liquid {RoW} | market for | Alloc Rec, U
Liquid Hydrogen – 1st Stage	29,500	Hydrogen, liquid {RoW} | market for | Alloc Rec, U
Liquid Oxygen – 2nd Stage	41,966	Oxygen, liquid {RoW} | market for | Alloc Rec, U
Liquid Hydrogen – 2nd Stage	7080	Hydrogen, liquid {RoW} | market for | Alloc Rec, U
Liquid Oxygen – Test Firings	174,857	Oxygen, liquid {RoW} | market for | Alloc Rec, U
Liquid Hydrogen – Test Firings	29,500	Hydrogen, liquid {RoW} | market for | Alloc Rec, U

Table 3-10 RP-1 and Liquid Oxygen Propellant SimaPro Data

Component	Mass Amount (kg)	SimaPro Material Category
Liquid Oxygen – 1st Stage	802,659	Oxygen, liquid {RoW} | market for | Alloc Rec, U
RP-1 (Kerosene) – 1st Stage	345,230	Kerosene {RoW} | market for | Alloc Rec, U
Liquid Oxygen – 2nd Stage	64,731	Oxygen, liquid {RoW} | market for | Alloc Rec, U
RP-1 (Kerosene) – 2nd Stage	27,255	Kerosene {RoW} | market for | Alloc Rec, U
Liquid Oxygen – Test Firings	802,658	Oxygen, liquid {RoW} | market for | Alloc Rec, U
RP-1 (Kerosene) – Test Firings	345,230	Kerosene {RoW} | market for | Alloc Rec, U

Table 3-11 LNG and LOx Propellant SimaPro Data

Component	Mass Amount (kg)	SimaPro Material Category
Liquid Oxygen (LOx) – 1st Stage	907,180	Oxygen, liquid {RoW} | market for | Alloc Rec, U
Liquefied Natural Gas (LNG) – 1st Stage	260,815	Natural gas liquids {GLO} | market for | Alloc Rec, U
Liquid Oxygen – 2nd Stage	217,724	Oxygen, liquid {RoW} | market for | Alloc Rec, U

[27] All propellant masses were determined using industry websites for the Delta IV Heavy, Falcon Heavy, and New Glenn liquid engines for the 1st Stage. For the 2nd Stage, 24% was assumed as propellant for one engine.

LNG – 2nd Stage	62,596	Natural gas liquids {GLO} | market for | Alloc Rec, U
Liquid Oxygen – Test Firings	907,180	Oxygen, liquid {RoW} | market for | Alloc Rec, U
LNG – Test Firings	260,815	Natural gas liquids {GLO} | market for | Alloc Rec, U

3.1.2.4 End-of-Life Phase Data and Assumptions

The end-of-life assumed for the five consumables to include two types of rocket boosters with the following:

1. Reusable rocket booster, 1st Stage only, will be used for 20 launches and after the 20th launch and landings, the rocket booster parts were assumed as 20% solid waste to landfill, 50% to reuse, and 30% to recycle. These waste streams will not be modeled in SimaPro for this study. These waste stream analyses are more complex and a detailed evaluation requires knowledge of site specific practices and conditions which was unavailable in the public domain. However, assumed mass amounts are shown below in Table 3-12.
2. Expendable rocket booster is consumed as 100% to be used for one launch and then disposed of through falling into the ocean. No additional reuse or recycle is considered from this rocket booster.
3. Electricity is considered consumed 100% at the launch facility and uses local power sources. Diesel-generator producing electricity is used for back-up and for certain support equipment and is consumed 100% based on the number of hours in operation.
4. Water used for: Personnel consumed 65% for drinking water, and other water uses around the launch facility, and 35% will be discharged to the municipal wastewater treatment plant (WWTP); Deluge water is used for acoustic energy suppression (sound suppression) of launch noise and will be consumed 50% in the launch, 30% is estimated to be reclaimed/recycled back into the process using settling ponds, and 20% discharged to the municipal WWTP. These estimated percentages for reclaimed and discharge to the WWTP are assumed based on experience with Air Force operations.

5. Chemicals at the launch pad will be consumed 95% in the use phase process and 5% will be disposed of as hazardous waste and managed through the Hazardous Materials Management Program (HMMP) applied by the CST activity-owner. The amount of hazardous materials not used in launch is estimated at 5% based on typical hazardous materials management practices with high efficiencies of use and not allowing material to expire as seen in Air Force operations. However, some materials might be spilled or have to be turned back due to limited shelf life. The hazardous waste would be permitted and then hauled to the approved hazardous waste facility. The liquid nitrogen and helium will be assumed as 100% consumed.
6. Propellant will be considered consumed 100% in the launch operation including pre-launch test firings. However realistically, the propellants might spill or off-gas at the launch facility and require additional handling. For this study, 100% is considered consumed in one launch.

These are all assumptions not based on any current known practice from protocols or elsewhere. Table 3-12 shows the quantitative amounts calculated from the percentages estimated mentioned above for each consumable.

For instance, diesel amount of 36851 kg x 0.05 = 1842 kg was considered hazardous waste based on the assumptions of 5% was not consumed but disposed of as hazardous waste. For personnel waste water was calculated as 0.35 x 429813 kg = 150,435 kg to WWTP. For reusable rocket booster, total mass for each of the elements was assumed to be 20% solid waste to landfill, 50% to reuse, and 30% to recycle. Calculations for 1st Stage engines were 0.20 x 12,690 kg (mass of 1st Stage) = 2538 kg to landfill; 0.5 x 12,690 = 6345 kg for reuse again for parts; and 0.30 x 12690 = 3807. The other calculations for the consumables used the assumed percentages above with total mass as the initial amount requiring some type of action.

Table 3-12 End-of-Life Processes for Consumables

Material	**Mass (kg) Total**	**Recycled Mass (kg)**	**Landfilled Mass (kg)**	**Reused/Hazardous Waste Mass (kg)**	**Treated (kg)**
Diesel	1842			1842	
Heavy Fuel Oil	34	X	X	34	X

Light Fuel Oil	15	X	X	15	X
Petrol, unleaded	61	x	X	61	X
Isopropanol	3.75	X	X	3.75	X
Wastewater-Personnel	429,813	X	X	X	429,813
Wastewater - Deluge	754,552	X	X	X	754,552
Reusable Rocket – 1st Stage (Engines)	12,690	3807	2538	6345	X
Reusable Rocket – 1st Stage (External Casing)	4489	1347	898	2244	X
Reusable Rocket – 1st Stage (Landing legs/grid fins)	2597	779	519	1298	X

3.1.2.5 Inventory Outputs

The following parameters will be outputs of the inventory analysis.

Energy consumption (renewable and non-renewable): The accounting for the energy consumption included the amount of electricity needed for launch operations in both mass (as part of each consumable as shown in Network figures) and energy calculations (Baumann, Tillman, 2004). However, electricity was also part of the other consumables during the other life cycle phases of raw materials acquisition, manufacturing, etc., and will be seen in the individual consumables. The transportation included will be from the manufacturing facilities for the chemicals, propellant, and expendable and reusable rocket boosters.

These types of transportation included diesel trucks, barge, tankers or gasoline cars and trucks. Water used in the water tower for deluge water will also be trucked in to the launch facility. Also, transportation to the refurbishment facility for the reusable rocket booster from the launch facility was included. This transportation energy was included as a separate energy accounting in most cases. However, where additional transportation was needed, then it is included as part of the consumable, such as added propellant transportation used for test firings.

Air Emissions (greenhouse gases and traditional (criteria) air emissions): Air emissions generated from the launch of one rocket with a payload to include power sources of electricity and on-site generators was accounted for both in traditional air pollutants and greenhouse gases. Air emissions were accounted for from transportation of the consumables to launch operations. All of the consumables had these air emissions such as carbon dioxide, nitrogen oxide and nitrogen dioxide, particulate matter, carbon monoxide, and sulfur dioxide. These emissions were assessed and included in the inventory analysis. Air emissions regulated under the Clean Air Act include: carbon monoxide (CO); lead (Pb); nitrogen dioxide (NO_2); ozone (O_3); particulate pollution ($PM_{2.5}$, PM_{10}); and sulfur dioxide (SO_2). These pollutants are called the "criteria" air pollutants. These six pollutants and the GHG gas emissions are the air emissions were focused on in the study as well as the hazardous air pollutants. However, 187 hazardous air pollutants (HAPs) or toxic air pollutants are considered for human health, such as benzene and methylene chloride. A complete listing of these HAPs can be found at: https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications. The criteria air pollutants were considered as the traditional air emissions for this study.

Emissions from the rocket itself and local air dispersion emissions **will not** be taken into account in this ELCA. Information on the operational performance of rocket boosters and design characteristics of the specific engines were not available. The products of combustion for a specific engine would be necessary to make an accurate model in SimaPro. In addition, no specific engine or launcher was modeled in this ELCA. Data derived from each launch and the sampling for those occupational and environmental health data would add addition greatly to understanding the full spectrum of environmental impacts from one launch and possibly the persistent and cumulative effect from multiple launches over shorter amount of time. Models have been used to help with these plume dispersions; however, data was not available to include in this study from the various organizations or industry. However, NASA at Wallops Island (Busquets, Miller, 2017) did share dispersion contaminants overall summaries and results for launches and launch-related mishaps. Data from previous Space Shuttle environmental analysis and other sampling done after launches (Bowden et al, 2014) provided limited information about dispersion contamination location, direction, types, and quantity of environmental impacts from the propellant combustion and engine blasts.

SimaPro results in the inventory analysis identified the chemicals emitted into the air throughout the life cycle phases of each of the consumables. These chemical inventory results also included water and soil contaminants from these consumables. However, a breakdown of each life cycle phase's release was not part of this study because SimaPro results do not separate these phases out. However, an overall output from the Use and Maintenance Phases inputs was unavailable.

Wastes (hazardous and solid): Hazardous wastes were generated from the chemicals and other liquid fuels after the launch has occurred and also from the stored hazardous materials on site. The stored hazardous materials may be disposed of as hazardous wastes if they reach a certain performance or product storage life. The solid wastes were generated from materials used at the launch facility such as rags, paper products, and plastics unless these have a specified recycling program. For the reusable rocket booster after the 20th life use, it was then accounted for as solid waste, possible recycle or reuse. These wastes were accounted for as part of the base-case where data were available. If no data was available from the data sources identified or interviews with key personnel supporting these launch facilities, then an estimate was generated based on other similar systems. As part of end-of-life, these wastes were distributed to a landfill or reuse and calculated for this disposal technique. The expendable rocket booster was assumed to land in the ocean and is not included in this accounting of hazardous wastes.

Water pollution: Deluge water was consumed 50% in the process of acoustic energy (noise) suppression while 30% was reclaimed or reused and 20% was sent to the wastewater treatment WWTP. The water used for personnel was accounted for and was used as part of the base-case of current operations. An estimated 35% of personnel water was considered going to the municipal WWTP based on engineering experience. Water use has been seen as having two uses-degradative and consumptive (Curran, 2012). This ELCA did not make a distinction but describe both as general water use. As part of the end-of-life for this study, the water pollution was treated at municipal WWTP. However, other treatment or reuse options might be available such as grey water for plants, lawn, etc. SimaPro will provide the damage areas associated with the amount of wastewater sent to a municipal WWTP. These results will be provided in Chapter 4.

The assumption was to use the local WWTP such Cocoa Beach WWTP for this study. This WWTP has a capacity of approximately 6 million gallons per day or 8.3 $x10^9$ liters per year so the SimaPro process used for this WWTP capacity was $1e^9$ liters. A Class 2[28] WWTP was chosen to treat the personnel wastewater and the deluge wastewater. For the personnel wastewater, 35% of total tap water used is treated at the WWTP is calculated as 150,435 liters per launch campaign. For the deluge water, 50% was used in noise sound suppression, 30% was reused back into the next launch and 20% was sent to the WWTP. So, deluge water contaminated sent back to WWTP is 150,910 liters per launch.

Noise pollution: The noise generated from the launch operations from the integration process (pre-launch), launch such as sonic booms, and post-launch activities was accounted for as data was available. These noise levels are shown in decibels and are compared to Occupational Safety and Health Administration (OSHA) standard for community health in a noise overview of one launch. Data taken from the various NEPA documents identifying either actual noise levels or estimated was used for this ELCA. Commercial noise models such as PAD and RNOISE and comparative analysis to other launchers were used to calculate the launch noise for recent NEPA documents (FAA, 2016). Contour maps are shown in various NEPA documents.

Noise data was located in several NEPA documents on three liquid-rocket booster and their launches with the equipment supporting the launch campaign. Sonic booms occur on the re-entry of the reusable rocket boosters similar to the Space Shuttle re-entry noise in the past. One of the ways used to mitigate noise levels at the launch pad is using the deluge water. Water is the main component of the sound suppression system because it helps protect the launch vehicle and its payload from damage caused by acoustical energy.[29] The deluge water is 50% consumed in suppressing this noise and acoustical energy and is not recovered.

---

[28] Class 2 WWTP consists of a primary system; biofiltration and a modified treatment pond, https://en.wikipedia.org/wiki/Wastewater_treatment#Wasterwater_treatment_plants, accessed 1/18.
[29] NASA, https://www.nasa.gov/sls/smat-acoustic-testing.html, accessed 3/18.

3.1.3 Impact Assessment

As discussed in Chapter 2, Figure 3-15 shows the sub-phases for conducting a LCIA. For this ELCA, all of the LCIA sub-phases will be included. The sub-phases are discussed in more detail below.

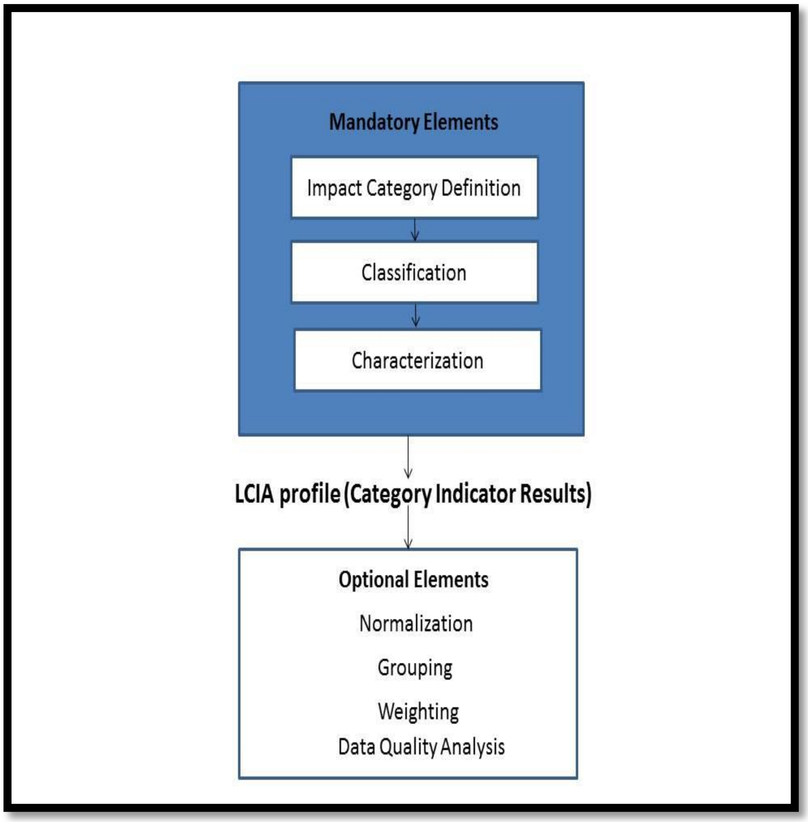


Figure 3-15 Life cycle impact assessment (LCIA) sub-phases (ISO 14040, 2006)

3.1.3.1 SimaPro Version 3.3 Impact Method and Categories

For the CST Activities ELCA, the SimaPro impact method used for evaluating the six consumables is the IMPact Assessment of Chemical Toxics 2002+ (IMPACT 2002+). Life Cycle Impact (LCI) results are grouped into midpoint categories and then allocated to end-point categories using equivalent units of reference such as CO_2 equivalent (eq). IMPACT 2002+ links 14 midpoint categories to four damage categories (Jolliet et al., 2003). The 14 midpoint categories and 4 damage (endpoint) categories are listed in Table 3-13:

The ability to evaluate the consumables by characterization (mid-point) and damage assessment (end-point) with four damage areas was valuable for this base-case study of CST activities in the United States. This impact method also allowed for weighting values to be changed based on stakeholders or other inputs. A U.S. Department, the DoD, has developed their sustainability life cycle assessment. Their sustainability guidance (DoD, 2016) also uses similar mid-points and end-points for their weapon systems sustainability with life cycle costs for decisions on current and future acquisition. A future study might be to use these DoD Scoring Factors in the Sustainability guidance on the CST activities as a comparison study**.** The DoD Environment, Safety and Health Network and Information Exchange (DENIX) website[30] provides the Sustainability guide with examples.

Table 3-13 IMPACT2002+Mid-Points and End-Points (Joliet et.al, 2003)

Midpoint Category	**Midpoint Reference Substance**	**Damage/Endpoint Category**
Human toxicity	kg equivalent (eq) chloroethylene into air	Human health
Respiratory effects	kg eq PM $_{2.5}$ into air	Human health
Ionizing radiation	Bq eq carbon-14 into air	Human health
Ozone layer depletion	kg eq CFC-11 into air	Human health
Photochemical oxidation [respiratory organics for human health]	kg eq ethylene into air	Human health/Ecosystem quality
Aquatic ecotoxicity	kg eq triethylene glycol into water	Ecosystem quality
Terrestrial ecotoxicity	kg eq triethylene glycol into water	Ecosystem quality
Aquatic acidification	kg eq SO_2 into air	Ecosystem quality
Aquatic eutrophication	kg eq PO_4^{3-}	
Terrestrial acidification/nitrification	kg eq SO_2 into air	Ecosystem quality
Land occupation	m^2 eq organic arable land-year	Ecosystem
Global warming	kg eq CO_2 into air	Climate change
Non-renewable energy	MJ Total primary non-renewable or kg eq crude oil (860 kg/m^3)	Resources
Mineral extraction	MJ additional energy or kg eq iron (in ore)	Resources

[30] DENIX website, https://denix.osd.mil/esohacq/home, accessed 4/16.

This study will also apply EPA's LCA Impact Method, TRACI for comparison or additional insight. The TRACI method (BARE, 2011) uses characterization impact categories of::

- global warming (kg CO_2 eq)
- depletion of ozone (kg CFC-11 eq)
- eutrophication (kg N eq)
- human health cancer effects (carcinogenic)
- acidification (kg SO_2 eq)
- tropospheric ozone (smog) formation (kg O_3 eq)
- fossil fuel depletion (MJ surplus)
- human health criteria-related effects (non-carcinogenic)
- and respiratory effects (kg $PM_{2.5}$ eq)

The characterization and normalization results applying TRACI for the base-case will be shown in Section 4.1.6 for comparison with the IMPACT2002+ results. The EPA Website has more information about the impact method, https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci.

Another Impact method used frequently is the ReCiPe (ReCiPe (World V1.12)) and it was applied to the CST Activities in United States processes from this study. A description taken from Pre' sustainability website, https://www.pre-sustainability.com/recipe, is provided below.

ReCiPe is the most recent and harmonized indicator approach available in life cycle impact assessment. The primary objective of the ReCiPe method is to transform the long list of life cycle inventory results, into a limited number of indicator scores. These indicator scores express the relative severity on an environmental impact category. In ReCiPe we determine indicators at two levels:

- Eighteen midpoint indicators
- Three endpoint indicators

Each method (midpoint, endpoint) contains factors according to the three cultural perspectives. These perspectives represent a set of choices on issues like time or expectations that proper management or future technology development can avoid future damages.

Individualist: short term, optimism that technology can avoid many problems in future.

Hierarchist: consensus model, as often encountered in scientific models, this is often considered to be the default model.

Egalitarian: long term based on precautionary principle thinking.

The results for the comparison of this impact method and the Base-Case IMPACT2002+ method is shown in Section 4.1.7.

3.1.3.2 Classification: The classification sub-phase is where the inventory data are assigned to categories according to the related known impact (Curran, 2012). For example, kg equivalent of ethylene might contribute to two impact categories such as human health potential and also to ecosystem quality potential. So, the 100% of the ethylene quantity would contribute to both impact categories. For the CST launch operations, classification will aid in showing the contributions of these propellants, chemicals, water, electricity, and transportation in the 15 mid-point characterization categories.

3.1.3.3 Characterization: Impact indicators are typically characterized using the following equation:

Impact indicator = (Inventory data) * (Characterization factor)

Indicator result for a specific category is the sum of the characterization that links the substance to the category (Curran, 2012). The formula shown above is considered the operation formula for characterization.

Characterization puts different quantities of chemicals on an equal scale to determine impacts. For example, methane has a global warming potential of 28 times that of carbon dioxide (CO_2) on a per mass basis (100-year time horizon), so is multiplied to a characterization factor of 28 to determine CO_2-equivalents.

SimaPro calculates characterization automatically using built-in characterization factors. For IMPACT2002+ the characterization mid-point units are:

- Carcinogens and Non-carcinogens - kg C_2H_3CL[31] eq
- Respiratory inorganics – kg $PM_{2.5}$ eq
- Ionizing radiation - Bq C-14 eq
- Ozone layer depletion – kg CFC-11 eq
- Respiratory organics – kg C_2H_4[32]
- Aquatic ecotoxicity and Terrestrial ecotoxicity – kg TEG[33] water and soil, respectively
- Terrestrial acid/nutrification and Aquatic acidification– kg SO_2 eq
- Land occupation – m^2org.arable[34]
- Aquatic eutrophication – kg PO_4 P-lim
- Global warming – kg CO_2 eq
- Non-renewable energy – MJ[35] primary
- Mineral extraction – MJ surplus

Impact categories of Aquatic acidification and Aquatic eutrophication are midpoint indicators only and not included in the endpoint damage areas (SimaPro, 2018).

3.1.3.4 Normalization: This step is an optional step within the ISO standard. The characterization results relate to the damage impact category, and cannot be directly compared, since they are presented in different units (e.g. CO_2-eq. for greenhouse gas emissions, SO_2-eq. for acid precipitation emissions) (Baumann and Tillman, 2004). The damage categories and their measured units for IMPACT2002+ impact method were: Human Health (DALY)[36]; Ecosystem quality (PDF[37]*m^2*yr); Climate change (kg CO_2 eq); and Resources (MJ primary). Also, the impact categories, their factors and specific unit were: Carcinogens and Non-carcinogens (2.8 E-6 DALY/kg C_2H_3Cl eq); Respiratory inorganics (7.0 E-4

[31] chloroethylene
[32] ethylene
[33] Triethylene glycol
[34] Organic arable land
[35] Mega joules
[36] Disability Adjusted Life Years
[37] Potentially Disappeared Fraction

DALY/kg PM $_{2.5}$ eq); Ionizing radiation (2.1 E-10 DALY/Bq C-14 eq); Ozone layer depletion (1.05 E-3 DALY/kg CFC-11 eq); and Respiratory organics (2.13 E-6 DALY/kg C_2H_4 eq).

Normalization calculates the magnitude of the category indicator results. It allows for a better relative magnitude and reference information for total impact between the categories (Curran, 2012). .The characterization value for each impact category is divided by a normal value, which typically is the average yearly environmental load in a country or continent divided by the number of inhabitants, e.g. per capita emissions (Pre' Sustainability, 2018). For example, the Human Health uses DALY to combine the DALY from carcinogens and other characterization categories. SimaPro automatically conducts the normalization step based on the impact method applied.

For IMPACT2002+ impact method, Normalization values are:

- Human health – 141
- Ecosystem quality – 7.3 E-5
- Climate change – 1.01 E-4
- Resources – 6.58 E-6

3.1.3.5 Grouping: The characterization results will be sorted to rank the impact categories in order of most environmental consequence. SimaPro results showed those categories based on the impact method. This result of grouping might be shown by local, regional, and national impacts for comparison and those indicators with high, medium and low priority impacts (Baumann and Tillman, 2004). So, this sub-phase may also highlight some areas of most importance in environmental burden such air emissions or water pollution. For the CST launch activities, sorting the characterization results into a grouping such as ozone layer depletion and global warming were captured in the SimaPro results. By evaluating these parameters in this manner, the environmental consequence from the launch operations can be better understood.

3.1.3.6 Weighting: Weighting is based on the impact method chosen for the LCA. IMPACT2002+ (Jolliet et al., 2003) uses a default weighting of "1" for each of the damage categories. Weighting begins with the normalization results for IMPACT2002+ impact method. Impacts per launch were generated using this standard weighting within the IMPACT2002+ impact method calculated using SimaPro.

Another approach for comparison to SimaPro weighting was using the Delphi Method drawing on the expertise of authoritative experts. The Delphi method may be conducted in several ways to include on-site forum or online forums using University developed tools (Scott, J.S., 2003) or QUALTRICS©[38]. For this study, the Delphi Method forum was comprised of authoritative experts as shown in Table 3-14. The Delphi Method is a qualitative method that can be applied for result comparison within the LCA.

For this LCA, a series of three surveys were developed to aid in evaluating the reusable versus expendable rocket boosters and the three liquid propellants. The study's Delphi Method was conducted in April 2017 using on-line tool, Qualtrics©, through UTA's license. A total of 18 participants partook in these surveys for five days on-line, answered independently and anonymously, using Qualtrics©. The methodology and the three surveys used are shown in Appendix A. Participants were selected based on their background and expertise as an environmental professional, system engineers, NEPA and LCA practitioners, DoD sustainability; PhD students in the space and LCA area; and academia involved in rocket-related studies. These participants' backgrounds and organizations are similar to those listed in Table 3-14 for the Delphi Method Forum. Overall, the use of the Delphi method provided a perspective from specific stakeholders or expertise on this ELCA.

Table 3-14 Forum for Delphi Method Authoritative Experts

Expert Type	Expertise Needed	Organizations
Environmental Engineers and Scientists	Pollution prevention, NEPA process, ESOH experience, Waste management	FAA, NASA, US Air Force, DoD, Granta

[38] QUALTRICS© software enables users to collect and analyze data online for different purposes; Qualtrics.com website.

Rocket Propulsion Engineers	Rocket design, Operations, maintenance, Expendable or reusable rocket boosters	Orbital ATK, US Air Force, Defense Contractors, NASA, DARPA
Systems Engineers	Rockets, Aircraft, Fuels	NASA, US Air Force, DoD, ESA, FAA
Green Technology Engineers or Technicians	Remediation, Electricity, Waste	US Air Force, NASA, National Labs, Green technology contractors, DOE
LCA Practitioners	LCA development for various organizations	Independent contractors, DoD, NASA, PhD students, ESA
Academia	Systems Engineering, Aerospace and Rocket, Environmental, Modeling	UTSA, New Mexico Institute of Mining and Technology, AF Institute of Technology

3.1.3.7 Data quality analysis: Data should be representative of the unit processes being evaluated for launch operations and the six consumables. Actual data was used when existing and obtainable. When actual data were unavailable, then generic or related data was used where appropriate. If no data were available, then this limitation was identified as a data gap. However, parametric data relevant to the unit processes of the consumables was used and stated as an estimated value. In some cases, data were limited due to the unknowns of the manufacturing and composition of the parts or the typical waste disposal processes or practices.

Monte Carlo analysis was performed on the SimaPro library databases used in this ELCA to determine the uncertainty of the calculated results. SimaPro has a Monte Carlo feature which performs a Monte Carlo analysis using the mean and variations cataloged for each material in the various library databases. For the SimaPro Monte Carlo analysis, a confidence interval of 95% was used and 2500 runs were conducted on the per Launch consumables product stage. This product stage included all six of the consumables together. Values entered into SimaPro manually were entered without distribution or variation so a Monte Carlo was not performed on this data. However, a sensitivity analysis was performed on those data inputs as described in Section 3.2.

3.1.4 Interpretation

The last sub-phase is interpretation to ensure that the results met the ELCA goals and scope. Other researchers familiar with LCA and space systems were asked to review and discuss the overall methods and results. The data and results were displayed in charts, graphs, diagrams and tables to illustrate the conclusions, recommendations and direct applications for CST activities in the launch operations (Use and Maintenance Phase). SimaPro results provided some of the charts and graphs related to the impact method chosen to assess the environmental consequences. Also, radar charts were used to provide a different perspective. These radar charts allow for intuitive pattern recognition within the consumables in both the characterization categories and damage areas more readily than the standard bar charts generated in SimaPro software.

3.2 Methodology Applied for Research Objective 2: Conduct a sensitivity analysis to determine range of environmental impacts.

The sensitivity analysis examined five parameters where uncertainty exists in the LCA for CST activities. These five sensitivity parameters are considered uncertain or might cause the greatest impact to the environment from the launch of one space vehicle. This analysis varied each of the sensitivity parameters one-at-a-time (OAT) compared to the base-case scenario. The sensitivity ranking (Hamby, 1994) will be determined by the amount of influence these parameters have on the base-case model. The sensitivity ranking from 1 to 5 with 1 as the highest was used to identify the sensitivity parameters influence on the ELCA base-case. The higher in the relative impacts to the characterization category or the damage assessment area then this sensitivity parameter was ranked higher. Some subjectivity existed based on judgment. So, this combined criterion was used in the evaluation to determine the ranking.

The sensitivity analysis provided insight into future data needs and recommendations of what is necessary to refine this ELCA. For example, for the consumables used at the launch complex, particularly the expendable and reusable rocket boosters had key data gaps because of the proprietary nature of these materials, quantities and manufacturing processes.

SimaPro version 8.2.3 was used for Monte Carlo analysis and scenario and sensitivity analysis. These analyses aided in identifying which characterization and damage assessment categories had the highest uncertainty of the calculated results based on the SimaPro library databases. The ELCA inputs to SimaPro did not have any variation in the data so no Monte Carlo analysis was performed on these data. However, sensitivity parameters were developed based on the base-case results to identify the parameter that posed the greatest impact.

3.2.1 Sensitivity Parameters

The sensitivity analysis included varying key parameters to determine a range of environmental impacts. The sensitivity analysis involved varying the following parameters:

1. **Reusable rocket booster use lives**– base-case is 20 uses; sensitivity analysis examined 15 and 25 uses with minimal repair and maintenance.
2. **Material composition** - engine component mass percentage was increased by 5% individually for combustion chamber, turbopump, nozzle, and miscellaneous housing and tubing, while also changing the other components a specified percentage based on the increase of 5 % and then each was compared to base-case. For instance, when the combustion chamber mass was increased by 5% then each of the other components were multiplied by 0.945 to hold the total mass constant. Material composition for engine parts were estimated based on textbooks and other images for liquid propulsion engines since exact design information were not available. Percentage weights were estimated based on these textbooks and images. Because of this uncertainty in the composition percentage, this parameter was chosen for sensitivity analysis.

3. **Electricity changes** – base-case is 3000 kWh/day and 224 hrs/launch; for the sensitivity analysis, diesel hours were changed to 120 hrs/launch and 400 hrs/launch.
4. **Test Firings** – changed from 100% of propellant used in 1st Stage to 75% and 50%.
5. **Chemicals** – amount of each chemical's contribution was cut in half from the base-case.

These parameters were determined based on the base-case analysis and overall potential influence to the environmental impacts shown in the characterization and the damage assessments.

3.2.2 Scenario Analysis

The scenario analysis varied two drivers of potential environmental impact – frequency of launches and reusable and expendable rocket boosters. Current launch rate is 21 per year in 2017 (FAA, 2018) for one space vehicle. This current launch rate is for CST to support the International Space Station (ISS) and launch other payload types into orbit. However, as the vision is to travel to Mars and even back to the Moon, these launches may increase. The increased frequency of launches, assumed in this study over the next 10 years, will produce added environmental burden in the upstream life cycle phases such as raw material acquisition and manufacturing.

Frequency of launches of space vehicles whether the LEO or GTO payloads was considered as a possible future scenario as the space industry continues to expand and become more efficient. The current rate of CST launches as recorded by FAA (FAA website, 2018) was 249 in August 2016 and 280 in February 2018. This frequency shows that 27 launches have occurred in 17 months with 23 of these launches in 2017 and 5 launches have occurred in 2018 (Feb 2018). This seems to show a current operational tempo of two launches per month which is consistent with the level of launch activity modeled in this base-case study.

For future launches over the next 10 years, a 10% increase per year will yield the following numbers of launches on the East and West Coast and Texas. This launch tempo does not include those launches from other spaceports such as Spaceport America. So, the following rate schedule, 10% increase; 15% increase; and 20% increase; per year from previous year is applied to identify those changes that might occur in the characterization and damage categories within the LCA. Table 3-15 gives the number of launches per year at the increased rates. Figure 3-16 provides a visual graph of these launch increases over the next ten years.

Table 3-15 Increase Launch Frequency Estimates from 2017-2026

Year	Number of Launches (10% Increase Per Year)	Number of Launches (15% Increase Per Year)	Number of Launches (20% Increase Per Year)
2017	23	23	23
2018	25	26	28
2019	28	30	33
2020	31	35	40
2021	34	40	48
2022	37	46	57
2023	41	53	69
2024	45	61	82
2025	49	70	99
2026	54	81	119

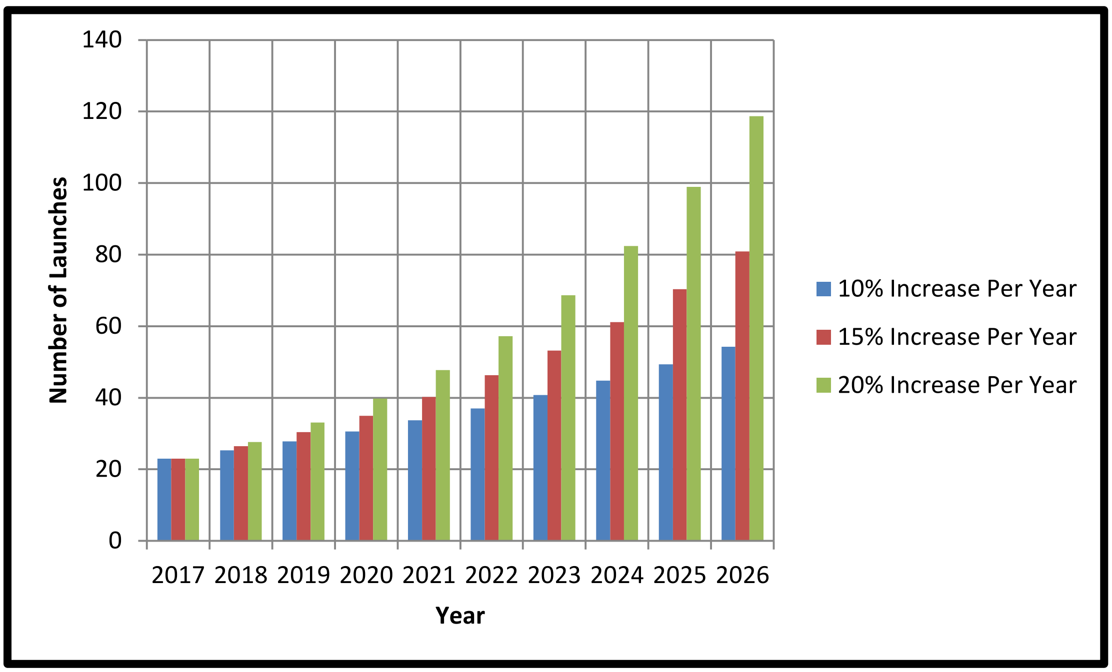


Figure 3-16 Increased Launches from 2017-2026 by 10, 15 and 20%

The other driver that might influence environmental impacts is the decision to use either a reusable versus the expendable rocket booster for the launch activity. Cost and time to manufacture parts and components may become a bigger factor in decision making for CST activities. These two drivers, frequency of launches and type of rocket booster, aided in the scenario analysis to identify those environmental impacts ranges from the launch of one space vehicle type used in increased launches. From evaluating the worst case scenario of more launches in less time and the use of the expendable rocket booster, this analysis identified those environmental impacts to aid in determining where alternative manufacturing or increased sampling might be necessary.

The sensitivity analysis and scenario analysis will identify a few of the parameters that may need further investigation so that the environmental burden is reduced and appropriately characterized in informing eco-design and material selections and alternatives. These sensitivity analyses will aid in developing a model to predict space transportation environmental profiles for Launch (STEP-L).

3.3 Methodology Applied for Research Objective 3: Conduct “green technology” LCA scenarios to identify strategies for reducing environmental impacts.

Plausible green technology scenarios were generated to revise the base-case inventory analysis and impact assessment. The environmental impact of the green technology scenarios was compared with base case using screening LCAs. Throughout the literature, green technology refers typically to alternative propellant or fuels such as hydrazine. NASA is currently researching replacements for hydrazine through the Green Propellant Infusion Mission (GPIM). So, even though hydrazine was a major contributor in the chemicals consumable, it was not evaluated because of current research such as GPIM. This ELCA considered other alternative fuels such as methane and identified possible green technologies for use at the launch phase or the end of life phase.

Green technology has been seen as one way to improve the environmental consequences from a product or a system particularly if used at high consumption rates. However, if the consumption is not at a high rate but the implications of changing to a greener technology would improve the environmental outcomes, then these green technologies should be considered. For this study, the ELCA results identified the materials and consumables that generated the greatest environmental impact. Human Health and Resources were seen most influenced from the propellant, electricity, and the engine materials. So for this study in recommendations on green technology, the focus will be on these materials or consumables.

- Replace diesel with solar power and electricity or use more electricity
- Replace titanium process used for grid fins
- Replace metals with additive manufacturing for space vehicle parts
- Replace kerosene with methane

3.3.1 Green Technology Recommendation: Replace Diesel with More Electricity or Solar Power

Diesel was shown in the sensitivity analysis to produce the most environmental impact compared with electricity, medium voltage. Two scenarios were examined: electricity only as power source and solar power substituted as a diesel replacement.

Scenario 1: No Diesel. Electricity from a power plant was the only source and was increased from 3000 kWh per day to 3229 kWh per day.

Scenario 2: No Diesel with Solar Power Substitution: Electricity will remain at 3000 kWh per day (42,000 kWh total for launch campaign) with the added solar, photovoltaic energy of 229 kWh per day (3200 kWh total for launch campaign).

3.3.2 Process Change Recommendation: Use Armstrong Process Titanium Powder for Titanium instead of Kroll Process

One use for titanium is as the material used for the SpaceX grid fins on the reusable rocket booster. These grid fins once were made out of aluminum but caught fire upon re-entry so ”titanium made from a single piece cast and cut” is being used now tweeted by Elon Musk (Musk, 2017). The Armstrong Process® (Araci, Mangabhai, et al., 2015) uses titanium tetrachloride with liquid sodium to yield titanium and sodium chloride (NaCl) as shown in the chemical formula below:

$$TiCl_4\,(g) + 4Na(l) \rightarrow Ti(s) + 4NaCl(s)$$

The conventional way to manufacture titanium is the Kroll process. For this comparison of the base-case applying the Kroll process for the titanium in the grid fins, the Armstrong process (proprietary) was built in SimaPro, based on best available data, to determine if the use of the titanium powder to make near net shape of the part versus having to use a single piece cast and milled. The titanium amount for finished grid fins in the base-case is 65 kg, so this amount is used in the comparison for these two processes (although production of the grid fins likely requires around 325 kg of Kroll titanium since most of the titanium is milled away to produce the final part). A screening LCA was developed using the below inputs for the Armstrong process shown in Figure 4-61:

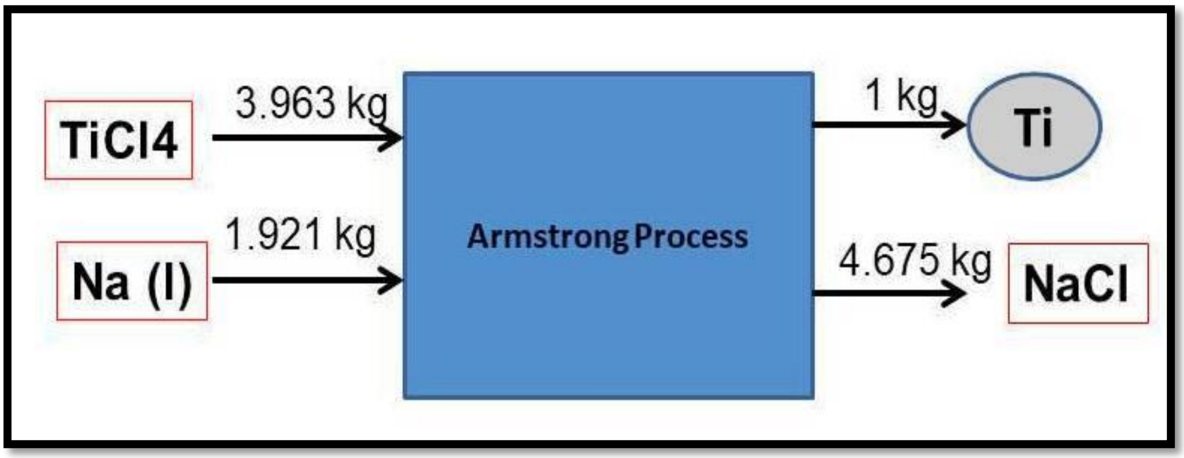


Figure 3-17 Notional Armstrong Process for Titanium Powder

In addition, aluminum (0.06 kg), added as an alloy metal, deionized water, assumed 10 kg needed for every 1 kg of titanium, to wash the NaCl for the next stage of the process prior to putting in the cast, and electricity of 3.23 kWh/kg (DOE, 2016) was added. This notional process is the best available representation of the Armstrong® process using the libraries available in SimaPro.

3.3.3 Material Change Recommendation: Additive Manufacturing for Parts

Reduced material weights, material reductions, and manufacturing timelines are some of the reasons this alternative to traditional manufacturing is being considered. This study only provides a discussion about this material changes performed using 3-D additive manufacturing since these manufacturing processes do not currently exist in SimaPro Software.

3.3.4 Propellant Change from LOx/RP-1 to LOx/CH_4 (Methane)

The use of various liquid propellants to achieve the goals set to travel to Mars has put more concentrated effort on which propellant could be used and manufactured in the Mars space environment such as using the Sabatier process (Meier et al., 2017). A comparison between RP-1 and CH_4 fuel has been studied (Burkhardt , Sippel, et al., 2002) for launchers and is currently in testing with launchers found in news reports about the SpaceX Raptor engine (Foust, 2016). The amount of LOx/CH_4 propellant used for comparison was calculated with the Tsiolkovsky rocket equation to be equivalent to rocket booster performance with LOx/RP-1 propellant. The comparison assumed the delta v (exhaust velocity) of the CH_4 rocket was the same as the RP-1 and then solved for the mass of the CH_4 propellant. The mixture with LOx and CH_4 is 3.8 to 1. So, the LOx amount used for this analysis was 853279 kg and CH_4 amount was 224,547 kg (342,297 m^3). For 2^{nd} Stage, LOx amount used is 204,786 kg and CH4 amount used was 53,891 kg (82151 m3). The SimaPro category input was the same for the other LOx. Methane SimaPro category input used was Methane, 96% by volume {GLO} market for/Alloc Rec, U.

3.3.5 Notional Green Technology Launch Campaign

The notional green technology launch campaign is generated to enhance or minimize the environmental impacts by applying and inserting those green technologies from this study. This framework can be applied for any similar operations as a means to quickly determine if the green technologies will provide environmental benefit. From the four green technologies, two of the launch-related technologies were inserted using one of the operational scenarios if the technology will enhance or improve the environmental impact. This notional green technology launch campaign was compared with the base-case operational scenario to determine the environmental enhancement or benefit from its insertion into the launch campaign.

Overall recommendations of possible green technologies and their application at the launch facility was identified in this ELCA. These recommendations may be used to provide eco-design inputs.

3.4 Methodology Applied for Research Objective 4. Operationalizing the LCA and the STEP-L Dashboard Development.

The framework developed to operationalize the ELCA for CST activities applied the base-case results and the sensitivity analysis. This framework can be transferable and applied to similar non-commercial or government activities space vehicles such as NASA Space Launch System (SLS). The

STEP-Ls were developed to represent an operational model for the launch activities. These operational scenarios used the consumables from this study to create the interactive Excel Dashboard.

The sensitivity analysis of the consumables using the SimaPro results aided in determining the kg per impact level from each of the consumables and represented in a damage assessment for operational scenarios. These operational scenarios are shown as either a reusable or expendable rocket booster and one of the three liquid propellants with the other consumables of water, electricity and chemicals. These scenarios were used as the basis for the STEP-L Dashboard using Excel. Appendix B provides the step-by-step procedures for the development of the STEP-L Dashboard. The dashboard is designed to determine the environmental impact when the quantities of those studied consumables are changed. Development of the STEP-L Dashboard assumes a linear relationship in SimaPro between the change in quantity of a consumable and the effect on each of the damage areas, and the contribution to the damage assessment areas from each consumable is independent from the other consumables. From determining the slopes for the STEP-L Dashboard, the chemicals and propellants with the greatest sensitivity per kg were discovered to be hydrazine, helium, and LOx/LH_2. Although helium has a higher sensitivity, helium was not present in large quantities so did not affect the base-case damage areas.

These scenarios can be tailored for specific launchers and consumables to support these launchers. For instance, data for the SLS might be used for generating a specific launch scenario with different chemicals. The chemicals and their mass amounts (kg) could be added in the SimaPro model and then a damage assessment (points or kilopoints) is generated. Since SimaPro results calculated using IMPACT2002+ impact method has shown a linear relationship between mass and damage assessment values, then a slope can be generated for each of the damage areas. This new information on each of the damage areas associated with these new chemicals can be added to Dashboard.

This STEP-L Dashboard can be used to generate “what-if” environmental scenarios using operational decisions based on amounts and types of consumables used during the launch activity or the Use Phase. By applying these “what-if” scenarios, minor operational changes might generate a significant environmental reduction not only for the launch activities (use and maintenance phases) but also in the other life cycle phases of these activities such as design or manufacturing or end of life (disposal). The STEP-Ls can aid in record-keeping so annual analysis can be accomplished on the overall environmental impacts from the launch operations as a whole.

This STEP-L Dashboard and its results related to the operational scenarios may also be useful to the NEPA authors and the compliance personnel while also informing the systems engineers about the possible design or operational changes that can be made without impeding or compromising the launch mission.

Chapter 4

RESULTS AND ANALYSIS

> "The rockets light! The shuttle leaps off the launch pad in a cloud of steam and a trail of fire." Sally Ride.

4.1 Results for Objective 1: ELCA Base Case Analysis for CST Activities

4.1.1 Inventory Analysis for CST Activities in the United States Base-Case

The inventory analysis describes the most relevant and major contributors for the functional unit of **per launch** focused on the six consumables of: **reusable rocket boosters; expendable rocket boosters; chemicals; electricity; water; and liquid propellants**. The following sections provide those inventory analysis results using the IMPACT2002+ method. In each of the inventories for the consumables per launch, more than 300 chemicals contribute to emissions in the air, soil and water and the raw materials. The following inventories include the top 10-15 highest mass contributors in the air, soil and water to include the radiation contribution in the air and water. These inventories provide a snapshot of total environmental emissions which occur in the raw acquisition, materials processing, manufacturing and transportation life cycle phases.

The greenhouse gases (GHG) include: carbon dioxide (CO_2); methane (CH_4); nitrous oxide; fluorinated gases (HFCs, PFCs, NF_3 and SF_6). Traditional air pollutants (TAP) include: carbon monoxide (CO); lead; nitrogen dioxide (NO_2); ozone (O_3); particulates ($PM_{2.5}$, PM_{10}); and sulfur dioxide (SO_2). These are specifically identified if within the top 10-15 chemicals with the highest mass.

4.1.1.1 Reusable Rocket Booster Inventory Analysis Per Launch

The LCA inventory for air, soil and water are shown in Tables 4-1 through 4-3 and the network showing damage assessment is shown in Figure 4-1. The network diagram shows the component modules with the higher contributors with thicker arrows. Electricity and petroleum in processes for the metal composite material (MCM), and the LOx, and RP-1 used for landing inputs are shown as the higher contributors to the characterization categories (mid-point) and damage areas (endpoints)

Table 4-1 Reusable Rocket Booster Air Pollutants

Substance	Media	Unit	Total	Reusable Rocket - 1st Stage	Reusable Rocket- 2nd Stage	Reusable Rockets- Fairing area	GHG or Criteria Air Pollutants (CAP)
Nitrogen oxides	Air	kg	3.66E+02	5.78E+01	1.45E+01	2.94E+02	CAP
Methane	Air	kg	2.43E+02	3.96E-01	6.62E-02	2.42E+02	GHG
Methane, fossil	Air	kg	1.93E+02	8.79E+01	1.45E+01	9.09E+01	GHG
Carbon monoxide, fossil	Air	kg	1.78E+02	5.40E+01	3.58E+01	8.88E+01	CAP
Carbon dioxide, land transformation	Air	kg	9.68E+01	5.53E+01	2.67E+01	1.48E+01	GHG
Particulates, unspecified	Air	kg	5.46E+01	3.10E-02	2.30E-02	5.46E+01	
Particulates, < 2.5 um	Air	kg	4.80E+01	3.47E+01	7.01E+00	6.31E+00	CAP
Particulates, > 10 um	Air	kg	3.93E+01	2.64E+01	6.84E+00	6.03E+00	
Carbon dioxide	Air	kg	3.87E+01	3.84E+01	1.08E-01	1.84E-01	GHG
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	3.29E+01	1.44E+01	3.46E+00	1.51E+01	
Particulates, > 2.5 um, and < 10um	Air	kg	2.49E+01	1.02E+01	4.13E+00	1.06E+01	CAP
Hydrogen chloride	Air	kg	2.32E+01	2.69E+00	5.38E-01	2.00E+01	
Sulfur monoxide	Air	kg	1.84E+01	0.00E+00	0.00E+00	1.84E+01	
Radon-222	Air	kBq	1.73E+06	1.43E+06	1.68E+05	1.34E+05	

Table 4-2 Reusable Rocket Booster Soil Pollutants

Substance	Media	Unit	Total	Reusable Rocket - 1st Stage	Reusable Rocket-2nd Stage	Reusable Rockets-Fairing area
Oils, unspecified	Soil	kg	3.13E+01	2.98E+01	7.77E-01	6.52E-01
Bark	Soil	kg	4.97E+00	0.00E+00	0.00E+00	4.97E+00
Calcium	Soil	kg	2.21E+00	1.23E+00	8.63E-02	8.87E-01

Chloride	Soil	kg	1.11E+00	8.93E-01	1.26E-01	8.85E-02
Iron	Soil	kg	1.02E+00	7.12E-01	1.82E-01	1.28E-01
Carbon	Soil	g	8.30E+02	7.54E+02	4.56E+01	3.08E+01
Sodium	Soil	g	6.47E+02	5.16E+02	8.10E+01	5.08E+01
Aluminum	Soil	g	2.76E+02	2.55E+02	1.17E+01	9.17E+00
Magnesium	Soil	g	2.42E+02	2.20E+02	1.23E+01	9.66E+00
Potassium	Soil	g	1.63E+02	1.39E+02	1.35E+01	9.95E+00
Sulfur	Soil	g	1.61E+02	1.50E+02	6.45E+00	4.96E+00
Silicon	Soil	g	1.42E+02	1.12E+02	1.78E+01	1.23E+01

Table 4-3 Reusable Rocket Booster Water Pollutants

Substance	Media	Unit	Total	Reusable Rocket - 1st Stage	Reusable Rocket-2nd Stage	Reusable Rockets-Fairing
Sodium	Water	kg	9.40E+02	2.63E+02	3.89E+01	6.38E+02
Calcium	Water	kg	5.96E+02	2.71E+02	1.12E+02	2.13E+02
Silicon	Water	kg	5.37E+02	2.96E+02	1.81E+02	5.99E+01
Magnesium	Water	kg	2.51E+02	1.37E+02	6.07E+01	5.31E+01
Process effluent	Water	kg	2.16E+02	0.00E+00	0.00E+00	2.16E+02
COD, Chemical Oxygen Demand	Water	kg	2.09E+02	1.22E+02	2.57E+01	6.14E+01
Potassium	Water	kg	1.34E+02	8.14E+01	3.50E+01	1.74E+01
BOD5, Biological Oxygen Demand	Water	kg	1.33E+02	9.86E+01	9.96E+00	2.40E+01
Iron	Water	kg	8.51E+01	4.11E+01	2.21E+01	2.19E+01
TOC, Total Organic Carbon	Water	kg	6.76E+01	4.00E+01	9.86E+00	1.77E+01
DOC, Dissolved Organic Carbon	Water	kg	6.74E+01	3.99E+01	9.86E+00	1.77E+01
Phosphate	Water	kg	6.14E+01	3.94E+01	1.46E+01	7.37E+00

Lithium	Water	kg	4.28E+01	1.54E+00	1.85E-01	4.11E+01
Hydrogen-3, Tritium	Water	kBq	5.54E+04	4.50E+04	5.71E+03	4.66E+03

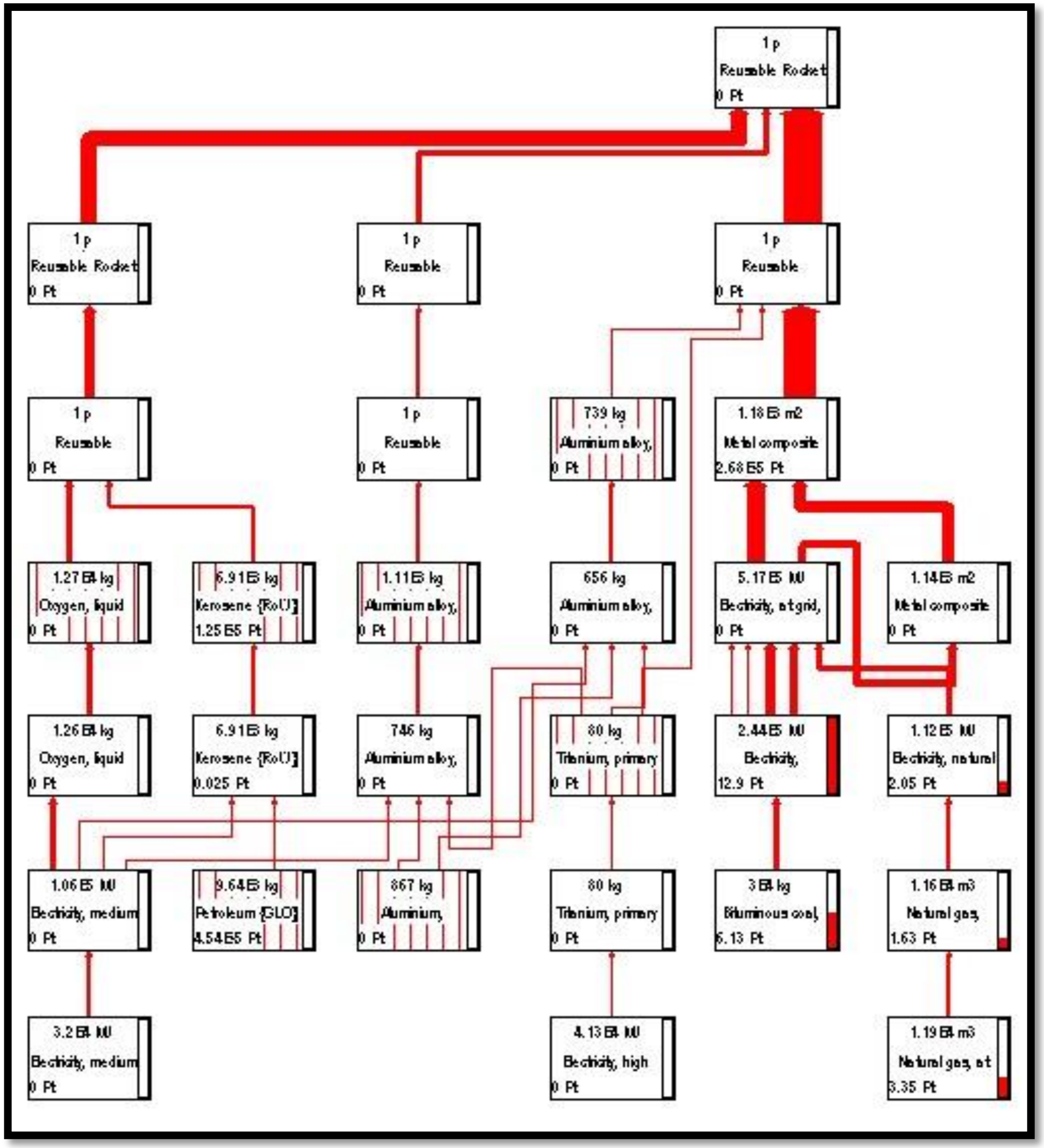


Figure 4-1 Reusable Rocket Network, Single Score, 5% cutoff, SimaPro Version 8.2.3 software

4.1.1.2 Expendable Rocket Booster Inventory Analysis Per Launch

The expendable rocket booster has a configuration similar to the reusable rocket booster with the exceptions of no grid fins, landing legs or additional propellant. These differences change the mass of the expendable 1st Stage to 25,600 kg, as shown in Figure 3-14. However, the key difference is these rocket boosters are one-time use and the reusable rocket booster, 1st Stage, is used 20 times. Tables 4-4 through 4-6 show the inventory results for air, soil and water emissions. Figure 4-2 shows the Network, Damage Assessment, Single Score, at 5% cutoff.

The air emission results for expendable rocket booster have the same large contributors such as nitrogen oxides, methane, particulates, as the reusable booster, however, not in the same order in their inventory. The highest for both boosters was the nitrogen oxides but the expendable rocket booster was over twice the amount for the reusable rocket booster. For methane, they were about the same. Overall, the expendable rocket booster released higher amounts in the various substances for air, as expected. For the soil emission, both had the same substances in the top 10, with the expendable having slightly greater amounts in calcium, chloride, and aluminum. Overall, the expendable rocket had higher substance amounts released in the soil, as expected. For the water emissions, the reusable rocket showed sodium and calcium as the highest substance contributors and the expendable rocket showed higher chemical oxygen demand (COD) and iron.as highest substance contributors. This result is unexpected but given there is more of the 1st Stage engines being manufactured, release of waste water during that process might create the higher COD and iron.

The network assessment was shown at the 5% cutoff because the processes with a relatively low contribution such as the 2nd Stage could be omitted for this part of the analysis. The focus was on those processes like the 1st Stage and the fairing which contained materials and processes that greatly contributed to the impacts. The thicker lines identify the 1st Stage engines and the fairing MCM as the greatest contributors.

Table 4-4 Expendable Rocket Booster Air Emission Results

Substance	Unit	Total	Expendable Rocket - 1st Stage	Expendable Rocket - 2nd Stage	Expendable Rockets - Fairing area	GHG or CAP
Nitrogen oxides	kg	8.24E+02	4.87E+02	3.25E+01	3.05E+02	CAP
Methane, fossil	kg	6.21E+02	4.84E+02	3.29E+01	1.05E+02	GHG
Particulates, < 2.5 um	kg	2.65E+02	2.37E+02	1.51E+01	1.29E+01	CAP
Methane	kg	2.44E+02	1.79E+00	6.62E-02	2.42E+02	GHG
Particulates, > 10 um	kg	2.32E+02	2.06E+02	1.38E+01	1.28E+01	CAP
Particulates, > 2.5 um, and < 10um	kg	1.22E+02	1.04E+02	5.99E+00	1.23E+01	CAP
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	8.93E+01	6.99E+01	3.83E+00	1.56E+01	
Particulates, unspecified	kg	5.52E+01	6.20E-01	2.30E-02	5.45E+01	
Aluminum	kg	5.33E+01	4.99E+01	2.88E+00	5.14E-01	
Hydrogen chloride	kg	4.43E+01	2.20E+01	1.54E+00	2.07E+01	
Carbon monoxide, biogenic	kg	2.95E+01	2.70E+01	1.94E+00	5.63E-01	CAP
Hydrogen fluoride	kg	2.75E+01	2.19E+01	1.88E+00	3.76E+00	
Sulfur monoxide	kg	2.53E+01	6.60E+00	2.44E-01	1.84E+01	
Water	kg	2.48E+01	3.00E-02	1.11E-03	2.48E+01	
Radon-222	Bq	8.45E+06	7.41E+06	5.53E+05	4.85E+05	

Table 4-5 Expendable Rocket Booster Soil Emission Results

Substance	Media	Unit	Total	Expendable Rocket - 1st Stage	Expendable Rocket - 2nd Stage	Expendable Rockets - Fairing
Oils, unspecified	Soil	kg	2.57E+01	2.26E+01	1.55E+00	1.53E+00
Bark	Soil	kg	4.97E+00	0.00E+00	0.00E+00	4.97E+00
Calcium	Soil	kg	2.41E+00	2.17E+00	1.34E-01	1.16E-01
Iron	Soil	kg	1.85E+00	1.61E+00	1.05E-01	1.27E-01
Chloride	Soil	kg	1.01E+00	8.89E-01	5.94E-02	5.79E-02
Carbon	Soil	g	9.30E+02	8.20E+02	5.58E+01	5.40E+01
Sodium	Soil	g	5.51E+02	4.85E+02	3.30E+01	3.34E+01
Silicon	Soil	g	4.30E+02	3.89E+02	2.24E+01	1.84E+01
Aluminum	Soil	g	3.70E+02	3.29E+02	2.15E+01	1.96E+01
Magnesium	Soil	g	3.63E+02	3.25E+02	2.06E+01	1.83E+01
Potassium	Soil	g	3.53E+02	3.18E+02	1.90E+01	1.60E+01

Table 4-6 Expendable Rocket Booster Water Emission Results

Substance	Media	Unit	Total	Expendable Rocket - 1st Stage	Expendable Rocket - 2nd Stage	Expendable Rockets - Fairing
COD, Chemical Oxygen Demand	Water	kg	8.74E+02	7.60E+02	3.92E+01	7.45E+01
Iron	Water	kg	7.86E+02	7.24E+02	4.55E+01	1.70E+01
Aluminum	Water	kg	5.91E+02	5.29E+02	3.95E+01	2.27E+01
Phosphate	Water	kg	5.53E+02	5.06E+02	3.33E+01	1.35E+01
BOD5, Biological Oxygen Demand	Water	kg	3.46E+02	3.00E+02	1.63E+01	3.02E+01
TOC, Total Organic Carbon	Water	kg	3.37E+02	2.99E+02	1.53E+01	2.28E+01
DOC, Dissolved Organic Carbon	Water	kg	3.37E+02	2.99E+02	1.53E+01	2.28E+01
Manganese	Water	kg	2.28E+02	2.11E+02	1.34E+01	3.59E+00
Titanium	Water	kg	1.86E+02	1.66E+02	1.17E+01	7.89E+00
Fluoride	Water	kg	1.52E+02	1.39E+02	9.21E+00	3.78E+00

Nitrate	Water	kg	1.23E+02	1.11E+02	7.76E+00	4.53E+00
Zinc	Water	kg	9.47E+01	8.83E+01	5.59E+00	7.84E-01
Hydrogen-3, Tritium	Water	kBq	2.65E+05	2.33E+05	1.76E+04	1.46E+04

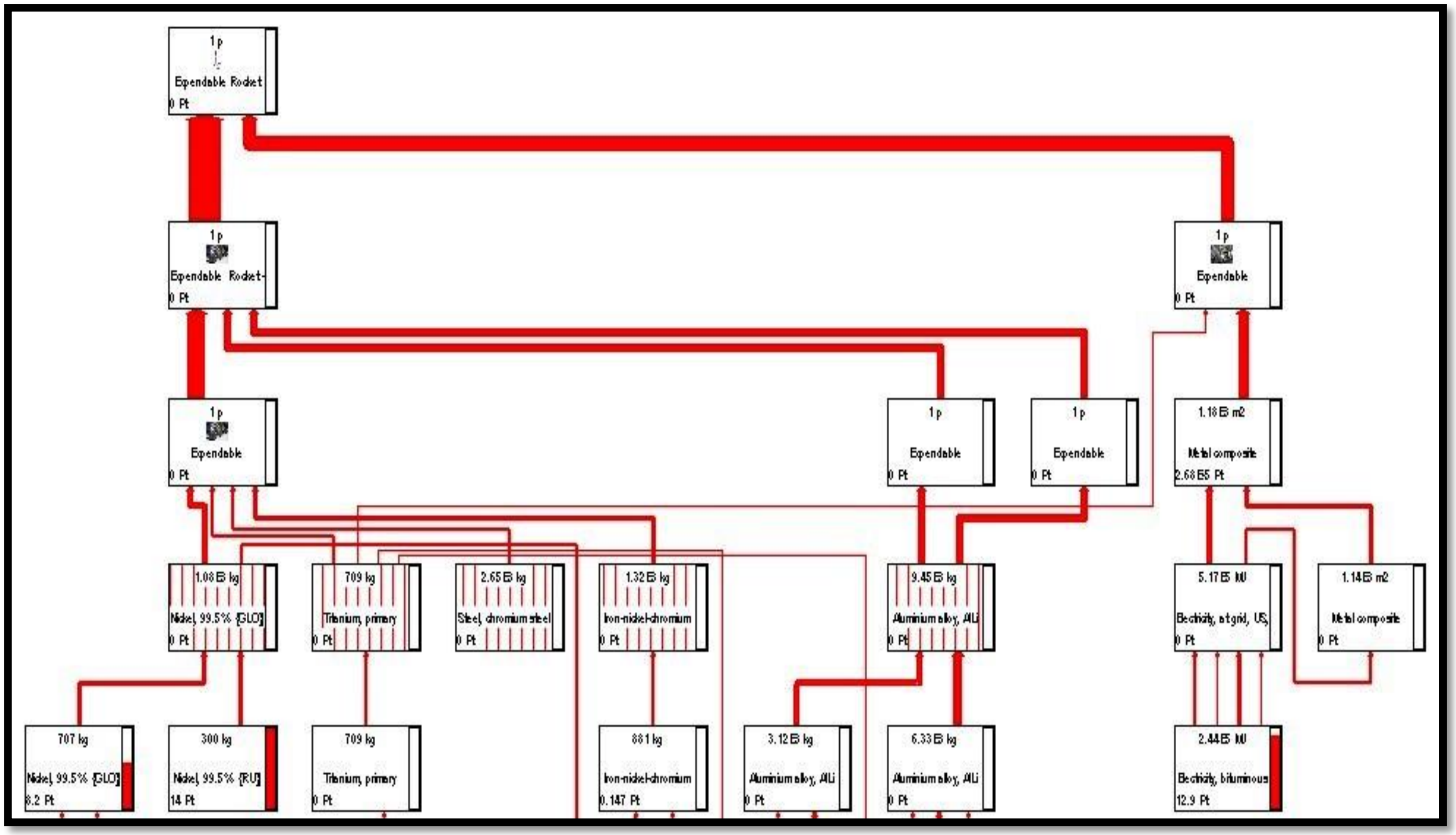


Figure 4-2 Expendable Rocket Booster Network, Single Score, at 5% Cutoff

4.1.1.3 Chemicals (Generic) Inventory Analysis Per Launch

The eight chemicals used to represent the consumable called Chemicals (generic) used for a launch operations include: diesel, heavy fuel oil (used for hydrazine spills), helium (used in 1st stage), hydrazine (used in 2nd stage and stored on the launch pad); light fuel oil, liquid nitrogen (used for 2nd stage, control center, and small amount used for cleaning lines when fueling), unleaded petrol (gasoline), and isopropanol used for cleaning equipment, etc. Tables 4-7 through 4-9 show the inventories for air, soil and water, respectively. A Network diagram for single score is also shown in Figure 4-3. This Network diagram shows the largest contribution of the chemicals typically used during a launch operation.

The air emissions from each of the chemicals revealed the greatest substance contributors were methane from fossil fuel, nitrogen oxides, and carbon dioxide from land transformation. These results are expected based on the energy needed to manufacturing these chemicals such as liquid nitrogen. The soil emissions inventory showed top substance contributors were oil, unspecified, calcium and iron. These types of substances are expected and most likely from manufacturing and the releases that might occur at this life cycle phase. The water emissions are expected with suspended solids and potassium, COD and biological oxygen demand as the greatest substance contributors for these chemicals. Again, most of these emissions most likely occur in the manufacturing.

The network damage assessment indicated diesel, hydrazine, and liquid nitrogen were the greatest contributors. The energy from petroleum and electricity are major influencers for the manufacturing of these chemicals. Also, ammonia, sodium, and hydrochloric acid used in the production of hydrazine are major contributors as well.

Table 4-7 Chemicals (Generic) Air Emission Results Per Launch

Substance	Total (kg)	Diesel {RoW}| market for | Alloc Rec, U	Heavy fuel oil {RoW}| market for | Alloc Rec, U	Helium {GLO}| market for | Alloc Rec, U	Hydrazine {GLO}| market for | Alloc Rec, U	Light fuel oil {RoW}| market for | Alloc Rec, U	Nitrogen, liquid {RoW}| market for | Alloc Rec, U	Nitrogen, liquid {RoW}| market for | Alloc Rec, U	Petrol, unleaded {RoW}| market for | Alloc Rec, U	Isopropanol {GLO}| market for | Alloc Rec, U	GHG or CAP
Methane, fossil	9.30E+02	7.66E+01	1.40E+00	2.82E+00	3.37E+02	6.54E-01	9.54E+01	4.13E+02	2.87E+00	7.67E-01	GHG
Nitrogen oxides	6.47E+02	6.64E+01	1.16E+00	5.55E-01	2.56E+02	5.66E-01	6.00E+01	2.60E+02	2.59E+00	2.27E-01	GHG
Carbon dioxide, land transformation	5.17E+02	8.92E+00	1.70E-01	3.55E-01	1.65E+02	7.27E-02	6.41E+01	2.78E+02	3.75E-01	3.58E-02	GHG
Particulates, < 2.5 um	4.27E+02	1.10E+01	1.97E-01	3.10E-01	1.37E+02	9.20E-02	5.20E+01	2.25E+02	4.75E-01	3.62E-02	CAP
Particulates, > 10 um	3.13E+02	7.98E+00	1.47E-01	2.39E-01	1.06E+02	6.62E-02	3.71E+01	1.61E+02	3.27E-01	3.72E-02	
Carbon monoxide, fossil	1.89E+02	3.37E+01	5.78E-01	3.71E-01	1.01E+02	2.73E-01	9.74E+00	4.22E+01	1.24E+00	1.66E-01	CAP
NMVOC, non-methane volatile organic compounds, unspecified origin	9.56E+01	4.01E+01	7.24E-01	4.63E-01	3.44E+01	3.44E-01	3.38E+00	1.47E+01	1.41E+00	1.33E-01	
Particulates, > 2.5 um, and < 10um	9.26E+01	2.98E+00	5.41E-02	7.88E-02	3.43E+01	2.46E-02	1.03E+01	4.47E+01	1.23E-01	2.10E-02	CAP
Chloramine	4.58E+01	6.97E-08	1.34E-09	2.97E-09	4.58E+01	5.73E-10	5.35E-07	2.32E-06	2.98E-09	2.74E-10	
Ammonia	3.81E+01	3.22E-01	5.05E-03	3.88E-03	3.52E+01	2.33E-03	4.77E-01	2.07E+00	1.21E-02	1.34E-03	
Hydrogen chloride	3.57E+01	8.31E-01	1.48E-02	2.42E-02	1.31E+01	6.78E-03	4.06E+00	1.76E+01	3.52E-02	5.78E-03	

Carbon dioxide	2.71 E+01	3.45E-01	6.73E-03	1.90E-02	7.74E+00	2.85 E-03	3.56E +00	1.54E +01	1.58E-02	1.40E-03	X

Table 4-8 Chemicals (Generic) Soil Emission Results Per Launch

Substance	Total (kg)	Diesel {RoW}| market for | Alloc Rec, U	Heavy fuel oil {RoW}| market for | Alloc Rec, U	Helium {GLO}| market for | Alloc Rec, U	Hydrazine {GLO}| market for | Alloc Rec, U	Light fuel oil {RoW}| market for | Alloc Rec, U	Nitrogen, liquid {RoW}| market for | Alloc Rec, U	Nitrogen, liquid {RoW}| market for | Alloc Rec, U	Petrol, unleaded {RoW}| market for | Alloc Rec, U
Oils, unspecified	2.15E+02	1.50E+02	2.71E+00	1.96E-02	4.42E+01	1.29E+00	2.31E+00	1.00E+01	5.01E+00
Calcium	1.05E+01	4.50E+00	8.17E-02	1.25E-02	3.22E+00	3.87E-02	4.62E-01	2.00E+00	1.51E-01
Iron	6.87E+00	2.32E+00	4.20E-02	6.81E-03	2.88E+00	1.99E-02	2.85E-01	1.23E+00	7.86E-02
Chloride	6.36E+00	3.87E+00	7.02E-02	9.34E-03	1.60E+00	3.33E-02	1.23E-01	5.33E-01	1.30E-01
Carbon	5.70E+00	3.45E+00	6.25E-02	8.07E-03	1.41E+00	2.96E-02	1.18E-01	5.10E-01	1.16E-01
Sodium	3.63E+00	2.21E+00	4.01E-02	5.33E-03	9.19E-01	1.90E-02	6.86E-02	2.97E-01	7.42E-02
Aluminum	2.02E+00	1.11E+00	2.01E-02	2.79E-03	5.34E-01	9.54E-03	5.84E-02	2.53E-01	3.73E-02
Magnesium	1.79E+00	8.92E-01	1.62E-02	2.33E-03	5.06E-01	7.66E-03	6.37E-02	2.76E-01	2.99E-02
Potassium	1.27E+00	4.01E-01	7.28E-03	1.29E-03	4.44E-01	3.44E-03	7.47E-02	3.24E-01	1.35E-02
Silicon	1.18E+00	1.34E-01	2.43E-03	8.22E-04	5.12E-01	1.14E-03	9.93E-02	4.30E-01	4.61E-03
Sulfur	1.18E+00	6.66E-01	1.21E-02	1.65E-03	3.05E-01	5.72E-03	3.08E-02	1.34E-01	2.23E-02
Barium	8.82E+02	5.52E+02	1.00E+01	1.32E+00	2.06E+02	4.74E+00	1.67E+01	7.24E+01	1.85E+01
Manganese	3.10E+02	4.96E+01	9.02E-01	2.40E-01	1.26E+02	4.24E-01	2.45E+01	1.06E+02	1.69E+00
Phosphorus	2.06E+02	5.85E+01	1.06E+00	1.98E-01	7.44E+01	5.02E-01	1.30E+01	5.63E+01	1.98E+00
Oils, biogenic	1.59E+02	3.93E+00	7.14E-02	1.16E-01	8.62E+01	3.23E-02	1.28E+01	5.53E+01	1.58E-01

Table 4-9 Chemicals (Generic) Water Emission Per Launch

Substance	Total (kg)	Diesel {RoW}| market for | Alloc Rec, U	Heavy fuel oil {RoW}| market for | Alloc Rec, U	Helium {GLO}| market for | Alloc Rec, U	Hydrazine {GLO}| market for | Alloc Rec, U	Light fuel oil {RoW}| market for | Alloc Rec, U	Nitrogen, liquid {RoW}| market for | Alloc Rec, U	Nitrogen, liquid {RoW}| market for | Alloc Rec, U	Petrol, unleaded {RoW}| market for | Alloc Rec, U	Isopropanol {GLO}| market for | Alloc Rec, U
Suspended solids, unspecified	8.85 E+02	2.42E+01	4.50E-01	1.60E+01	4.28E+02	2.05E-01	8.21E+01	3.33E+02	1.21E+00	2.02E-01
Potassium	8.21 E+02	2.32E+01	4.31E-01	5.60E-01	3.40E+02	1.95E-01	8.58E+01	3.70E+02	9.25E-01	1.33E-01
COD, Chemical Oxygen Demand	6.96 E+02	4.48E+02	8.09E+00	2.51E-01	1.65E+02	3.85E+00	9.24E+00	3.63E+01	1.51E+01	1.07E+01
BOD5, Biological Oxygen Demand	6.61 E+02	4.40E+02	7.97E+00	1.73E-01	1.43E+02	3.78E+00	8.01E+00	3.27E+01	1.48E+01	1.07E+01
Phosphate	4.37 E+02	7.33E+00	1.39E-01	3.07E-01	1.72E+02	6.02E-02	4.82E+01	2.08E+02	3.20E-01	5.75E-02
Iron	4.27 E+02	6.47E+00	1.20E-01	2.87E-01	2.36E+02	5.25E-02	3.50E+01	1.49E+02	3.03E-01	1.03E-01
Chloramine	4.08 E+02	1.37E-06	2.61E-08	5.48E-08	4.08E+02	1.11E-08	9.65E-06	2.07E-05	5.80E-08	7.68E-09
Ammonium, ion	3.76 E+02	2.18E-01	2.09E-03	4.62E-03	3.76E+02	1.86E-03	4.50E-02	1.83E-01	7.49E-03	2.46E-04
TOC, Total Organic Carbon	2.18 E+02	1.37E+02	2.47E+00	9.08E-02	5.56E+01	1.18E+00	3.13E+00	1.19E+01	4.60E+00	2.29E+00

DOC, Dissolved Organic Carbon	2.17E+02	1.36E+02	2.47E+00	9.06E-02	5.54E+01	1.17E+00	3.11E+00	1.18E+01	4.58E+00	2.29E+00
Oils, unspecified	2.00E+02	1.38E+02	2.51E+00	3.57E-02	4.18E+01	1.19E+00	2.29E+00	9.64E+00	4.63E+00	1.30E-02
Solids, inorganic	1.88E+02	2.23E+00	4.27E-02	9.86E-02	9.72E+01	1.83E-02	1.66E+01	7.18E+01	9.64E-02	1.11E-02
Nitrate	1.45E+02	2.61E+00	4.93E-02	9.87E-02	5.90E+01	2.15E-02	1.61E+01	6.73E+01	1.10E-01	1.60E-02
Aluminum	1.37E+02	2.61E+00	4.83E-02	9.52E-02	7.49E+01	2.14E-02	1.11E+01	4.76E+01	1.16E-01	3.78E-02
Manganese	1.14E+02	1.93E+00	3.63E-02	7.74E-02	5.14E+01	1.59E-02	1.13E+01	4.87E+01	8.67E-02	2.04E-02
Strontium	4.95E+01	4.73E+00	8.65E-02	4.99E-02	1.80E+01	4.04E-02	4.98E+00	2.15E+01	1.66E-01	5.59E-03
Hydrogen-3, Tritium (kBq)	6.42E+05	9.52E+03	1.83E+02	4.41E+02	2.14E+05	7.84E+01	7.85E+04	3.39E+05	4.15E+02	4.39E+01

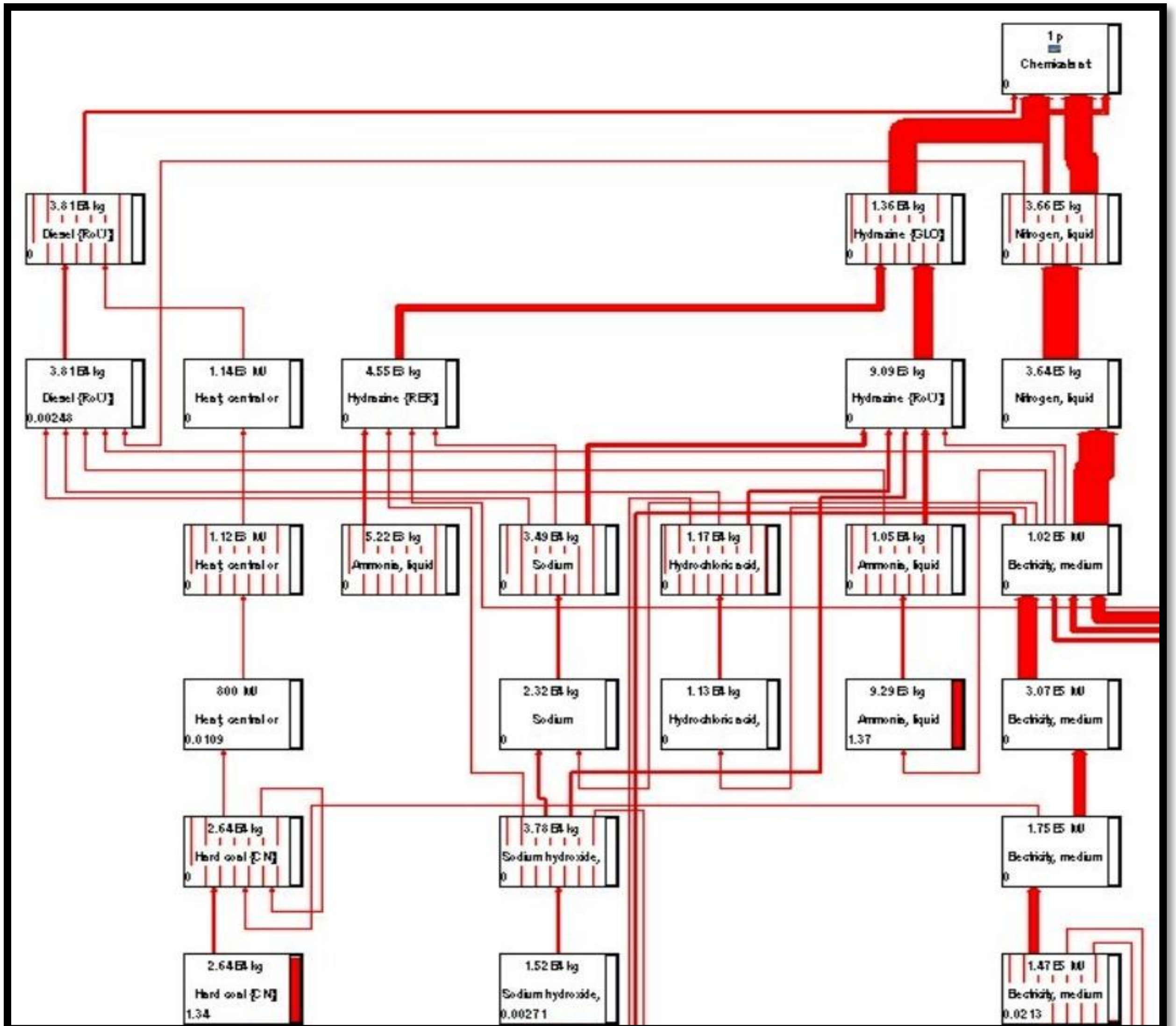


Figure 4- 3 Chemicals (Generic) Network, Damage Assessment, Single Score (SimaPro Software)

4.1.1.4 Electricity Inventory Analysis Per Launch

Tables 4-10 through 4-12 show the inventory for air, soil and water, respectively. Figure 4- 4 represents the electricity Network, Damage Assessment, Single Score at 5% Cutoff.

The air emissions for the medium voltage electricity and the diesel generator revealed the greatest of the top 12 substance contributors were nitrogen oxides and sulfur dioxide. This result is expected for electricity sources that might rely on natural gas or other materials such as uranium and petroleum and the use of the diesel generators. The soil emissions result revealed oils, unspecified, calcium and chloride were the greatest contributors of the 12 substance contributors and this result is expected most likely due to the production processes. The water emissions seem expected again based on the manufacturing process with the tritium found in the water from possible use of a nuclear power plant in the production life cycle phase.

The network damage assessment at the 5% cutoff revealed diesel generators contributed more to the impacts than electricity use and generation. The use of petroleum to manufacture may be one source of this contribution.

Table 4-10 Electricity Air Emissions Per Launch

Substance	Media	Unit	Total	Electricity, medium voltage {NPCC, US only}| market for | Alloc Rec, U	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Alloc Rec, U	GHG or CAP
Nitrogen oxides	Air	kg	1.48E+02	1.54E+01	1.33E+02	CAP
Sulfur dioxide	Air	kg	1.11E+02	7.07E+01	4.05E+01	CAP
Carbon dioxide, land transformation	Air	kg	8.51E+01	8.15E+01	3.64E+00	GHG
Carbon monoxide, fossil	Air	kg	7.05E+01	1.14E+01	5.90E+01	CAP
Methane, fossil	Air	kg	6.79E+01	4.49E+01	2.30E+01	GHG
NMVOC, non-methane volatile organic compounds, unspecified	Air	kg	2.27E+01	3.58E+00	1.92E+01	

origin						
Particulates, < 2.5 um	Air	kg	2.00E+01	1.05E+01	9.55E+00	CAP
Particulates, > 10 um	Air	kg	9.28E+00	4.25E+00	5.03E+00	
Particulates, > 2.5 um, and < 10um	Air	kg	4.54E+00	2.00E+00	2.54E+00	CAP
Dinitrogen monoxide	Air	kg	1.94E+00	7.95E-01	1.15E+00	
Carbon monoxide, biogenic	Air	kg	1.50E+00	1.32E+00	1.86E-01	CAP
Radon-222	Air	kBq	9.92E+06	9.75E+06	1.69E+05	

Table 4-11 Electricity Soil Emissions Per Launch

Substance	Media	Unit	Total	Electricity, medium voltage {NPCC, US only}| market for | Alloc Rec, U	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Alloc Rec, U
Oils, unspecified	Soil	kg	3.65E+01	4.89E-01	3.60E+01
Calcium	Soil	kg	1.76E+00	6.58E-01	1.10E+00
Chloride	Soil	kg	1.09E+00	1.57E-01	9.36E-01
Carbon	Soil	g	9.87E+02	1.52E+02	8.35E+02
Iron	Soil	g	7.43E+02	1.58E+02	5.84E+02
Sodium	Soil	g	6.22E+02	8.68E+01	5.35E+02
Aluminum	Soil	g	3.48E+02	7.88E+01	2.69E+02
Magnesium	Soil	g	3.06E+02	8.95E+01	2.17E+02
Potassium	Soil	g	2.08E+02	1.08E+02	9.94E+01
Silicon	Soil	g	2.45E+02	2.07E+02	3.81E+01
Sulfur	Soil	g	2.12E+02	5.04E+01	1.61E+02
Barium	Soil	g	1.55E+02	2.21E+01	1.33E+02

Table 4-12 Electricity Water Emissions Per Launch

Substance	Media	Unit	Total	Electricity, medium voltage {NPCC, US only}| market for | Alloc Rec, U	Machine operation, diesel, >= 74.57 kW, high load factor {GLO}| machine operation, diesel, >= 74.57 kW, high load factor | Alloc Rec, U
Chloride	Water	kg	6.07E+02	3.21E+02	2.86E+02
Sulfate	Water	kg	4.35E+02	3.28E+02	1.07E+02

Suspended solids, unspecified	Water	kg	3.88E+02	3.78E+02	1.04E+01
Sodium	Water	kg	3.00E+02	1.24E+02	1.76E+02
Calcium	Water	kg	1.44E+02	1.00E+02	4.40E+01
COD, Chemical Oxygen Demand	Water	kg	1.17E+02	5.79E+00	1.11E+02
BOD5, Biological Oxygen Demand	Water	kg	1.12E+02	4.08E+00	1.07E+02
Silicon	Water	kg	7.68E+01	4.22E+01	3.46E+01
Magnesium	Water	kg	5.98E+01	4.28E+01	1.70E+01
TOC, Total Organic Carbon	Water	kg	3.66E+01	2.37E+00	3.42E+01
DOC, Dissolved Organic Carbon	Water	kg	3.64E+01	2.36E+00	3.40E+01
Oils, unspecified	Water	kg	3.41E+01	8.36E-01	3.32E+01
Hydrogen-3, Tritium	Water	kBq	6.18E+05	6.14E+05	4.02E+03

.

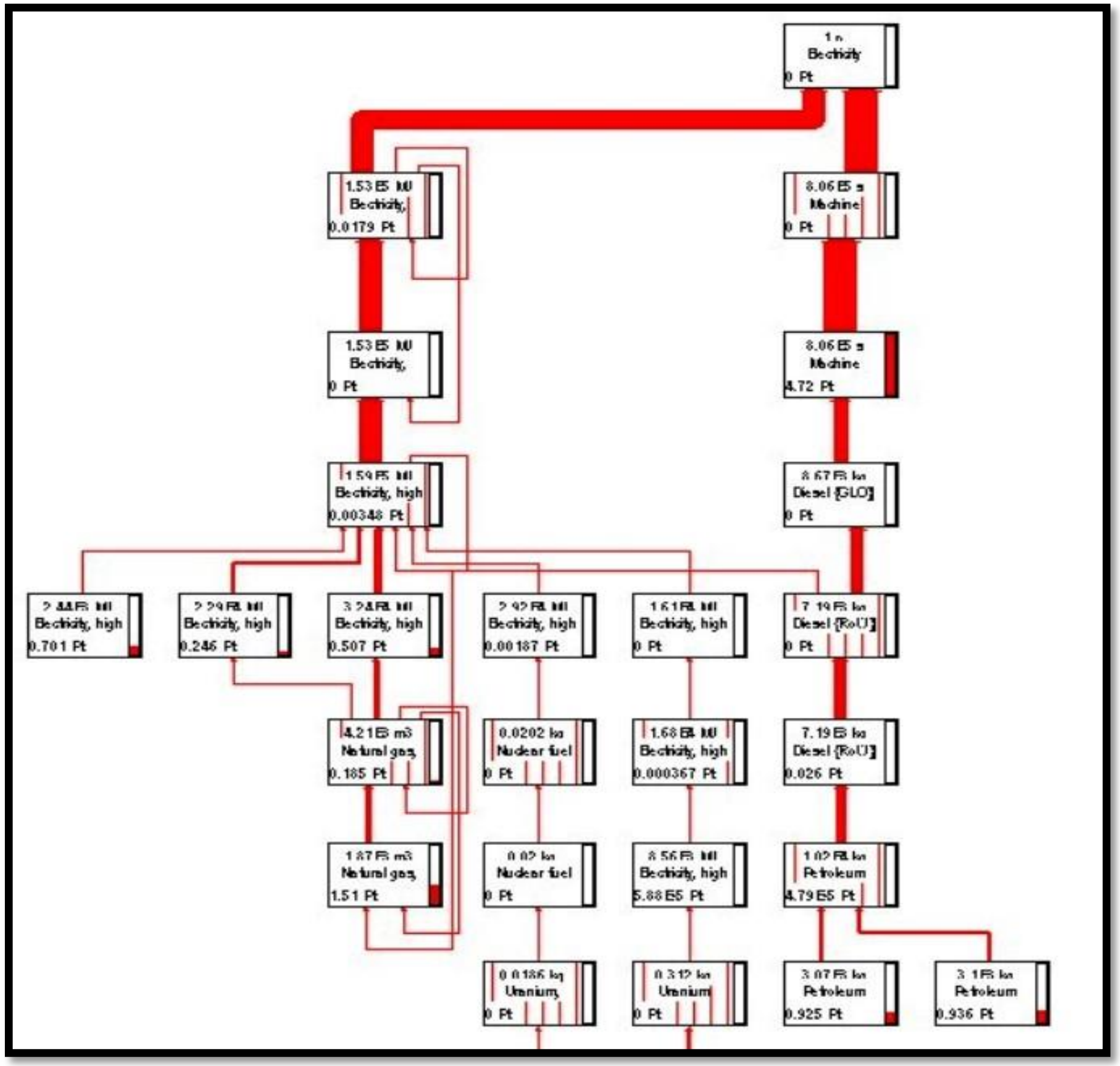


Figure 4- 4 Electricity Network, Damage Assessment, Single Score, 5% Cutoff (SimaPro Software)

4.1.1.5 Water Inventory Analysis Per Launch

Water was divided into the Personnel use water and the Deluge acoustic energy (noise suppression) water. Both water requirements for launch used tap water but at different quantities. Personnel water was estimated to be 4.29 x10^5 kg per launch campaign and Deluge water was estimated to be 7.54 x 10^5 kg per launch. Personnel water is used for both drinking, toilets, washing, pad wash down and other purposes on the launch complex. Tables 4-13 through 4-15 show the inventory for air, soil, and water, respectively. The inventory also includes the transportation from the local WTP to the launch facility, estimated at less than 100 miles away.

The air emissions of carbon dioxide from fossil fuel and the non-volatiles, non-methane were the greatest substance contributors and are expected given the electricity needed for pumping water from the treatment plant and the treating of raw water to make potable. The soil emissions results are not expected, particularly the pesticides, insecticides, and iron substances found as contributors to the emission. One explanation might be where the soil samples were taken might be contaminated with pesticides, herbicides, and insecticides to treat insects and other vegetation. The water emission results are expected for treatment processes of raw water, and possible electricity sources using coal. The transportation of the deluge water is now having an impact and contributes to the water emissions.

Table 4-13 Water Air Emissions Per Launch

Substance	Media	Unit	Total	Tap water, at user/US-US-EI U	Tap water, at user/US-US-EI U	Transport, single unit truck, short-haul, diesel powered/tkm/RNA	GHG or CAP
Carbon dioxide, fossil	Air	kg	3.64E+02	1.16E+02	2.04E+02	4.46E+01	GHG
Carbon dioxide, biogenic	Air	kg	2.22E+01	8.05E+00	1.41E+01	3.64E-02	GHG
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	6.46E+00	2.33E+00	4.10E+00	2.79E-02	
Methane, fossil	Air	kg	1.22E+00	4.42E-01	7.76E-01	2.35E-03	GHG
Sulfur dioxide	Air	kg	1.17E+00	4.16E-01	7.30E-01	2.70E-02	CAP
Nitrogen oxides	Air	g	9.40E+02	3.41E+02	5.99E+02	0.00E+00	GHG
Carbon monoxide, biogenic	Air	g	8.01E+02	1.92E+02	3.38E+02	2.71E+02	CAP
Carbon monoxide, fossil	Air	g	4.22E+02	4.88E+01	8.57E+01	2.87E+02	CAP
Particulates, > 10 um	Air	g	2.18E+02	7.90E+01	1.39E+02	0.00E+00	
Methane, biogenic	Air	g	2.02E+02	7.34E+01	1.29E+02	0.00E+00	GHG
Nitrogen oxide	Air	g	1.86E+02	0.00E+00	0.00E+00	1.86E+02	GHG
Particulates, > 2.5 um, and < 10um	Air	g	1.19E+02	9.51E+01	2.26E+01	1.50E+00	
Particulates, < 2.5 um	Air	g	8.58E+01	6.01E+01	1.43E+01	1.13E+01	CAP
Carbon dioxide	Air	g	7.54E+01	6.09E+01	1.45E+01	0.00E+00	GHG
Radon-222	Air	kBq	1.40E+05	1.13E+05	2.69E+04	0.00E+00	

Table 4-14 Water Soil Emissions Per Launch

Substance	Media	Unit	Total	Tap water, at user/US- US-EI U	Tap water, at user/US- US-EI U	Transport, single unit truck, short-haul, diesel powered/tkm/RNA
Oils, unspecified	Soil	g	1.53E+01	5.54E+00	9.72E+00	0.00E+00
Iron	Soil	g	6.10E+00	2.22E+00	3.89E+00	0.00E+00
Glyphosate	Soil	µg	8.20E+02	2.97E+02	5.22E+02	0.00E+00
Copper	Soil	µg	3.89E+02	1.41E+02	2.48E+02	0.00E+00
Chromium	Soil	µg	3.85E+02	1.40E+02	2.45E+02	0.00E+00
Dichlorprop-P	Soil	µg	3.63E+02	1.32E+02	2.31E+02	0.00E+00
Sodium	Soil	µg	2.95E+02	1.07E+02	1.88E+02	0.00E+00
Mancozeb	Soil	µg	2.51E+02	9.10E+01	1.60E+02	0.00E+00
Thiazole, 2-(thiocyanatemethylthio) benzo	Soil	µg	2.27E+02	8.23E+01	1.44E+02	0.00E+00
Chlorothalonil	Soil	µg	2.11E+02	7.65E+01	1.34E+02	0.00E+00

Table 4-15 Water Water Emissions Per Launch

Substance	Media	Unit	Total	Tap water, at user/US- US-EI U	Tap water, at user/US- US-EI U	Transport, single unit truck, short-haul, diesel powered/tkm/RNA
Chloride	Water	kg	1.53E+01	4.85E+00	8.52E+00	1.91E+00
Suspended solids, unspecified	Water	kg	1.02E+01	2.79E+00	4.89E+00	2.49E+00
Sulfate	Water	kg	7.82E+00	2.84E+00	4.98E+00	4.36E-03
Sodium	Water	kg	3.49E+00	1.07E+00	1.88E+00	5.37E-01
Calcium	Water	kg	2.52E+00	8.52E-01	1.50E+00	1.70E-01
Silicon	Water	kg	2.00E+00	7.25E-01	1.27E+00	0.00E+00
Aluminum	Water	kg	1.83E+00	6.63E-01	1.16E+00	4.55E-03
Magnesium	Water	kg	1.13E+00	3.98E-01	6.99E-01	3.31E-02
Potassium	Water	g	7.48E+02	2.71E+02	4.76E+02	0.00E+00

Phosphate	Water	g	3.34E+02	1.21E+02	2.13E+02	0.00E+00
Iron	Water	g	2.51E+02	8.78E+01	1.54E+02	9.08E+00
Hydrogen-3, Tritium	Water	kBq	3.28E+02	2.65E+02	6.30E+01	0.00E+00

4.1.1.6 Liquid Propellants Inventory Analysis Per Launch

Three liquid propellants were considered as the input per launch. LOx is considered as the oxidizer for each propellant and the fuels are: LH_2, LNG, and RP-1. The additional propellant used for re-entry and landing at the launch pad for the reusable rocket booster was included in the reusable rocket booster inventory. Tables 4-16 through 4-24 show the inventory for each of the propellants for the media of air, soil, and water, respectively.

Each inventory shows all of the propellant that might be used in a launch campaign: test firings, 1^{st} Stage, and 2^{nd} Stage supporting LEO or GTO payload orbits. Also, the transportation for East and West Coast using diesel-powered, short-hauled (100 miles maximum) trucks is included in this inventory because these trucks are needed to bring the additional fuel and oxidizer for the test firings and any additional propellant for the launch.

The air emissions inventory is expected particularly in the emissions from production of the fuels and the energy to produce both the LOx and LH_2. The highest substance amounts are from carbon dioxide, land transformation and particulates. The soil emission results are expected again due to manufacturing and production of these chemicals with unspecified oils as greatest substance contributor. The water emissions for LOx/LH_2 propellant do show a great amount of phosphate, iron, solids and nitrates. These substances may be by-products from the electricity generation needed in manufacturing and also the transportation is contributing to this inventory. A network diagram is not shown but the greatest impact came from the LOx and electricity for production.

The air emissions result is expected for LOx/RP-1 is expected, with large substance contributions from non-methane volatile organic compounds, particulates, hydrogen chloride, carbon dioxide and methane. These substances would come from kerosene manufacturing and the production of LOx. The soil emissions revealed chloride, carbon, iron, and sodium were the highest substance contributors. This result is expected, as the kerosene and other LOx production. The water emissions result showed high quantities of nitrate, manganese, aluminum and strontium. These emissions seem unexpected, particularly the metals, however, the production process may require these chemicals in making kerosene. Another reason might be the sampling site might have some previous contamination or outfall from another facility.

The air emissions from the propellant LOx/LNG does seem to be expected for manufacturing of liquefied natural gas. The soil emissions result was similar to the other two propellants with chloride, iron, sodium, and carbon. This finding might indicate that all three propellants are influenced by the LOx production and its electricity by-products. The water emissions results showed similar substances of aluminum, lithium, and strontium as the other two propellants.

Overall, the LOx contributed the greatest in all of the propellant combinations. The electricity throughout the life cycle seemed to be the driver for its impact.

Figure 4-5 shows the Damage Assessment Network Single Score for the propellant, LOx/LNG with the contributors to this impact network. This network figure was selected because it is the propellant with the greatest impacts. This higher impact may also be based on the amount of fuel and oxidizer needed per launch. The network shows how the LOx contributes more than the LNG to the impacts.

Table 4-16 Propellant – LOx/LH_2 Air Emissions Per Launch

Substance	Unit	Total	Propellant -Test Firings LOx + LH_2	Propellant LOx+LH_2 1st Stage	Payload LOx+LH_2 2nd Stage	Transport, short-haul, diesel powered, West/tkm/RNA	Transport short-haul, diesel powered, Southeast/ tkm/RNA	GHG or CAP
Carbon dioxide, land transformation	kg	1E+03	4.46 E+02	4.46 E+02	1.07E+02	0.00E+00	0.00E +00	GHG
Particulates, < 2.5 um	kg	8.19E+02	3.66E+02	3.66E+02	8.78E+01	4.47E-03	4.15E -03	CAP
Particulates, > 10 um	kg	5.89E+02	2.63E+02	2.63E+02	6.31E+01	0.00E+00	0.00E +00	
Carbon monoxide, fossil	kg	3.29E+02	1.47E+02	1.48E+02	3.48E+01	9.04E-02	8.77E -02	CAP
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	1.87E+02	8.34E+01	8.35E+01	2.00E+01	9.98E-03	9.85E -03	
Particulates, > 2.5 um, and < 10um	kg	1.73E+02	7.74E+01	7.74E+01	1.86E+01	5.34E-04	5.27E -04	CAP
Hydrogen chloride	kg	6.52E+01	2.91E+01	2.91E+01	6.99E+00	1.86E-04	1.84E -04	
Carbon dioxide	kg	5.55E+01	2.48E+01	2.48E+01	5.95E+00	0.00E+00	0.00E +00	GHG
Methane, biogenic	kg	3.87E+01	1.73E+01	1.73E+01	4.14E+00	0.00E+00	0.00E +00	GHG
Carbon monoxide, biogenic	kg	3.19E+01	1.42E+01	1.42E+01	3.41E+00	0.00E+00	0.00E +00	CAP
Dinitrogen monoxide	kg	1.46E+01	6.54E+00	6.54E+00	1.57E+00	3.93E-05	3.67E -05	

Aluminum	kg	1.30E+01	5.78E+00	5.78E+00	1.39E+00	0.00E+00	0.00E+00	
Hydrogen	kg	9.17E+00	4.09E+00	4.09E+00	9.82E-01	0.00E+00	0.00E+00	
Ammonia	kg	8.41E+00	3.75E+00	3.76E+00	9.00E-01	2.79E-04	2.73E-04	
Hydrogen fluoride	kg	8.02E+00	3.58E+00	3.58E+00	8.60E-01	2.19E-05	2.16E-05	
Ethane	kg	5.50E+00	2.46E+00	2.46E+00	5.90E-01	0.00E+00	0.00E+00	
Nitrogen oxide	kg	3.16E+00	1.13E+00	1.88E+00	0.00E+00	8.08E-02	7.55E-02	GHG
Ozone	kg	2.79E+00	1.25E+00	1.25E+00	2.99E-01	0.00E+00	0.00E+00	CAP
Radon-222	kBq	3.84E+07	1.71E+07	1.71E+07	4.11E+06	0.00E+00	0.00E+00	

Table 4-17 Propellant – LOx/LH_2 Soil Emissions Per Launch

Substance	**Unit**	**Total**	**Propellant-Test Firings LOx + LH_2**	**Propellant LOx+LH_2 1st Stage**	**Payload (LOx+LH_2) 2nd Stage**	**Transport, short-haul, diesel powered, West/tkm/RNA**	**Transport, short-haul, diesel powered, Southeast/tkm /RNA**
Oils, unspecified	kg	3.53E+01	1.57E+01	1.57E+01	3.78E+00	0.00E+00	0.00E+00
Calcium	kg	7.31E+00	3.26E+00	3.26E+00	7.83E-01	0.00E+00	0.00E+00
Iron	kg	3.89E+00	1.74E+00	1.74E+00	4.16E-01	0.00E+00	0.00E+00
Chloride	kg	1.92E+00	8.57E-01	8.57E-01	2.06E-01	0.00E+00	0.00E+00
Carbon	kg	1.86E+00	8.30E-01	8.30E-01	1.99E-01	0.00E+00	0.00E+00
Silicon	kg	1.58E+00	7.08E-01	7.08E-01	1.70E-01	0.00E+00	0.00E+00
Potassium	kg	1.19E+00	5.29E-01	5.29E-01	1.27E-01	0.00E+00	0.00E+00
Sodium	kg	1.07E+00	4.78E-01	4.78E-01	1.15E-01	0.00E+00	0.00E+00
Magnesium	kg	1.00E+00	4.49E-01	4.49E-01	1.08E-01	0.00E+00	0.00E+00
Aluminum	g	9.17E+02	4.09E+02	4.09E+02	9.82E+01	0.00E+00	0.00E+00
Sulfur	g	4.84E+02	2.16E+02	2.16E+02	5.18E+01	0.00E+00	0.00E+00

Manganese	g	3.90E+02	1.74E+02	1.74E+02	4.18E+01	0.00E+00	0.00E+00
Barium	g	2.58E+02	1.15E+02	1.15E+02	2.77E+01	0.00E+00	0.00E+00

Table 4-18 Propellant - LOx/LH$_2$ Water Emissions Per Launch

Substance	Unit	Total	Propellant -Test Firings (LOx + LH$_2$)	Propellant (LOx+LH$_2$)- 1st Stage	Payload LOx+LH$_2$ 2nd Stage	Transport,short-haul, diesel powered, West/tkm/RNA	Transport, short-haul, diesel powered, Southeast/tkm/RNA
Phosphate	kg	7.64E+02	3.41E+02	3.41E+02	8.18E+01	0.00E+00	0.00E+00
Iron	kg	5.69E+02	2.54E+02	2.54E+02	6.09E+01	3.24E-03	3.20E-03
Solids, inorganic	kg	2.90E+02	1.29E+02	1.29E+02	3.10E+01	1.62E-11	1.60E-11
Nitrate	kg	2.48E+02	1.11E+02	1.11E+02	2.66E+01	7.04E-14	6.95E-14
Aluminum	kg	1.92E+02	8.56E+01	8.56E+01	2.05E+01	1.63E-03	1.61E-03
COD, Chemical Oxygen Demand	kg	1.87E+02	8.33E+01	8.34E+01	2.00E+01	6.54E-03	6.46E-03
Manganese	kg	1.81E+02	8.07E+01	8.07E+01	1.94E+01	2.14E-05	2.12E-05
BOD5, Biological Oxygen Demand	kg	1.38E+02	6.14E+01	6.14E+01	1.47E+01	3.45E-03	3.40E-03
Strontium	kg	7.84E+01	3.50E+01	3.50E+01	8.39E+00	1.03E-03	1.01E-03
TOC, Total Organic Carbon	kg	6.70E+01	2.99E+01	2.99E+01	7.18E+00	0.00E+00	0.00E+00
DOC, Dissolved Organic Carbon	kg	6.67E+01	2.98E+01	2.98E+01	7.14E+00	6.42E-13	6.34E-13
Oils, unspecified	kg	3.54E+01	1.58E+01	1.58E+01	3.79E+00	4.35E-04	4.29E-04
Lithium	kg	2.82E+01	1.26E+01	1.26E+01	3.02E+00	1.02E-03	1.01E-03

Table 4-19 Propellant – LOx/RP-1 Air Emissions Per Launch

Substance	Unit	Total	Propellant-Test Firings (LOx + RP-1)	Propellant (LOx+RP-1) 1st Stage	Payload (LOx+RP-1) 2nd Stage	GHG or CAP
NMVOC, non-methane volatile organic compounds, unspecified origin	kg	9.82E+02	4.72E+02	4.72E+02	3.74E+01	
Particulates, > 2.5 um, and < 10um	kg	6.82E+02	3.28E+02	3.28E+02	2.64E+01	GHG
Hydrogen chloride	kg	2.64E+02	1.27E+02	1.27E+02	1.02E+01	
Carbon dioxide	kg	2.24E+02	1.08E+02	1.08E+02	8.69E+00	GHG
Methane, biogenic	kg	1.47E+02	7.05E+01	7.05E+01	5.68E+00	GHG
Carbon monoxide, biogenic	kg	1.29E+02	6.21E+01	6.21E+01	5.00E+00	CAP
Pentane	kg	7.09E+01	3.41E+01	3.41E+01	2.70E+00	
Dinitrogen monoxide	kg	6.35E+01	3.05E+01	3.05E+01	2.46E+00	
Propane	kg	5.98E+01	2.88E+01	2.88E+01	2.28E+00	
Butane	kg	5.66E+01	2.72E+01	2.72E+01	2.16E+00	
Aluminum	kg	5.35E+01	2.57E+01	2.57E+01	2.07E+00	
Ethane	kg	3.75E+01	1.80E+01	1.80E+01	1.44E+00	
Ammonia	kg	3.44E+01	1.65E+01	1.65E+01	1.33E+00	
Hydrogen fluoride	kg	3.23E+01	1.55E+01	1.55E+01	1.25E+00	
Hexane	kg	2.92E+01	1.41E+01	1.41E+01	1.11E+00	
Benzene	kg	1.61E+01	7.73E+00	7.73E+00	6.18E-01	
Xylene	kg	1.53E+01	7.36E+00	7.36E+00	5.89E-01	
Toluene	kg	1.37E+01	6.57E+00	6.57E+00	5.24E-01	
Heptane	kg	1.18E+01	5.67E+00	5.67E+00	4.48E-01	
Ozone	kg	1.13E+01	5.44E+00	5.44E+00	4.39E-01	CAP
Potassium	kg	9.49E+00	4.56E+00	4.56E+00	3.67E-01	
Hydrocarbons, aromatic	kg	8.78E+00	4.22E+00	4.22E+00	3.40E-01	
Radon-222	kBq	9.60E+07	1.53E+07	7.58E+07	3.50E+06	

Table 4-20 Propellant – LOx/RP-1 Soil Emissions Per Launch

Substance	Unit	Total	Propellant-Test Firings (LOx + RP-1)	Propellant (LOx+RP-1) 1st Stage	Payload (LOx+RP-1) 2nd Stage
Chloride	kg	8.24E+01	3.96E+01	3.96E+01	3.13E+00
Carbon	kg	7.40E+01	3.56E+01	3.56E+01	2.81E+00
Iron	kg	5.94E+01	2.86E+01	2.86E+01	2.27E+00
Sodium	kg	4.70E+01	2.26E+01	2.26E+01	1.79E+00
Aluminum	kg	2.51E+01	1.21E+01	1.21E+01	9.54E-01
Magnesium	kg	2.12E+01	1.02E+01	1.02E+01	8.07E-01
Sulfur	kg	1.48E+01	7.10E+00	7.10E+00	5.62E-01
Potassium	kg	1.23E+01	5.92E+00	5.92E+00	4.71E-01
Barium	kg	1.17E+01	5.63E+00	5.63E+00	4.45E-01
Silicon	kg	8.62E+00	4.15E+00	4.15E+00	3.32E-01
Manganese	kg	2.45E+00	1.18E+00	1.18E+00	9.43E-02
Phosphorus	kg	1.93E+00	9.26E-01	9.26E-01	7.37E-02
Fluoride	kg	1.35E+00	6.51E-01	6.51E-01	5.16E-02

Table 4-21 Propellant – LOx/RP-1 Water Emissions Per Launch

Substance	Media	Unit	Total	Propellant-Test Firings (LOx + RP-1)	Propellant (LOx+RP-1) 1st Stage	Payload (LOx+RP-1) 2nd Stage
Nitrate	Water	kg	9.97E+02	4.79E+02	4.79E+02	3.86E+01
Manganese	Water	kg	7.24E+02	3.48E+02	3.48E+02	2.81E+01
Aluminum	Water	kg	7.19E+02	3.46E+02	3.46E+02	2.78E+01
Strontium	Water	kg	3.95E+02	1.90E+02	1.90E+02	1.52E+01
Carboxylic acids, unspecified	Water	kg	1.90E+02	9.12E+01	9.12E+01	7.21E+00
Lithium	Water	kg	1.14E+02	5.49E+01	5.49E+01	4.42E+00
Zinc	Water	kg	1.08E+02	5.19E+01	5.19E+01	4.17E+00
Barium	Water	kg	9.47E+01	4.57E+01	4.53E+01	3.62E+00
Nickel	Water	kg	8.28E+01	3.98E+01	3.98E+01	3.21E+00

Copper	Water	kg	7.50E+01	3.60E+01	3.60E+01	2.90E+00
Barite	Water	kg	7.26E+01	3.49E+01	3.49E+01	2.77E+00
Bromine	Water	kg	5.45E+01	2.62E+01	2.62E+01	2.09E+00
Fluoride	Water	kg	4.26E+01	2.05E+01	2.05E+01	1.64E+00
Hydrocarbons, aromatic	Water	kg	2.40E+01	1.16E+01	1.16E+01	9.13E-01
Titanium	Water	kg	2.03E+01	9.77E+00	9.77E+00	7.86E-01
Cobalt	Water	kg	1.84E+01	8.84E+00	8.84E+00	7.12E-01
Boron	Water	kg	1.70E+01	8.16E+00	8.15E+00	6.55E-01
Hydrogen-3, Tritium	Water	kBq	2.98E+06	4.30E+05	2.40E+06	1.10E+05

Table 4-22 Propellant – LOx/LNG Air Emissions Per Launch

Substance	Media	Unit	Total	Propellant-Test Firings LOx+LNG	Propellant (LOx+LNG) 1st Stage	Payload LOx+LNG 2nd Stage	GHG or CAP
Particulates, > 2.5 um, and < 10um	Air	kg	8.09E+02	3.61E+02	3.61E+02	8.66E+01	**CAP**
NMVOC, non-methane volatile organic compounds, unspecified origin	Air	kg	7.94E+02	3.55E+02	3.55E+02	8.51E+01	
Hydrogen chloride	Air	kg	3.13E+02	1.40E+02	1.40E+02	3.35E+01	
Carbon dioxide	Air	kg	2.72E+02	1.21E+02	1.21E+02	2.91E+01	**GHG**
Methane, biogenic	Air	kg	1.76E+02	7.85E+01	7.85E+01	1.88E+01	**GHG**
Carbon monoxide, biogenic	Air	kg	1.52E+02	6.78E+01	6.78E+01	1.63E+01	**CAP**
Ethane	Air	kg	8.64E+01	3.86E+01	3.86E+01	9.25E+00	
Dinitrogen monoxide	Air	kg	7.31E+01	3.26E+01	3.26E+01	7.83E+00	
Aluminum	Air	kg	6.25E+01	2.79E+01	2.79E+01	6.70E+00	
Hydrocarbons, aromatic	Air	kg	4.49E+01	2.00E+01	2.00E+01	4.81E+00	
Hydrogen fluoride	Air	kg	3.89E+01	1.74E+01	1.74E+01	4.17E+00	

Ammonia	Air	kg	3.73E+01	1.67E+01	1.67E+01	4.00E+00	
Propane	Air	kg	3.33E+01	1.49E+01	1.49E+01	3.57E+00	
Toluene	Air	kg	2.41E+01	1.07E+01	1.07E+01	2.58E+00	
Benzene	Air	kg	2.37E+01	1.06E+01	1.06E+01	2.54E+00	
Xylene	Air	kg	2.24E+01	9.99E+00	9.99E+00	2.40E+00	
Helium	Air	kg	1.90E+01	8.46E+00	8.46E+00	2.03E+00	
Radon-222	Air	kBq	1.72E+08	8.42E+07	8.42E+07	8.43E+05	

Table 4-23 Propellant – LOx/LNG Soil Emissions Per Launch

Substance	Media	Unit	Total	Propellant-Test Firings (LOx +LNG)	Propellant (LOx+LNG) 1st Stage	Payload LOx+LNG 2^{nd} Stage
Oils, unspecified	Soil	kg	1.72E+02	7.70E+01	7.70E+01	1.85E+01
Calcium	Soil	kg	4.72E+01	2.11E+01	2.11E+01	5.06E+00
Iron	Soil	kg	2.44E+01	1.09E+01	1.09E+01	2.61E+00
Chloride	Soil	kg	1.97E+01	8.78E+00	8.78E+00	2.11E+00
Carbon	Soil	kg	1.79E+01	7.98E+00	7.98E+00	1.92E+00
Sodium	Soil	kg	1.11E+01	4.96E+00	4.96E+00	1.19E+00
Silicon	Soil	kg	7.89E+00	3.52E+00	3.52E+00	8.46E-01
Aluminum	Soil	kg	7.42E+00	3.31E+00	3.31E+00	7.95E-01
Magnesium	Soil	kg	7.25E+00	3.24E+00	3.24E+00	7.76E-01
Potassium	Soil	kg	6.76E+00	3.02E+00	3.02E+00	7.24E-01
Sulfur	Soil	kg	4.13E+00	1.84E+00	1.84E+00	4.42E-01
Barium	Soil	kg	2.75E+00	1.23E+00	1.23E+00	2.95E-01

Table 4-24 Propellant – LOx/LNG Water Emissions Per Launch

Substance	Media	Unit	Total	Propellant-Test Firings (LOx +LNG)	Propellant (LOx+LNG) 1st Stage	Payload (LOx+LNG) 2nd Stage
Manganese	Water	kg	8.72E+02	3.89E+02	3.89E+02	9.34E+01
Aluminum	Water	kg	8.64E+02	3.86E+02	3.86E+02	9.26E+01
COD, Chemical Oxygen Demand	Water	kg	8.31E+02	3.71E+02	3.71E+02	8.90E+01
BOD5, Biological Oxygen Demand	Water	kg	6.93E+02	3.09E+02	3.09E+02	7.42E+01
Lithium	Water	kg	5.99E+02	2.67E+02	2.67E+02	6.42E+01
Strontium	Water	kg	4.06E+02	1.81E+02	1.81E+02	4.36E+01
TOC, Total Organic Carbon	Water	kg	2.81E+02	1.25E+02	1.25E+02	3.01E+01
DOC, Dissolved Organic Carbon	Water	kg	2.79E+02	1.25E+02	1.25E+02	2.99E+01
Barium	Water	kg	1.91E+02	8.55E+01	8.51E+01	2.04E+01
Oils, unspecified	Water	kg	1.87E+02	8.35E+01	8.35E+01	2.00E+01
Zinc	Water	kg	1.23E+02	5.47E+01	5.47E+01	1.31E+01
Hydrogen-3, Tritium	Water	kBq	5.48E+06	2.68E+06	2.68E+06	2.68E+04

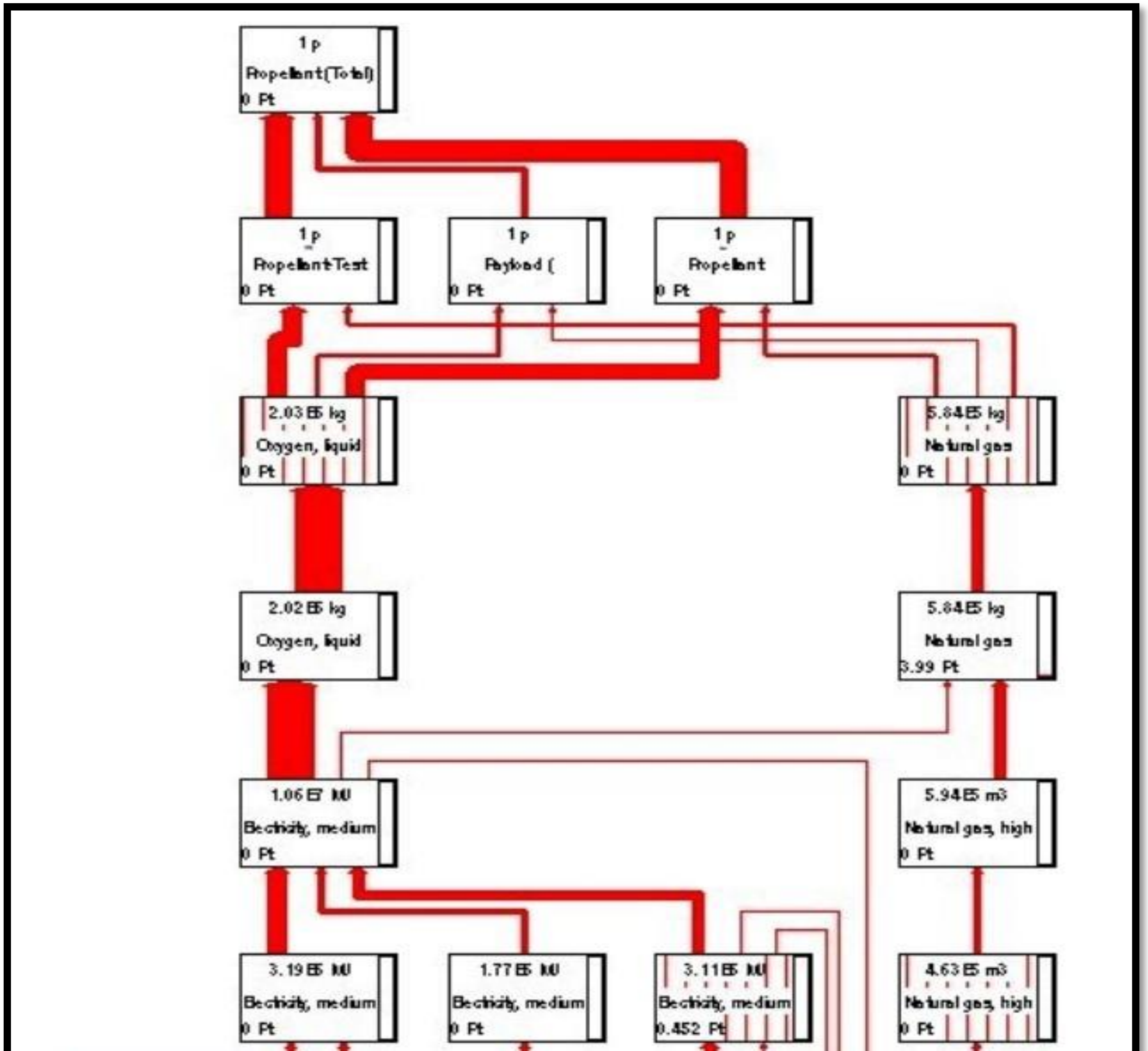


Figure 4-5 Propellant – LOx/LNG Network Damage Assessment – Single Score at 10 % Cutoff (SimaPro Software)

4.1.1.7 Outputs of the Use and Maintenance Phase Per Launch

4.1.1.7.1 Greenhouse Gas Emissions and Traditional (Criteria) Air Emissions

The inventory results in Section 4.1.1 showed the GHG and traditional air pollutants (criteria air pollutants) which were found in the six consumables included: NOx; CH_4; CO; CO_2; and particulates (PM 2.5, PM 10). Of course, other air pollutants were found in these consumables, but these contaminants were the ones observed in the top 10-15 shown in the inventory results. These air emissions contributed to the characterization categories as shown in Table 3-13, and thus contributed to the damage assessment areas of Human health, Climate Change, Ecosystem Quality and Resources. **Future study is recommended to evaluate the environmental conditions around launch sites before and after for a set period of time to determine if the launches are adding contaminants to the local environment.**

The information gathered from current NEPA documents provides realistic GHG CO_2 emission for launchers. For instance, the Falcon 9 with the Merlin 1-C engines using LOx/RP-1 would generate 976 metric tons per year of CO_2 equivalents (FAA, 2011). These launches are considered stationary sources. The emissions from landing (boost-back) of a SpaceX Falcon Heavy using three engines generate 127.75 metric tons of CO_2 equivalents (FAA, 2017). For Blue Origin's New Glenn using BE-4 engines, the estimated emissions below 3000 feet is 187 tons per launch (USAF, 2016). The BE-4 engine testing emits approximately 15195 metric tons CO_2 annually (USAF, 2016).

4.1.1.7.2 Solid and Hazardous Wastes

Solid waste would be generated from personnel, industry processes at the launch facility, any deluge retention pond sediment requiring disposal, reusable rocket, 1st Stage, material on the last use (20th), and any packaging materials. This study did not assess the whole process of end-of-life, which would include solid waste generated from the six consumables: the chemicals' handling materials, such as aprons, and gloves, if characterized as non-hazardous material; the water retention pond sediment (estimated at 1%), requiring incineration or other landfilling, and reusable rocket, 1st Stage, parts that are unable to be reused (5% by mass of 1st Stage material). This study identified that solid waste would be generated and would impact landfills and incineration, based on the practices of the CST operators and agreements with the local and state regulators. This study did not assess comprehensive end-of-life accounting for solid waste. For future studies, a more comprehensive analysis of the total waste stream of solid waste would add better insight into the environmental impacts associated with one launch of a space vehicle. Overall understanding of the implications of solid waste generated per launch and increased frequency of launches would impact the environment would be beneficial.

Hazardous waste is assumed to be generated from chemicals not used per launch at 5% of total amounts. Any other handling material used, such as protective gloves and spill recovery kits, will be assumed to be 0.5% of total mass of chemicals; and unused propellant in the reusable rocket booster will not be accounted for as part of the hazardous waste. This study did not assess the end of life for the hazardous waste. A future analysis of this waste is recommended to identify those costs and other related environmental burdens from one launch. As more launches occur, environmental professionals need to understand whether or not the hazardous waste quantities are less from combined usage or if these wastes when generated independently per launch are more costly and harder to manage.

4.1.1.7.3 Water Contamination

The total water requiring treatment required for 14-day launch campaign is 301,345 kg (301, 345 liters) from a Class 2 WWTP. The notional treatment plant used had a capacity of 6 MGD (2.27E+7 liters/day). An estimated: 21,525 liters/day would be treated and was considered using 0.011 % of treatment capacity per day for this WWTP. Human health was shown as the highest damage area impacted, with Climate change next highest. The contribution of constituents of particulates <2.5 µm, nitrogen oxides, and sulfur dioxide influenced Human Health impacts. The contribution constituents for Climate change were carbon dioxide, and methane.

4.1.1.7.4 Noise

Typical launch noise, measured or modeled, ranged from 145-160 decibels A-weighted (dBA). Down range at least 2.44 km from the launch facility, noise was measured ranging from 126-129 dBA. Typical landing noise ranged from 110-120 dBA for approximately 60 – 300 seconds. The generator noise at the pad was measured at 96-110 dBA for continuous use up to 48 hours during preparation for launch and during the day of launch. The noise also was heard down range of about 30-40 miles (48.3 – 64.4 km) for sonic booms.

Table 4-25 provides a perspective of the noise encountered per each launch and possible impacts ranges from minimal to high from this noise based on the time and distances involved. Recent articles focused on propulsion launch noise (James, Salton, 2017) provide additional actual data for these rocket launchers.

Table 4-25 Noise Levels for Per Launch

Activity	Noise Level (dBA)	Distance (km)	Time (sec)	Impacts
Launch	145-160	7350 feet	10-15	Minimal to Medium
Down Range	126-129	2.44	230 (est.)	Minimal
Landing	110-120	400 feet (est.)	60-300	Minimal to Medium
Sonic Booms	60	48.3 – 64.4	15-45	Minimal
Diesel Generator	95-110	50 feet (est.)	172800	Medium to High

4.1.1.8 Summation of Inventory Analysis Per Launch

The inventory analysis per launch results revealed the environmental emissions to the air, water and soil based on the inputs for each of the consumables shown in Chapter 3. GHGs (Carbon dioxide, methane, nitrous oxides) and traditional air pollutants (carbon monoxide, $PM_{2.5}$) were seen in all six of these consumable inventories as some of the top 10-15 contributors. Tables 4-26 through 4-28 show the inventory results for all consumables of reusable rocket booster, three propellants, electricity and water.

The overall results from the air emissions inventory show the top GHG or TAP contributors as carbon dioxide, methane and carbon monoxide. The soil and water emissions inventory reveal the same substances as shown in the previous inventories in this section. Calcium, iron and silicon were the greatest contributors to the soil emissions. For the water emissions, strontium and lithium were the greatest substance contributors. As previously discussed, these emissions may be due to the manufacturing processes and even possibly the materials processing. The Damage Assessment Networks provided additional insight into the contributors within the consumable. The primary contributors were electricity in the manufacturing from coal or nuclear power generation. This network information can aid when identifying potential eco-design factors to examine more closely to reduce impacts.

Table 4-26 All Consumables without Expendable Rocket Booster Air Emissions Results Per Launch

Substance	Total	Reusable Rocket Booster	Propellant (Total) _LOX/LH$_2$	Propellant (Total) _LOX/LNG	Propellant (Total) _LOX/RP1	Electricity (Launch site)	Chemicals at Launch Facilities (Generic)	Water at Launch Site	GHG or CAP[39]
Hydrogen chloride	6.70E+02	2.55E+01	6.42E+01	3.08E+02	2.56E+02	4.67E-01	1.63E+01	5.10E-02	
Carbon dioxide	5.64E+02	1.08E+01	5.49E+01	2.68E+02	2.19E+02	6.25E-02	1.11E+01	0.00E+00	GHG
Methane, biogenic	3.78E+02	1.16E+01	3.82E+01	1.73E+02	1.43E+02	3.14E+00	9.17E+00	2.02E-01	GHG
Carbon monoxide, biogenic	3.18E+02	4.71E+00	3.09E+01	1.48E+02	1.24E+02	8.76E-01	8.19E+00	9.40E-01	CAP
Methane	2.46E+02	2.44E+02	1.06E+00	3.79E-01	3.82E-01	2.67E-06	9.40E-06	6.13E-02	GHG
Dinitrogen monoxide	1.52E+02	1.94E+00	1.41E+01	7.04E+01	5.95E+01	1.59E+00	4.21E+00	1.02E-02	
Ethane	1.31E+02	9.09E-01	5.29E+00	8.47E+01	3.59E+01	5.03E-01	3.45E+00	3.73E-02	
Propane	1.00E+02	7.84E-01	2.57E+00	3.27E+01	5.90E+01	7.46E-01	4.28E+00	1.54E-03	
Ammonia	9.21E+01	2.82E+00	5.90E+00	2.57E+01	2.32E+01	4.83E-01	3.39E+01	7.81E-03	
Pentane	9.06E+01	8.28E-01	2.40E+00	1.17E+01	6.99E+01	9.38E-01	4.84E+00	2.42E-03	
Hydrogen fluoride	8.51E+01	7.14E+00	7.69E+00	3.75E+01	3.08E+01	5.80E-02	1.82E+00	6.36E-03	
Aluminum	8.19E+01	5.77E+00	7.33E+00	3.56E+01	3.05E+01	2.83E-01	2.43E+00	1.73E-02	

Table 4-27 All Consumables without Expendable Rocket Booster Soil Emissions

Substance	Media	Unit	Total	Reusable Rocket Booster	Propellant (Total) _LOX/LH$_2$	Propellant (Total) _LOX/LNG	Propellant (Total) _LOX/RP1	Electricity (Launch site)	Chemicals at Launch Facilities (Generic)	Water at Launch Site
Calcium	Soil	kg	5.32E+01	3.47E-01	5.12E+00	2.46E+01	2.09E+01	3.71E-01	1.79E+00	5.49E-04
Iron	Soil	kg	2.92E+01	3.09E-01	2.69E+00	1.24E+01	1.15E+01	6.84E-02	2.18E+00	6.10E-03
Silicon	Soil	kg	1.54E+01	1.02E-01	1.50E+00	7.17E+00	6.04E+00	1.07E-01	5.29E-01	1.61E-04
Potassium	Soil	kg	1.02E+01	6.61E-02	9.81E-01	4.72E+00	3.97E+00	7.05E-02	3.38E-01	1.04E-04
Magnesium	Soil	kg	5.98E+00	3.89E-02	5.78E-01	2.78E+00	2.34E+00	4.16E-02	2.00E-01	6.21E-05
Carbon	Soil	kg	5.50E+00	5.56E-02	2.90E-01	1.25E+00	3.56E+00	4.75E-02	3.07E-01	3.92E-05

[39] CAP is Criteria Air Pollutants

Bark	Soil	kg	4.97E+00	4.97E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Aluminum	Soil	kg	4.03E+00	2.70E-02	3.91E-01	1.87E+00	1.58E+00	2.71E-02	1.38E-01	4.13E-05
Manganese	Soil	kg	3.73E+00	2.43E-02	3.60E-01	1.73E+00	1.46E+00	2.59E-02	1.24E-01	3.83E-05
Phosphorus	Soil	kg	1.84E+00	1.20E-02	1.76E-01	8.49E-01	7.27E-01	1.28E-02	6.14E-02	1.88E-05

Table 4-28 All Consumables without Expendable Rocket Booster Water Emissions

Substance	Media	Unit	Total	Reusable Rocket Booster	Propellant (Total) _LOX/LH_2	Propellant (Total) _LOX/LNG	Propellant (Total) _LOX/RP1	Electricity (Launch site)	Chemicals at Launch Facilities (Generic)	Water at Launch Site
Strontium	Water	kg	8.91E+02	1.16E+01	7.60E+01	3.96E+02	3.81E+02	2.16E+00	2.39E+01	4.78E-02
Lithium	Water	kg	7.96E+02	4.40E+01	2.78E+01	5.95E+02	1.11E+02	6.42E+00	1.19E+01	1.88E-01
Chloramine	Water	kg	4.08E+02	5.20E-06	7.36E-05	3.61E-04	2.94E-04	2.60E-05	4.08E+02	1.83E-09
Barium	Water	kg	3.25E+02	1.95E+01	1.48E+01	1.89E+02	9.24E+01	2.24E+00	7.21E+00	1.16E-01
Zinc	Water	kg	2.31E+02	1.13E+01	2.15E+01	1.04E+02	8.83E+01	3.05E-01	5.58E+00	1.23E-02
Process effluent	Water	kg	2.16E+02	2.16E+02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Carboxylic acids, unspecified	Water	kg	2.15E+02	2.06E+00	2.03E+00	9.82E+00	1.87E+02	2.19E+00	1.21E+01	9.29E-04
Nickel	Water	kg	1.99E+02	3.20E+00	1.93E+01	9.46E+01	7.72E+01	2.41E-01	4.74E+00	9.38E-03
Bromine	Water	kg	1.87E+02	9.89E-01	6.15E+00	1.20E+02	5.34E+01	1.65E+00	4.42E+00	3.74E-02
Chlorate	Water	kg	7.08E+01	6.72E-01	2.70E+01	1.16E-01	2.22E-01	3.32E-03	4.28E+01	2.48E-04
Fluoride	Water	kg	6.88E+01	1.93E+01	5.15E+00	2.14E+01	2.11E+01	3.75E-01	1.56E+00	7.15E-03
Titanium	Water	kg	6.66E+01	2.89E+01	3.67E+00	1.81E+01	1.49E+01	1.53E-01	9.34E-01	2.32E-02
Cobalt	Water	kg	43.77744	1.12038045	4.199919	20.56873	16.79625	0.053087	1.037055	0.002027
Copper	Water	kg	30.35765	3.90510998	2.680067	12.62726	10.41915	0.056089	0.668096	0.001876

4.1.2 Impact Assessment for CST Activities in the United States Base-Case

4.1.2.1 Reusable Rocket Booster Per Launch

Figure 4-6 shows the reusable rocket booster's elements' impact in the 15 characterization categories. The highest contributor to most of the categories was the Fairing and the 1st Stage (which included the landing propellant) was the next highest contributor. Each element of the reusable rocket booster contributed to ozone layer depletion, with the reusable rocket 1st Stage contributing the most. This perspective provides a system view of the reusable rocket booster. When evaluated as a whole system, Normalization shows the **reusable rocket booster** (20 times per use) impacts **Human health and Resources** the most and then climate change, as shown in Figure 4-7 of the Damage Assessment, Normalization. The Human health constituents that influence this damage area the most include: sulfur dioxide; particulates, <2.5 µm; nitrogen oxides; dioxin, 2,3,7,8 Tetrachlorodibenzo-p-; and aromatic hydrocarbons in the air. For Resources, the constituents influencing this damage area the most include: coal, natural gas, crude oil, uranium, copper, and nickel. These are all used as raw materials in the production processes. The constituents influencing climate change the most are carbon dioxide and methane, fossil; methane and dinitrogen monoxide in the air.

Figure 4-8 provides the single score and shows the Fairing is the greatest contributor overall to all four damage areas and is more than twice the 1st Stage.

The following sections will provide individual element contributions to better understand what may be the influencing factor for their contribution.

4.1.2.1.1 Impact Assessment of 1st Stage Reusable Rocket Booster with Landing Propellant

The 1st Stage rocket booster impact assessment revealed in the characterization categories as shown in Figure 4-9 that the **added propellants for the landing** contributed the most to each of the characterization categories, with the exception of mineral extraction. A NEPA document (FAA, 2017) on a Falcon 9 launch showed a boost back and landing of one core[40] would generate 42.6 metric tons of CO_2.

[40] Core consists of casing, nine engines and other elements comprising a 1st Stage rocket booster. This study with the generic rocket uses three cores and 27 engines for the 1st Stage.

The engines contributed most to the mineral extraction category and were next highest contributor in the other 13 categories. With more accurate engine data, a better understanding of its contribution to these categories could occur. However, with the limited data available and simplified materials selected, the engine does show it is a major contributor.

In Figure 4-10, the damage assessment shows the propellants for landing are the major contributor to Human health, Ecosystem quality, Climate change and Resources. The next greatest contributor was the engines to all four damage assessment categories. The Normalization results indicate that the two most impacted damage areas are Human Health at 47.5% and Resources at 32%. The major contributors again are propellant for landing and engines. Single score damage assessment identifies propellants and engines are the most contributing to the damage areas. Climate Change seems to be impacted by the propellant, engines, propellant tanks; external casing and landing legs/grid fins, respectively. Figure 4-11 shows the single score for each Stage 1 input, including barge transportation.

The 2^{nd} Stage of the reusable rocket booster characterization results shown in Figure 4-12 indicate the one engine used in the second stage contributes the most to all of the 15 categories. The next highest contributors are the external casing and propellant tank structures. These results of the engine and the external casing and propellant tanks are the similar in the damage assessment, with the engine contributing the highest to Human Health damage. Human health in the Normalization results is the highest impacted damage area, with the engine contributing the highest to Human health as shown in Figure 4-13. The Single Score results shown in Figure 4-14 reveal that the external casing and propellant tank structures impact the Human health area overall at 57.8%. The primary contributing constituents found in Air at the 5% cutoff are nitrogen oxides; particulates, < 2.5 µm and sulfur dioxide. Climate Change is in total impacted about 19.6% from the 2^{nd} Stage life cycle. The main constituent contributors for climate change at the 1% cutoff are the carbon dioxide, fossil; methane, fossil; methane, and tetrafluoro-, CFC.

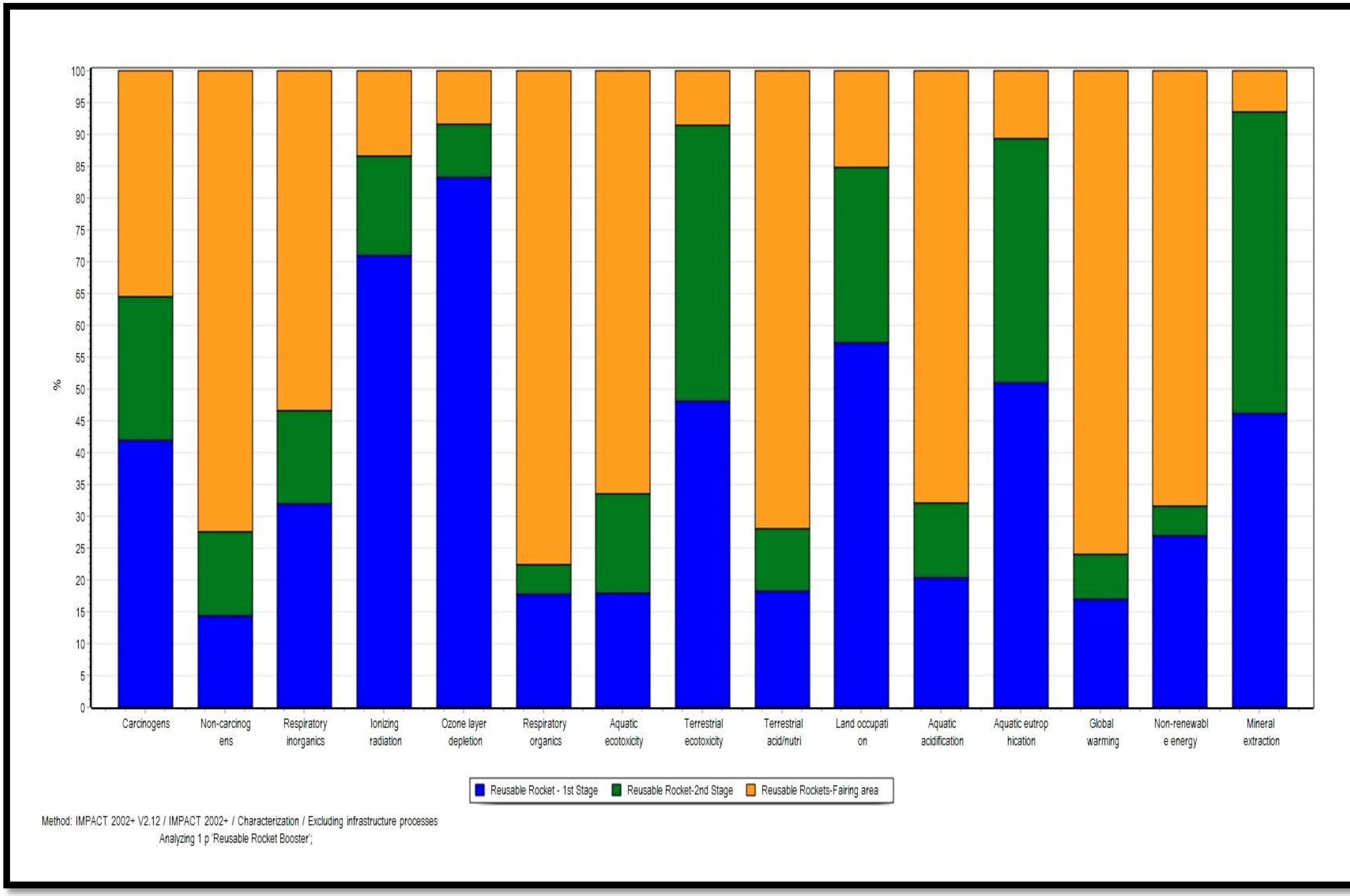


Figure 4-6 Reusable Rocket, Characterization Categories (SimaPro Software)

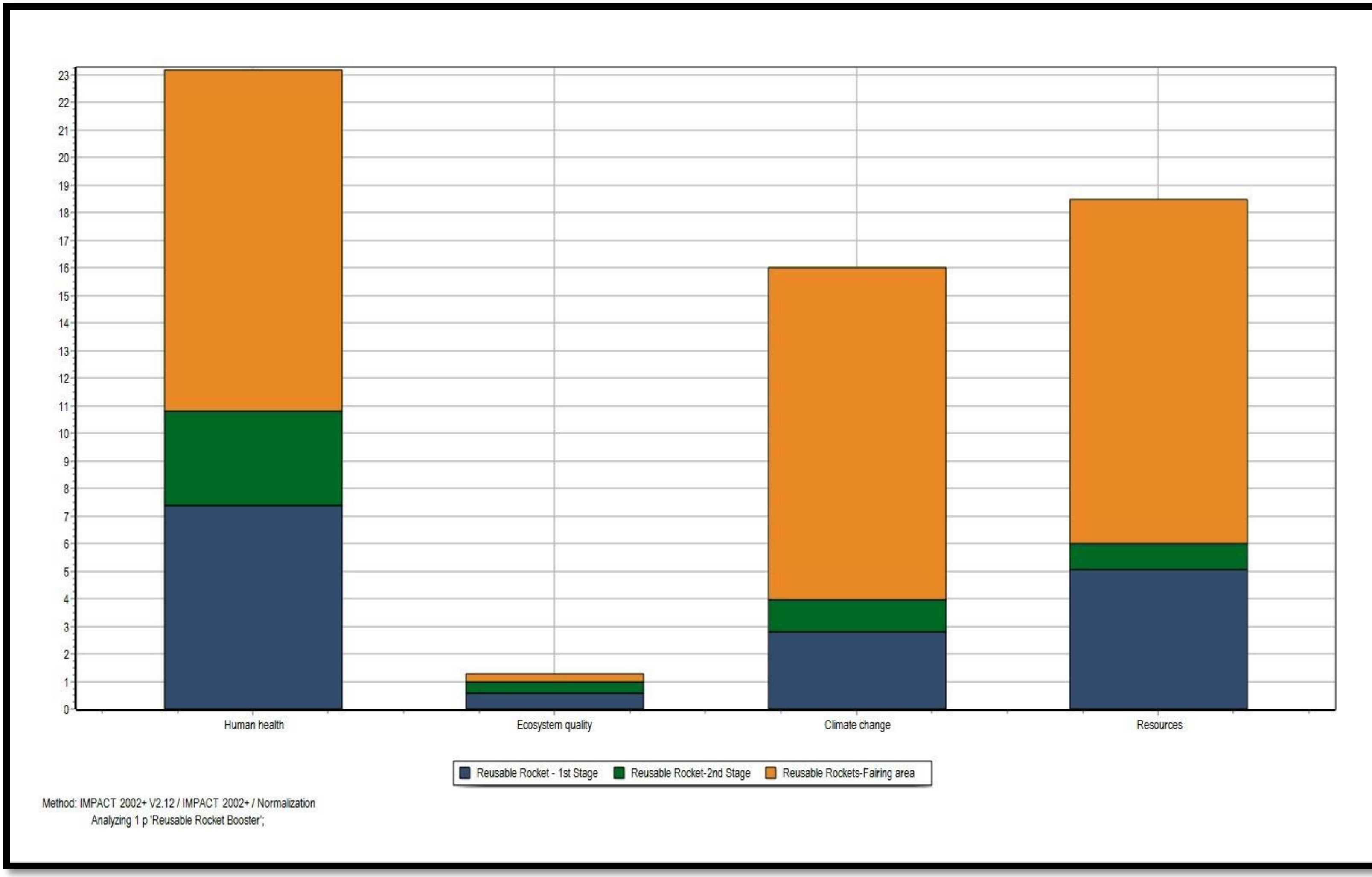


Figure 4-7 Reusable Rocket, Damage Assessment Normalization Results

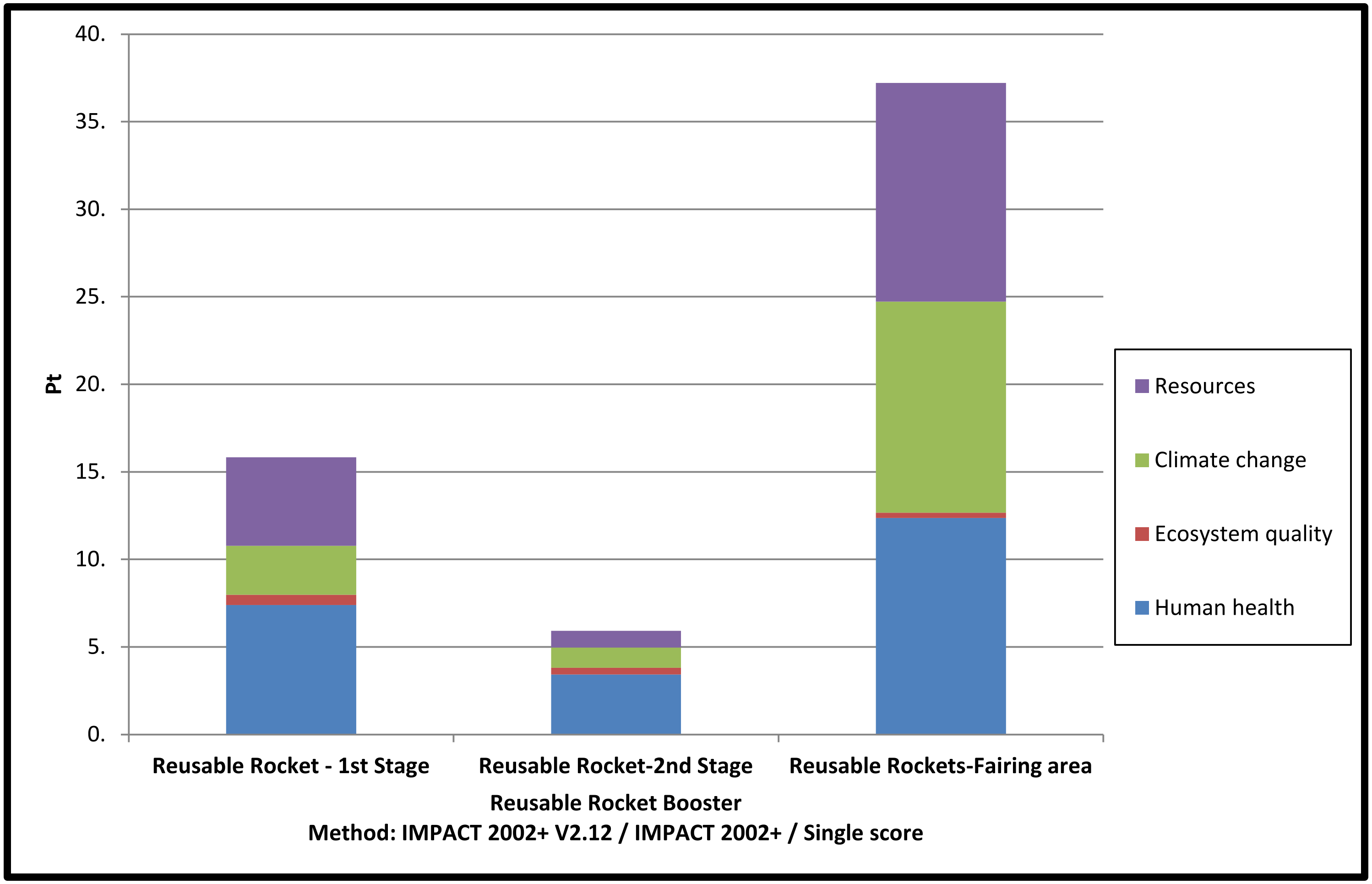


Figure 4-8 Reusable Rocket, Damage Assessment Single Score Results

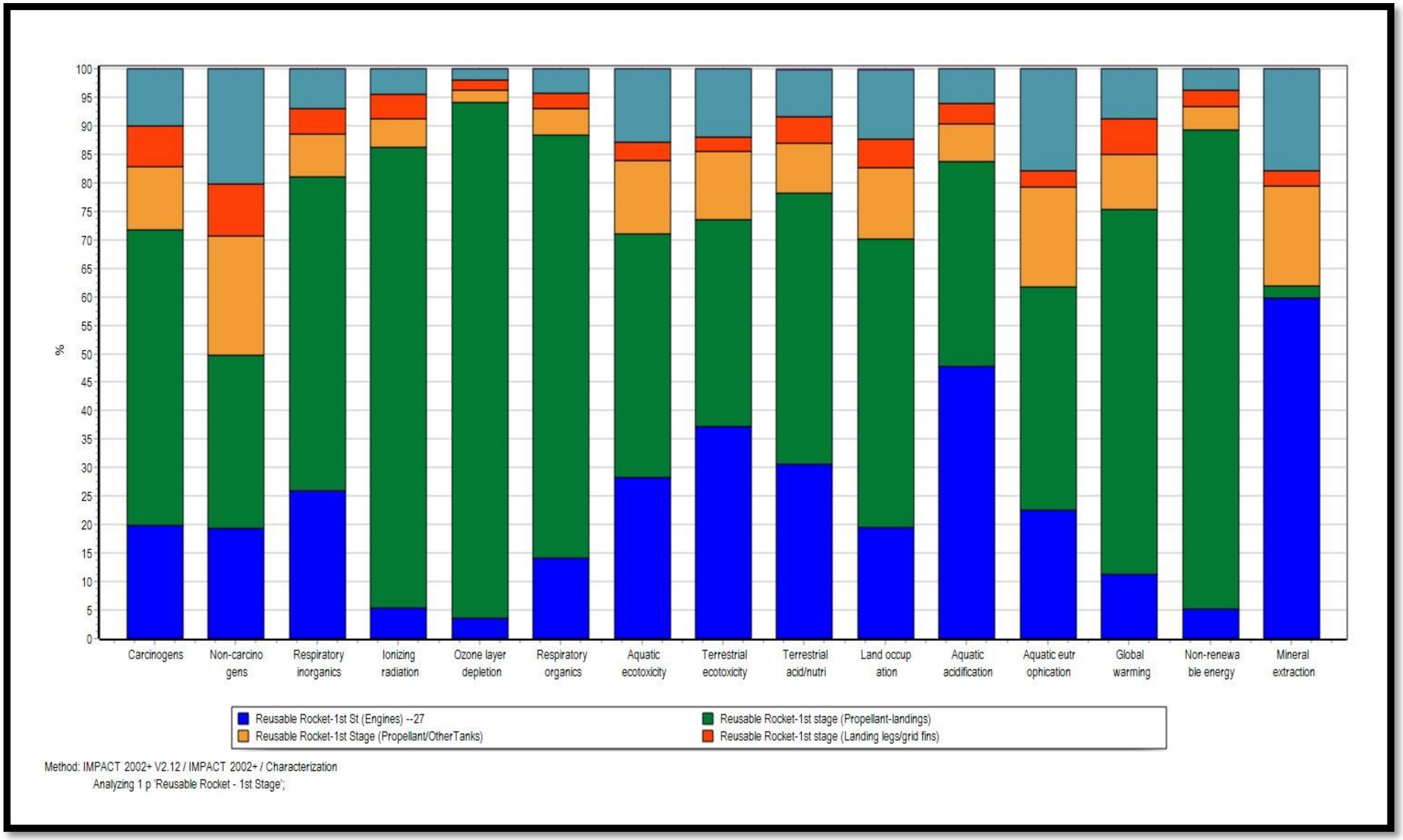


Figure 4-9 Reusable Rocket, 1st Stage Characterization Categories (SimaPro Software)

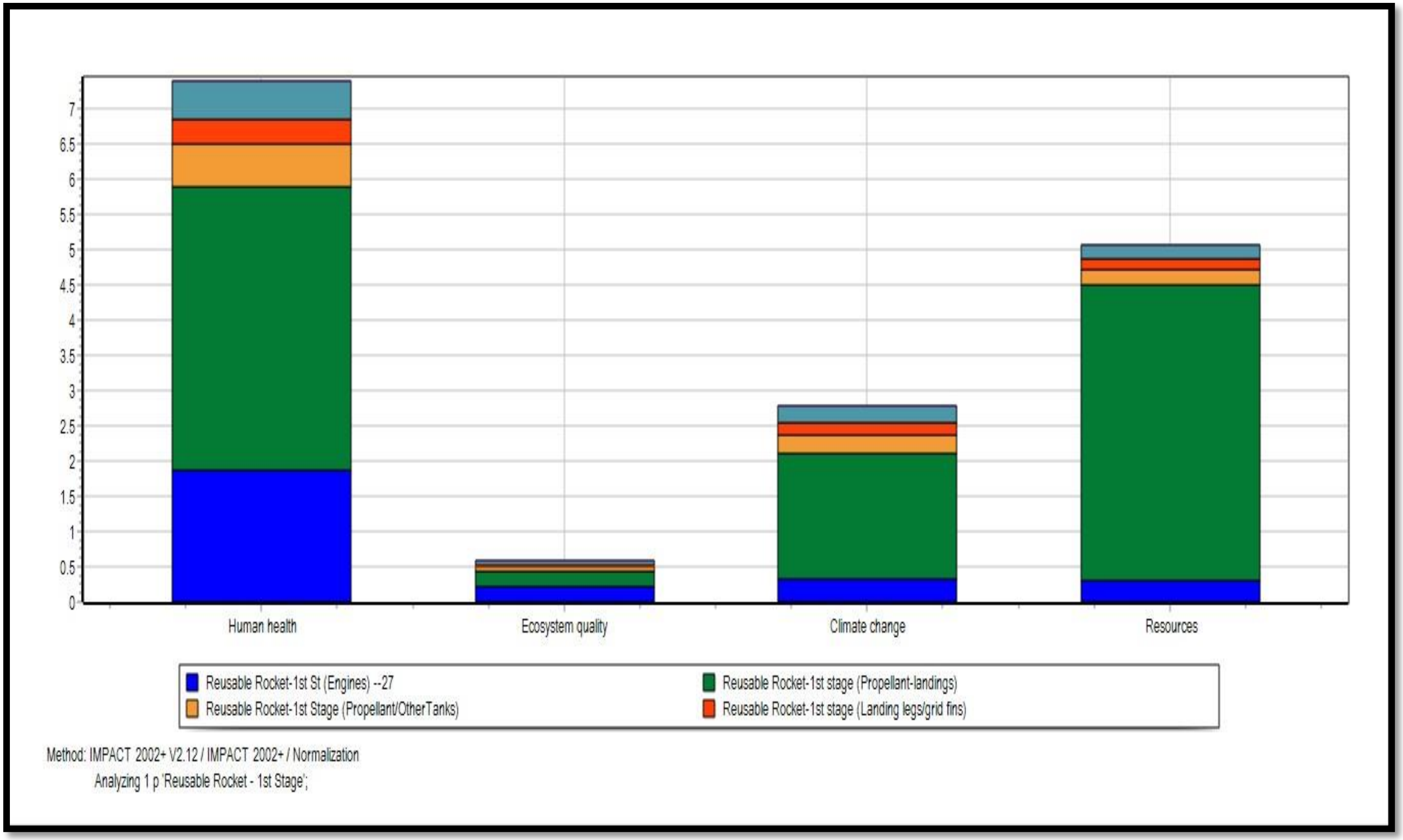


Figure 4-10 Reusable Rocket, 1st Stage Damage Assessment Normalization Results (SimaPro Software)

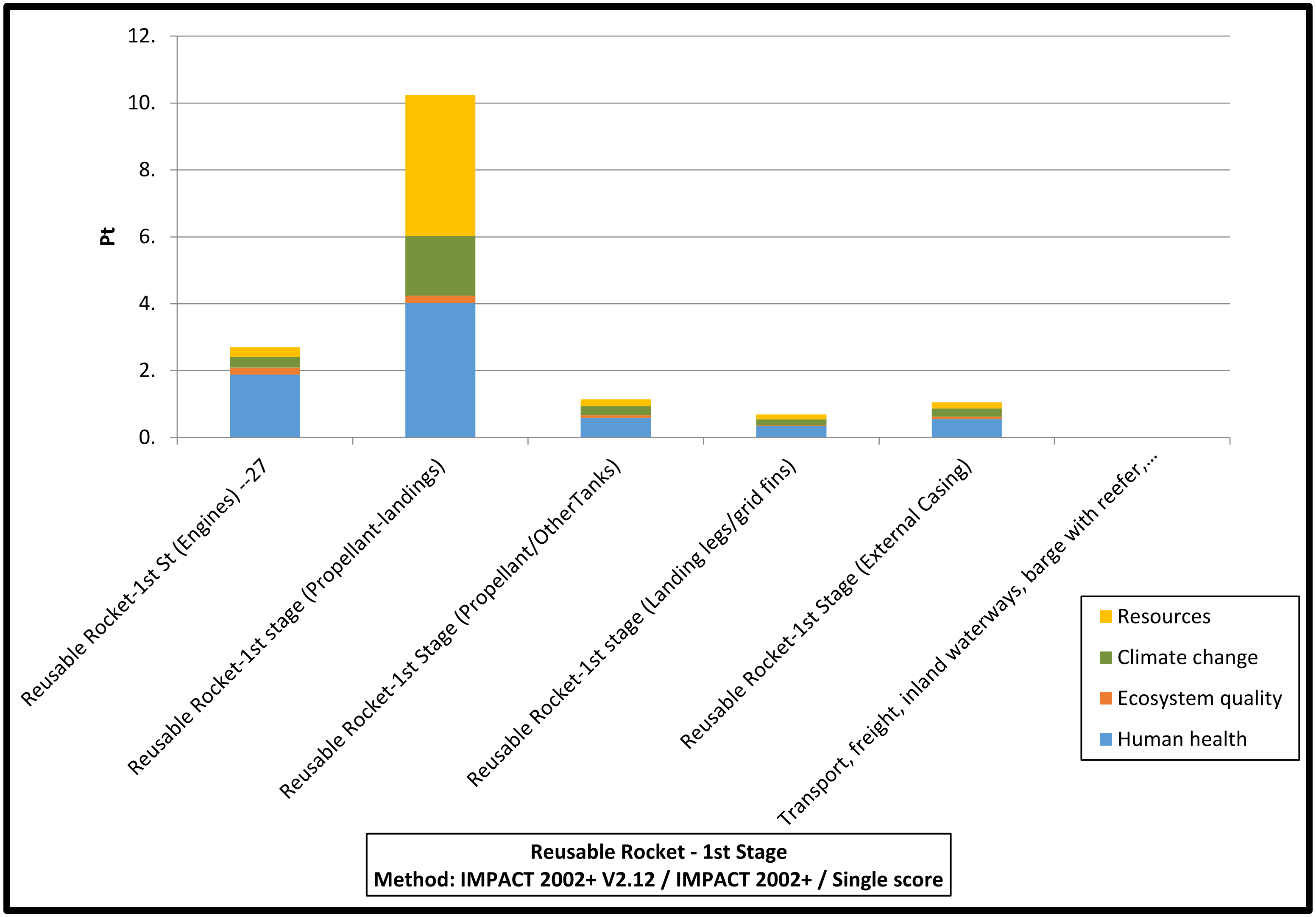


Figure 4-11 Reusable Rocket, 1st Stage Damage Assessment - Single Score (SimaPro Software)

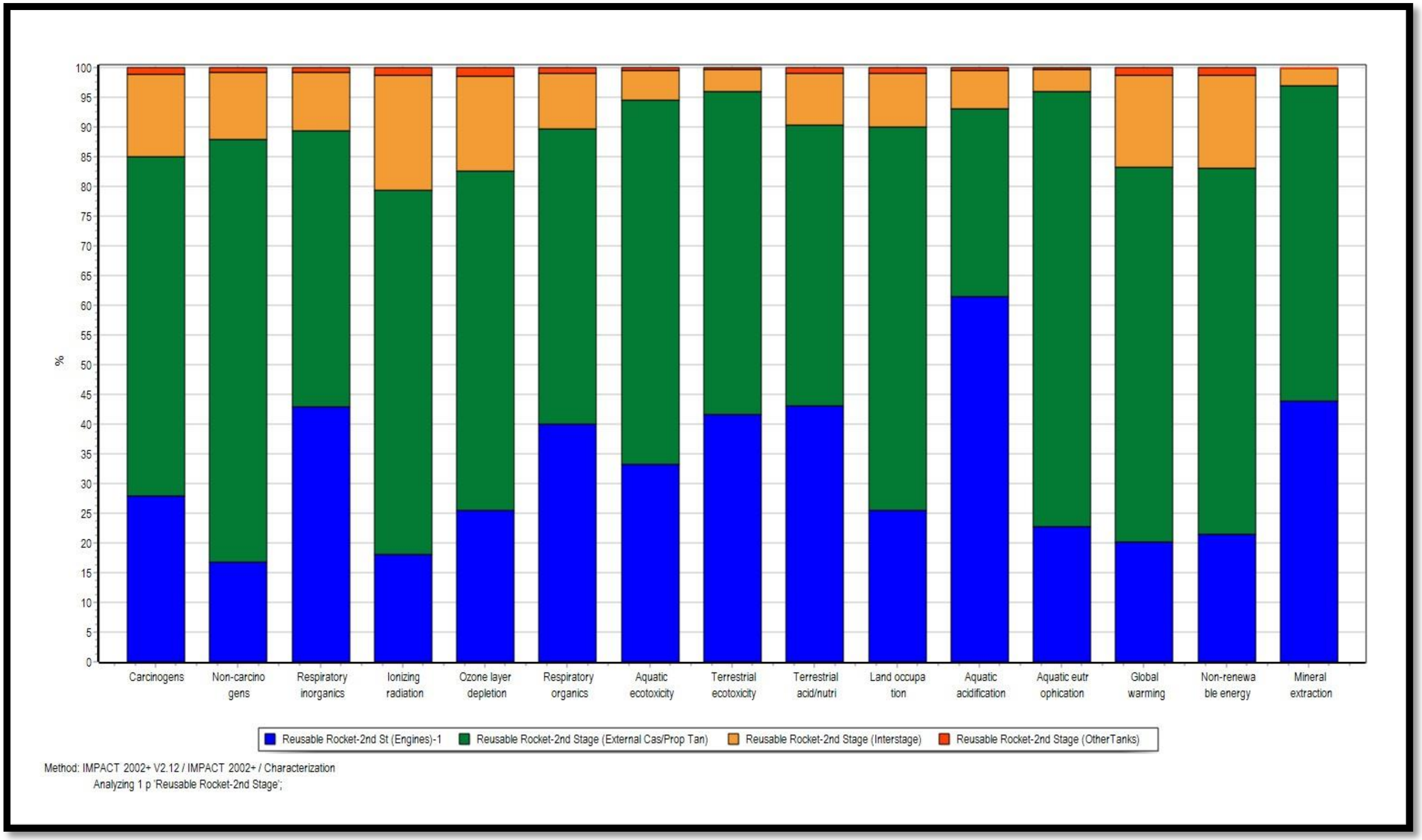


Figure 4-12 Reusable Rocket, 2^{nd} Stage Characterization Categories (SimaPro Software)

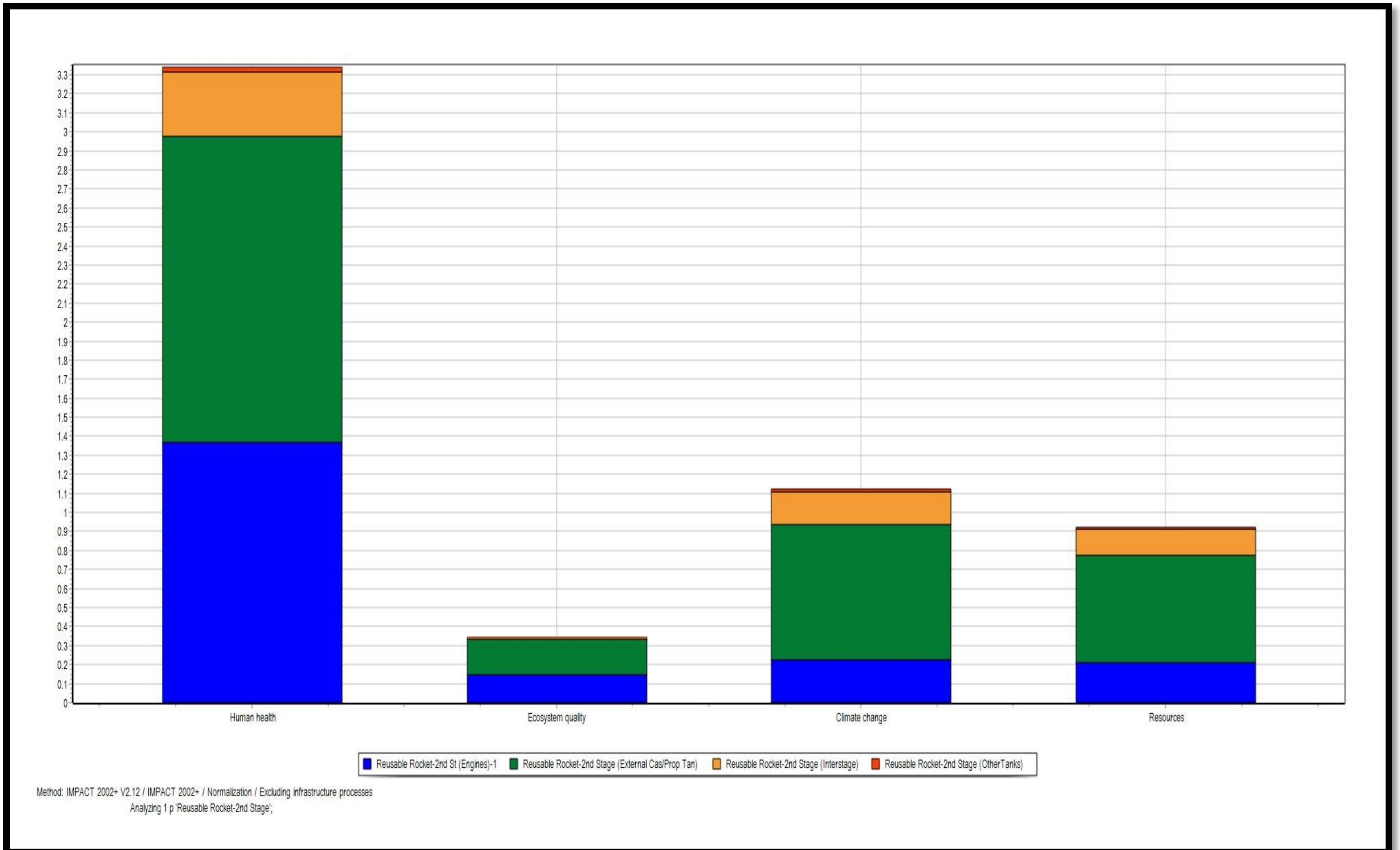


Figure 4-13 Reusable Rocket, 2nd Stage Damage Assessment Normalization (SimaPro Software)

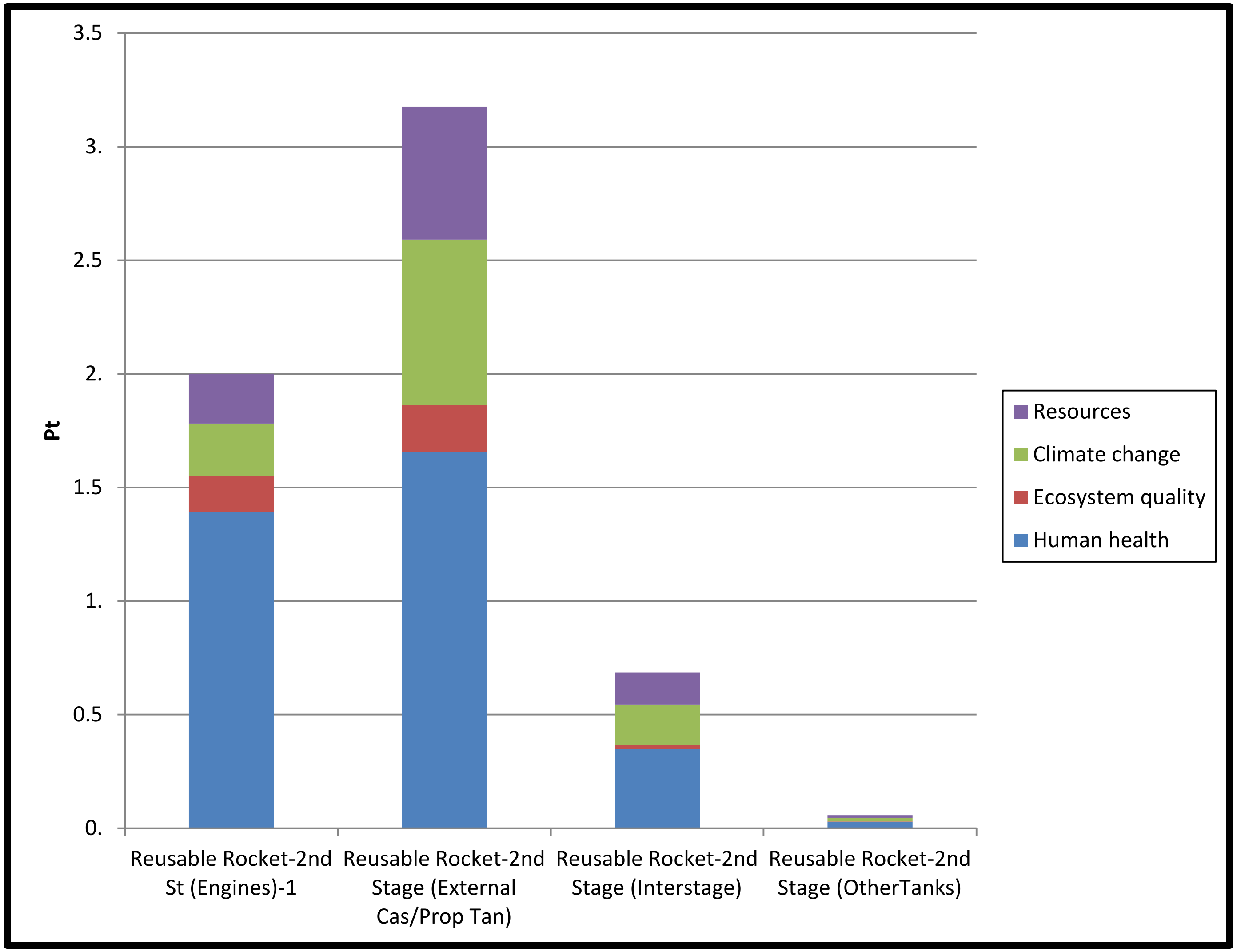


Figure 4-14 Reusable Rocket, 2nd Stage Damage Assessment Single Score

Fairing results showed metal composite material (MCM) impacted nine of the 15 categories, Figure 4-15. Aluminum alloy, metal matrix composite influenced six of the 15 categories at high percentages. Bisphenol A epoxy influenced carcinogens, respiratory inorganics, ionizing radiation, ozone layer depletion, respiratory organics, terrestrial ecotoxicity, land occupation, and aquatic eutrophication in relatively high percentages and influenced the other categories as well. Finally, aluminum ingot influenced carcinogens, ionizing radiation and mineral extraction in higher percentages, and terrestrial ecotoxicity.

Damage assessment, shown in Figure 4-16, revealed that the MCM panel contributed the most in all four damage categories for the Fairing. MCM had the largest effect on global warming and carcinogens. Aluminum alloy, metal matrix composite influenced the Ecosystem quality to the greatest extent after the MCM. The results for this Fairing could be modified and may show a different result with better data on the manufacturing and materials composition. For the Damage Assessment Normalization results, the most impacted areas were Resources, Climate Change and Human Health, respectively. The least impacted was Ecosystem Quality by the Fairing use. For Single score, the MCM influenced approximately equally Human Health, Climate Change and Resources. A Network analysis illustrates the factors contributing to MCM's influence in the Damage Assessment, as shown in Figure 4-17.

4.1.2.2 Expendable Rocket Booster Per Launch

The expendable rocket booster is built in the same manner as the reusable rocket booster, with the exception that it is one-time use, and has no added propellants, and no landing legs or grid fins in the 1st Stage. The expendable rocket booster may have other realistic differences than these identified in this study, but these differences were the ones chosen for the study because of data access and manufacturing and design information. The characterization category results are shown in Figure 4-18. The 1st Stage expendable rocket contributes the most to each of the 15 categories versus the 2nd Stage or the Fairing. This result is different than the reusable rocket booster but expected since this is a one-time use of the expendable 1st Stage, so more materials are needed to produce these boosters each time for launch. Figure 4-19 shows Human health is impacted the most and then Climate change. This result is different than the reusable rocket because the 1st Stage is more influential due this element being manufactured each time, whereas, the reusable is used 20 times. The single score of the expendable rocket booster, Figure 4-20, shows the 1st Stage engine and its overall contribution to the damage areas.

The engines were the highest contributor in all of the Damage Assessment areas in the 1st Stage, with propellant and other tank structures the next highest contributors. For 2nd Stage, the engine again was the major contributor to the Damage Assessment areas and external casing and propellant tanks were the next greatest contributors. The Damage Assessment Human health area, 10% cutoff of constituent contribution as shown in Figure 4-21 gives some insight into the life cycle inputs for the system of the expendable rocket.

Figure 4-22 shows the 1st Stage characterization with the engines as the main contributor to all categories. The propellant and gas tanks contribute the next to all of these categories. Figure 4-23 damage assessment reveals the Human health damage area is the greatest impacted with the 1st Stage engines as the main contributor.

For the 1st Stage expendable rocket engine, Figure 4-24 and Figure 4-25 show the main influencers to the Human health and Climate change damage areas at the 10% cutoff. These data provide additional detail into the life cycle phase contributions found in the raw materials acquisition, materials processing, and manufacturing needed to produce the engine detailed in this study.

For the 2nd Stage expendable rocket shown in Figure 4-26, the characterization results show the external casing and propellant tanks contribute the most to the categories. Figure 4-27 shows the damage assessment where Human health is the most affected damage area with the external casing and propellant tanks contributing the most.

For the Fairing, shown in Figure 4-28, MCM contributes the most to 8 categories but not the following: ionizing radiation, ozone layer depletion, terrestrial ecotoxicity, aquatic eutrophication, mineral extraction and land occupation. The other major contributor was aluminum alloy, metal matrix composite. Figure 4-29 shows the damage assessment where Human health, Climate change, and the Resources had similar levels of impact.

The materials composition and how these raw materials are extracted and the energy needed to manufacture these components are important in order to determine the environmental burden from each launch both the expendable and the reusable rockets. Additive or 3-D manufacturing is now being used to produce engine parts or components at a faster rate and with less impact on raw materials or specialized materials. Additive manufacturing will be discussed in the green technology, Objective 3, of this study as a means to reduce the environmental footprint from one launch for the expendable rocket booster.

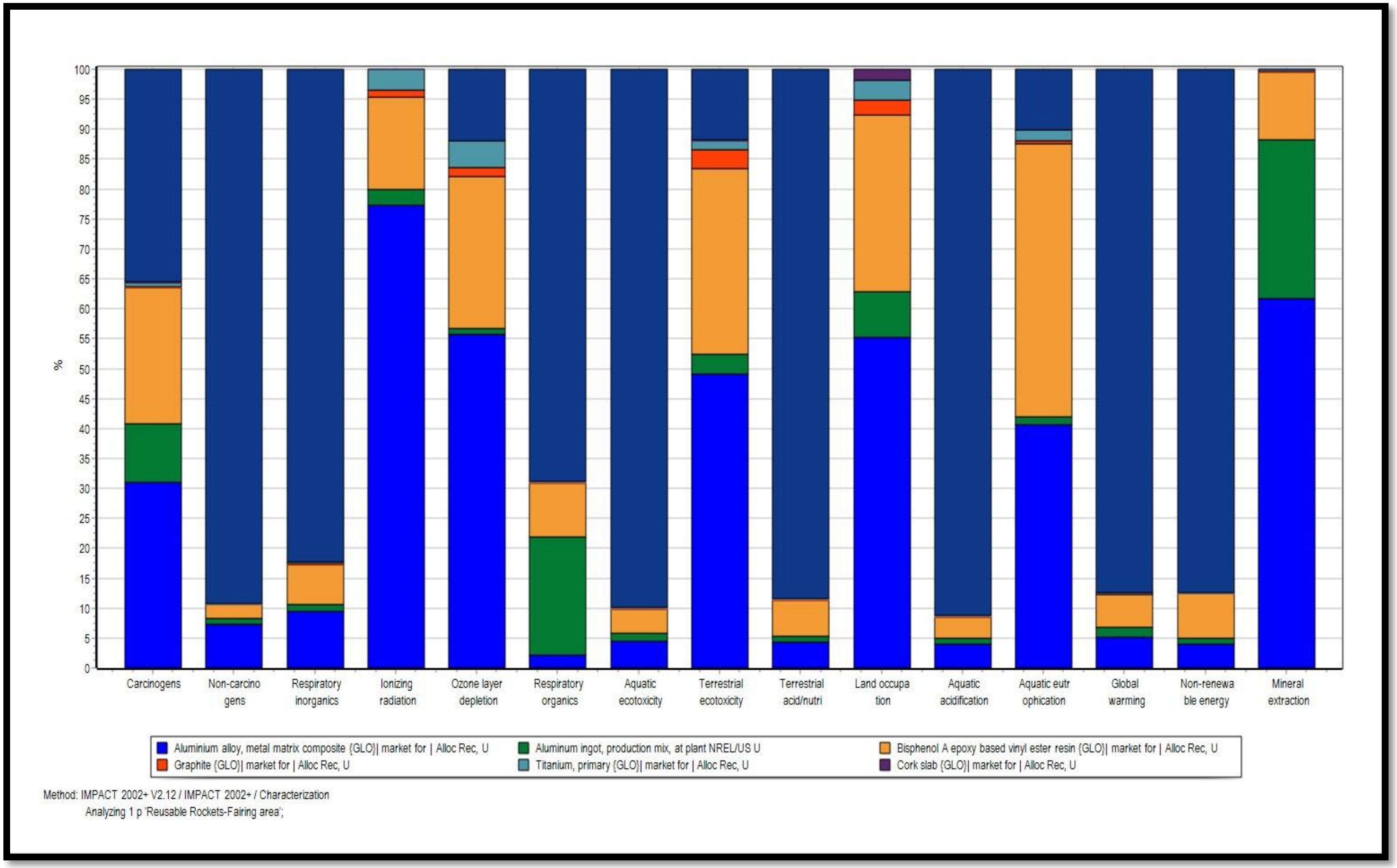


Figure 4-15 Reusable Rocket, Fairing Characterization Areas (SimaPro Software)

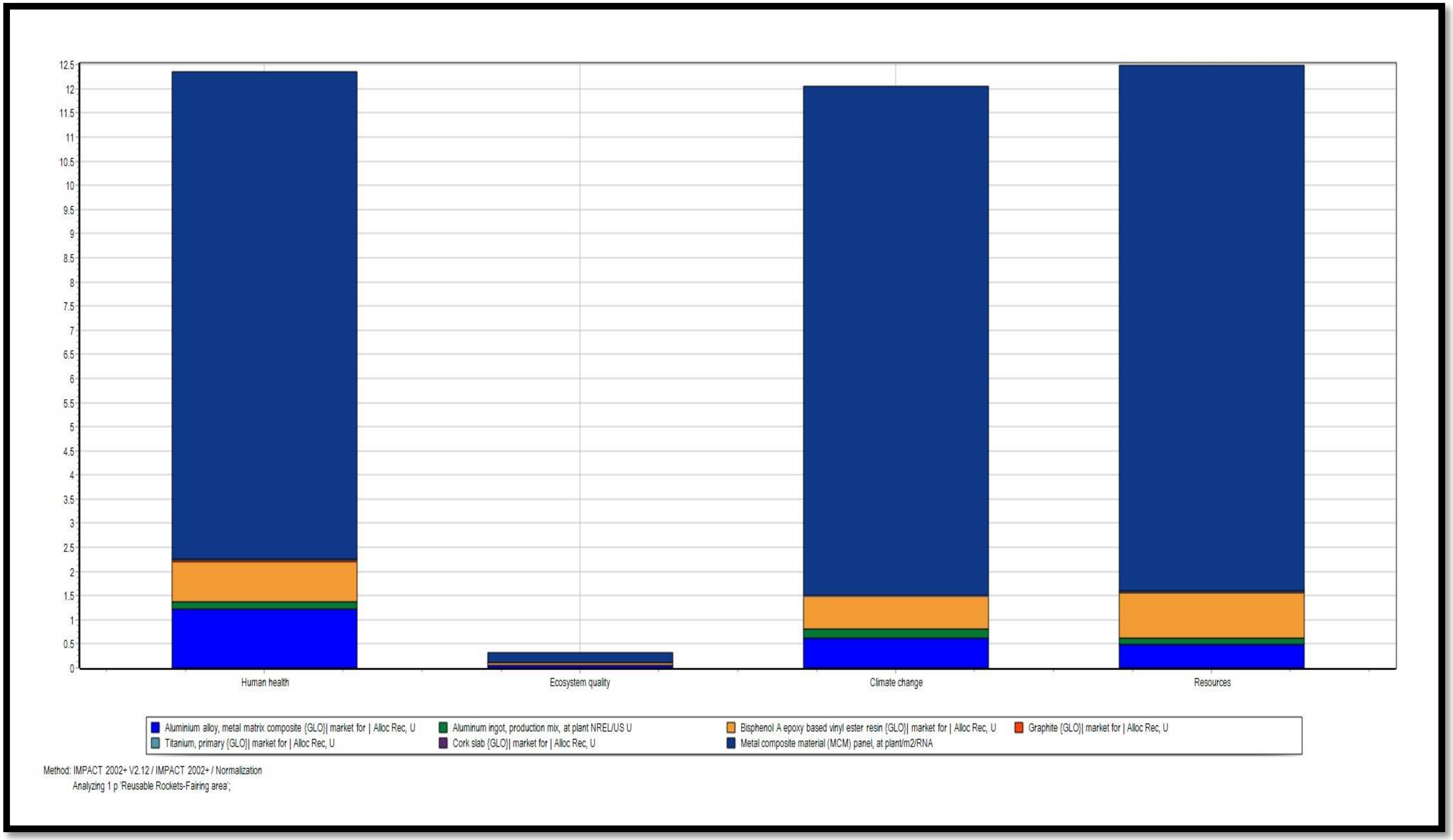


Figure 4-16 Reusable Rocket, Fairing Damage Assessment Normalization (SimaPro Software)

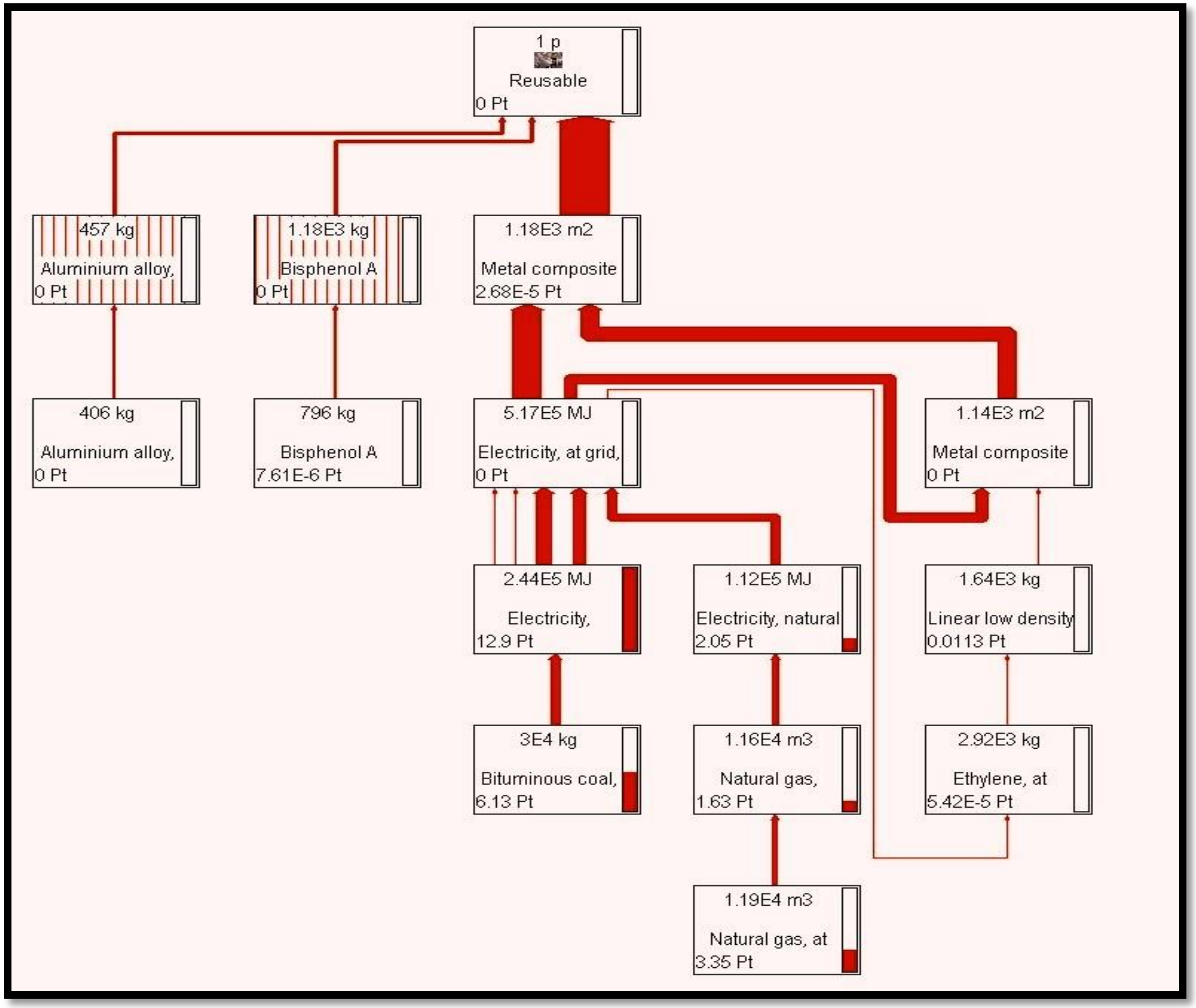


Figure 4-17 Reusable Rocket, Fairing Network – Single Score (SimaPro Software)

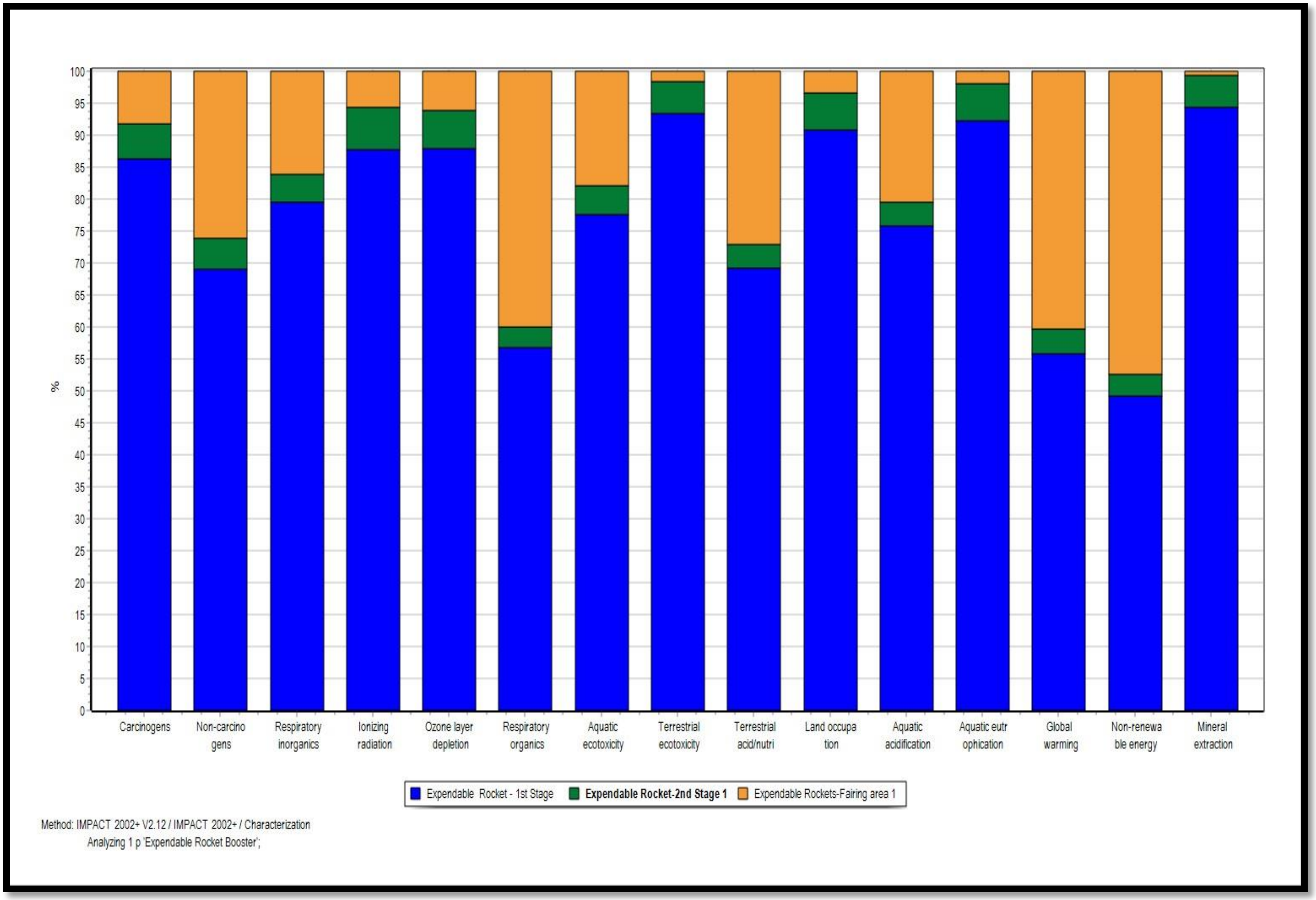


Figure 4-18 Expendable Rocket Booster Characterization Categories (SimaPro Software)

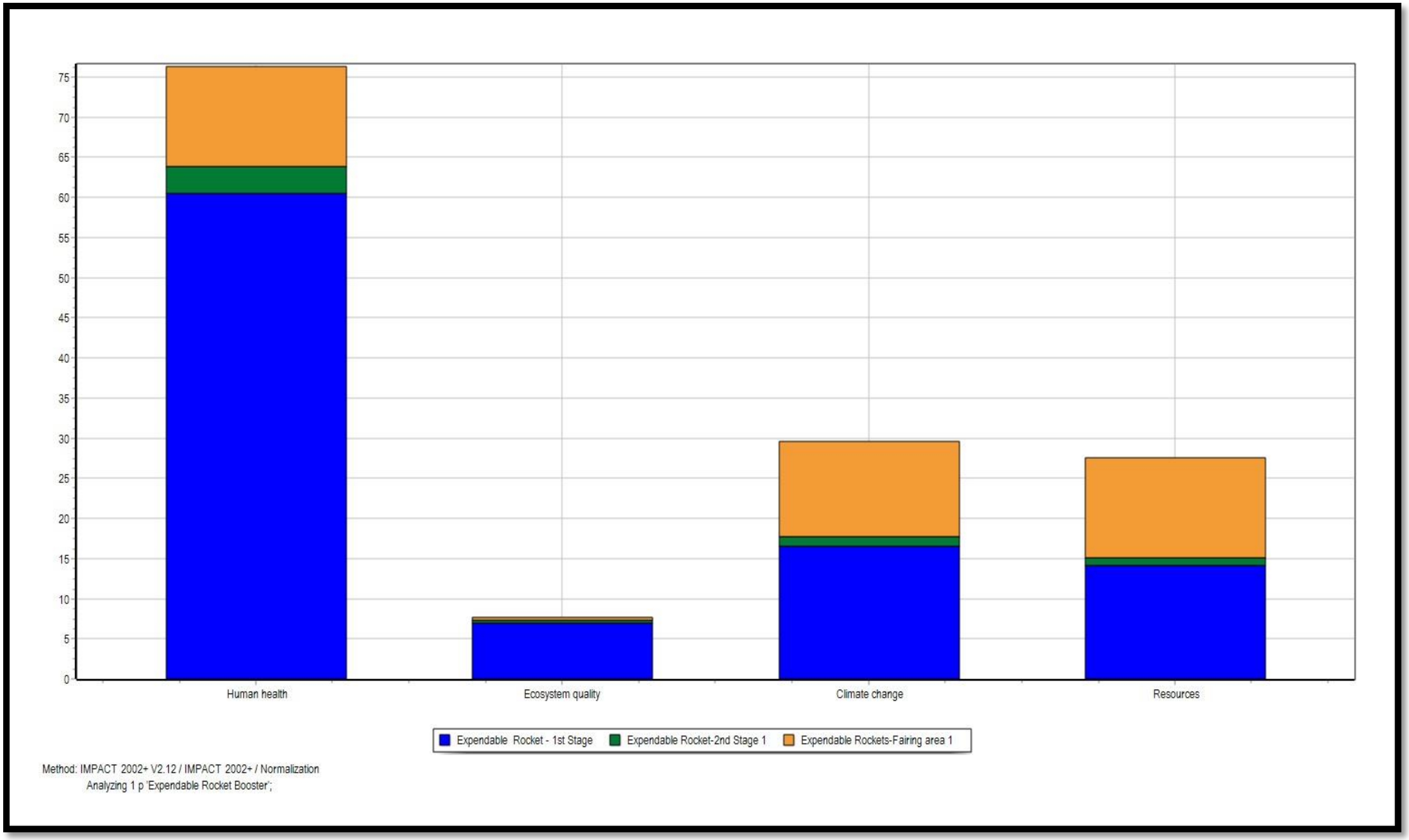


Figure 4-19 Expendable Rocket Booster Damage Assessment Normalization (SimaPro Software)

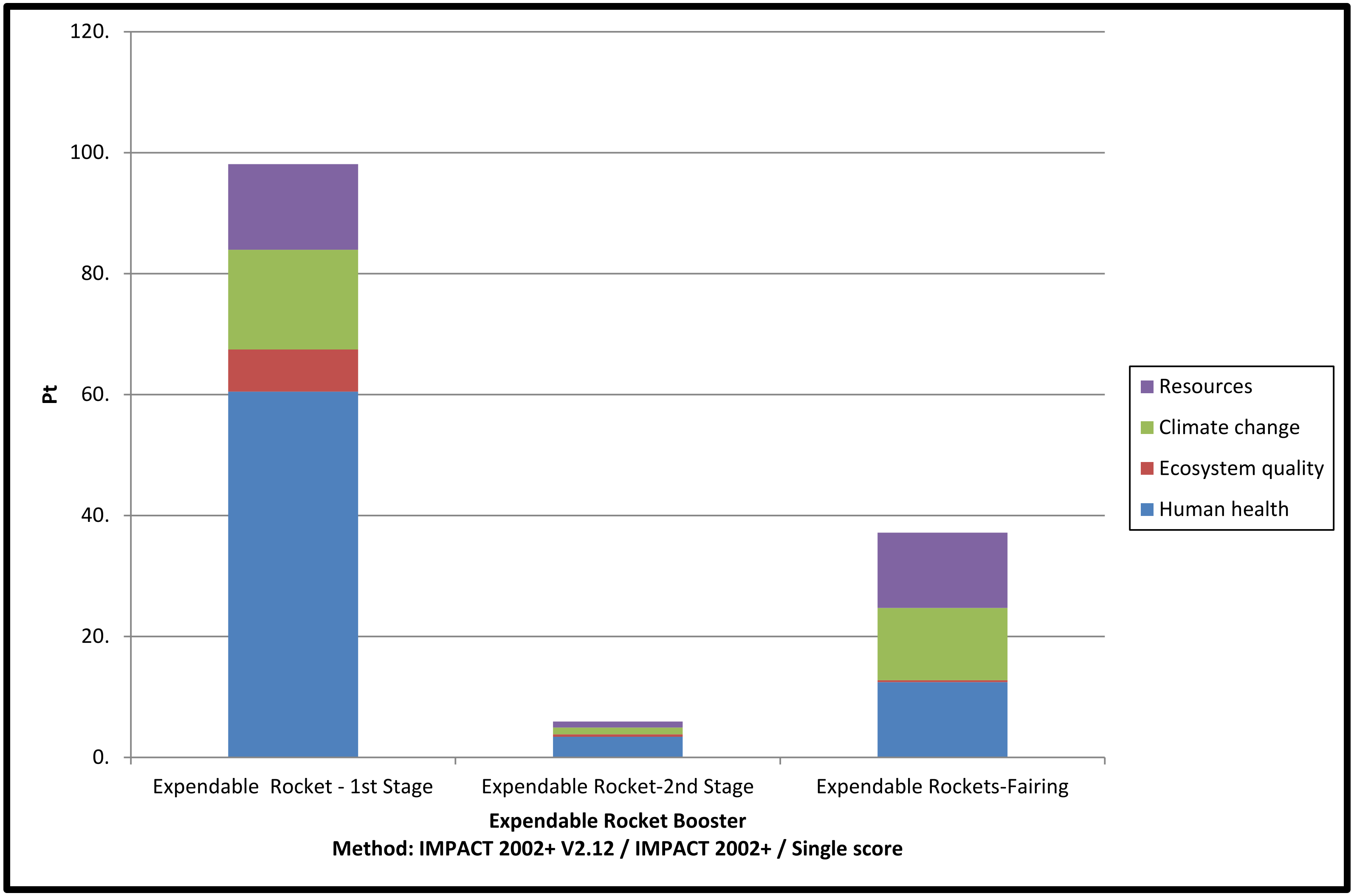


Figure 4-20 Expendable Rocket Booster Damage Assessment Single Score

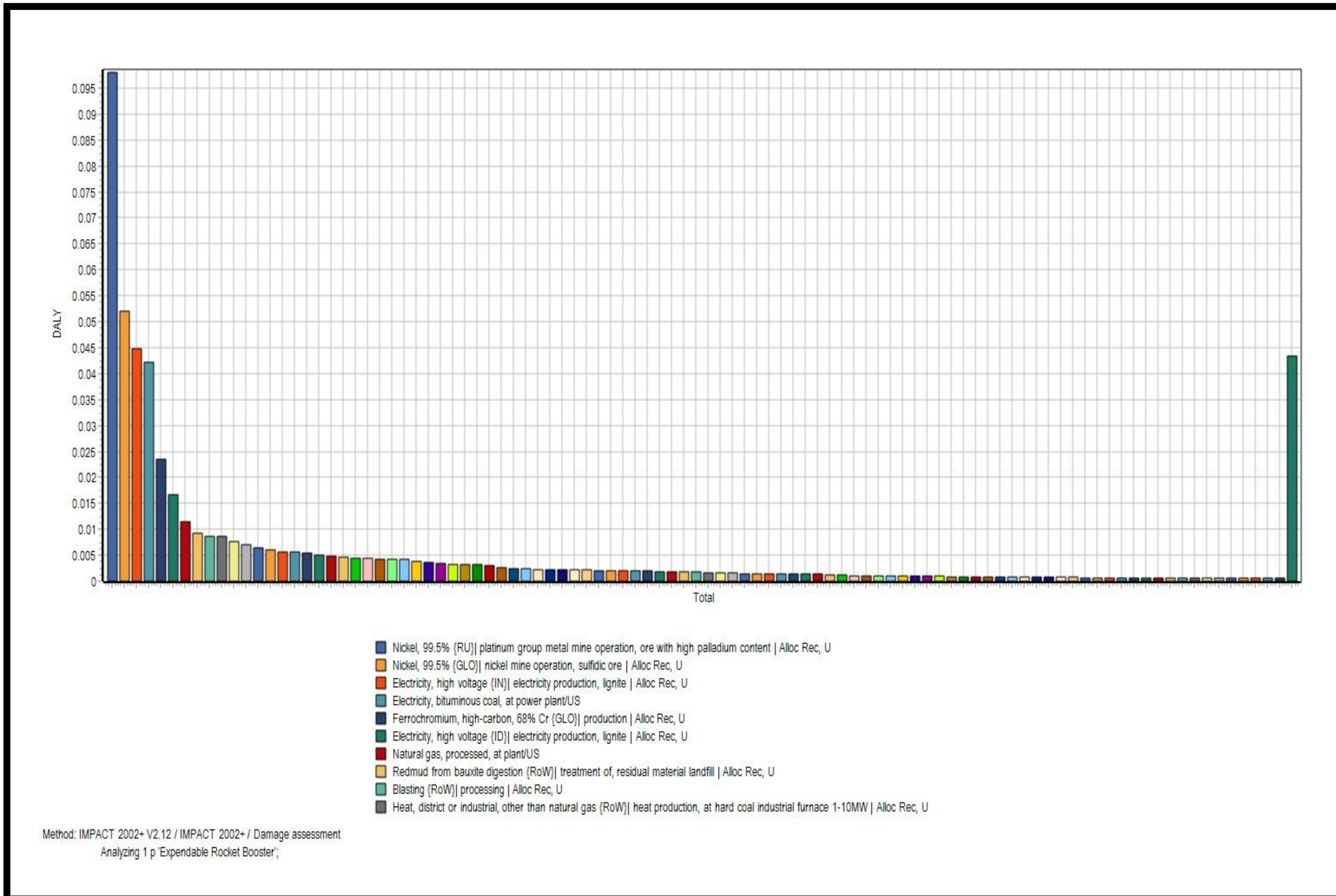


Figure 4-21 Expendable Rocket Normalization – Human Health, Constituents in Processes at 10% Cutoff (SimaPro Software)

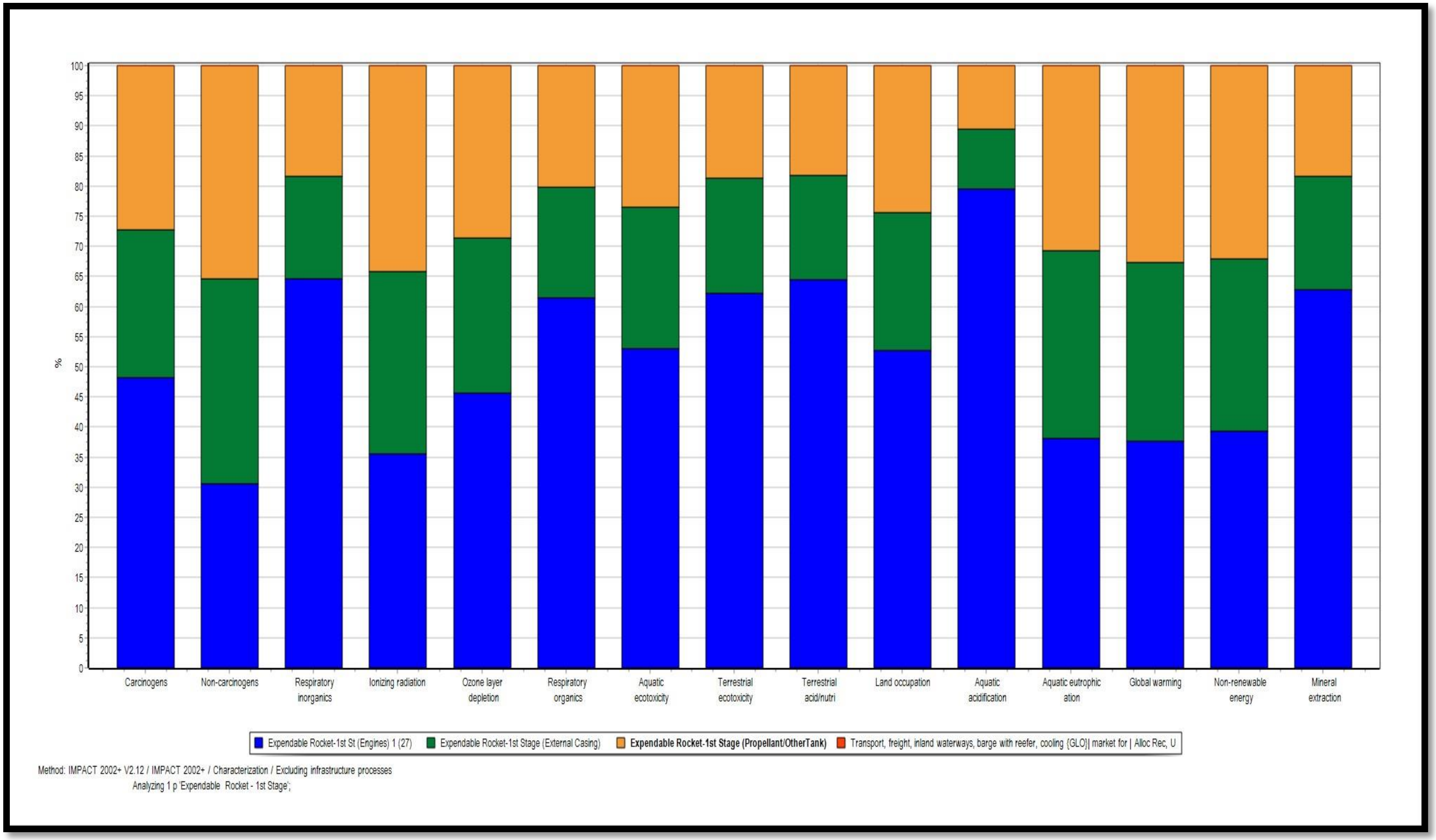


Figure 4-22 Expendable Rocket 1st Stage Characterization Categories (SimaPro Software)

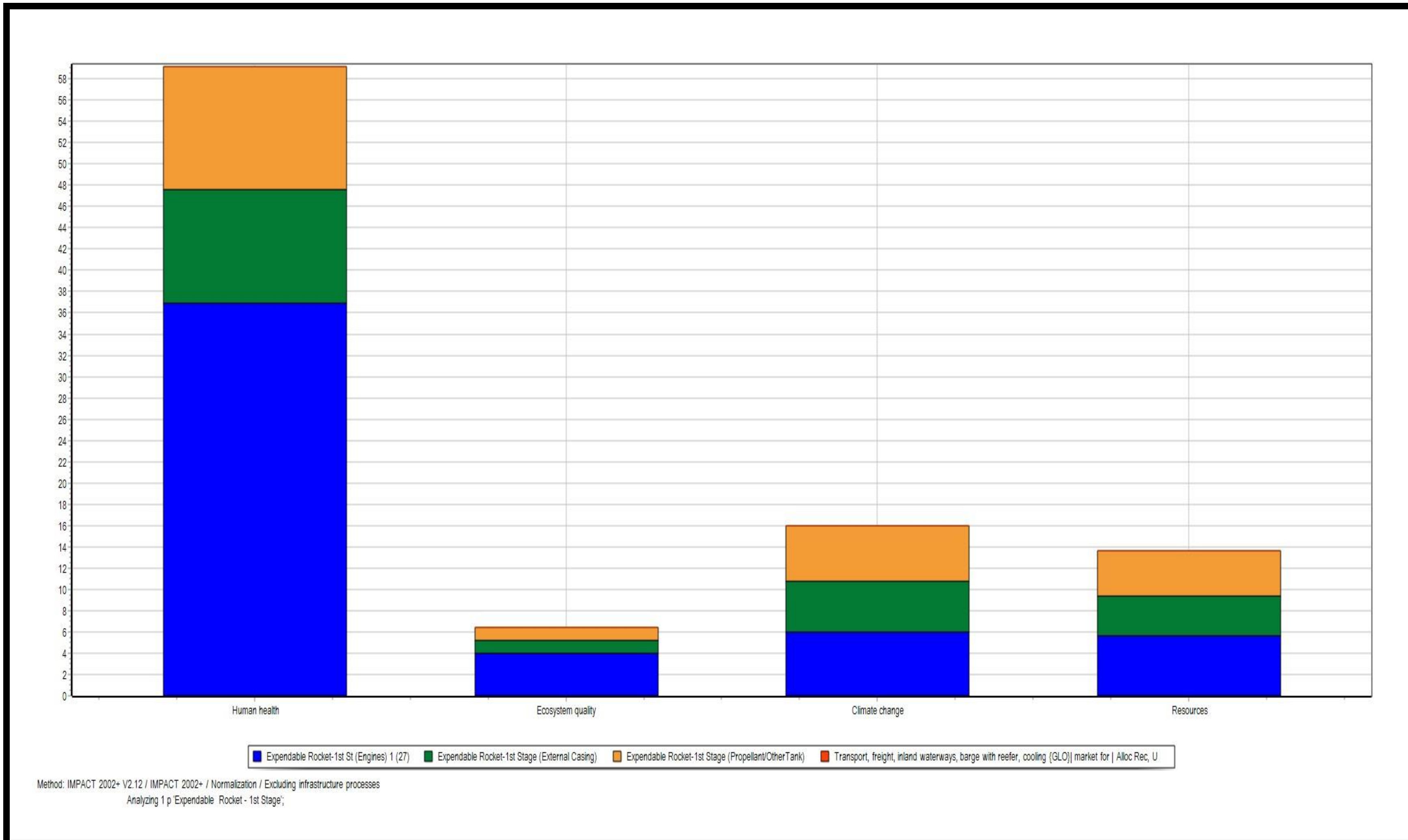


Figure 4-23 Expendable Rocket 1st Stage Damage Assessment Normalization (SimaPro Software)

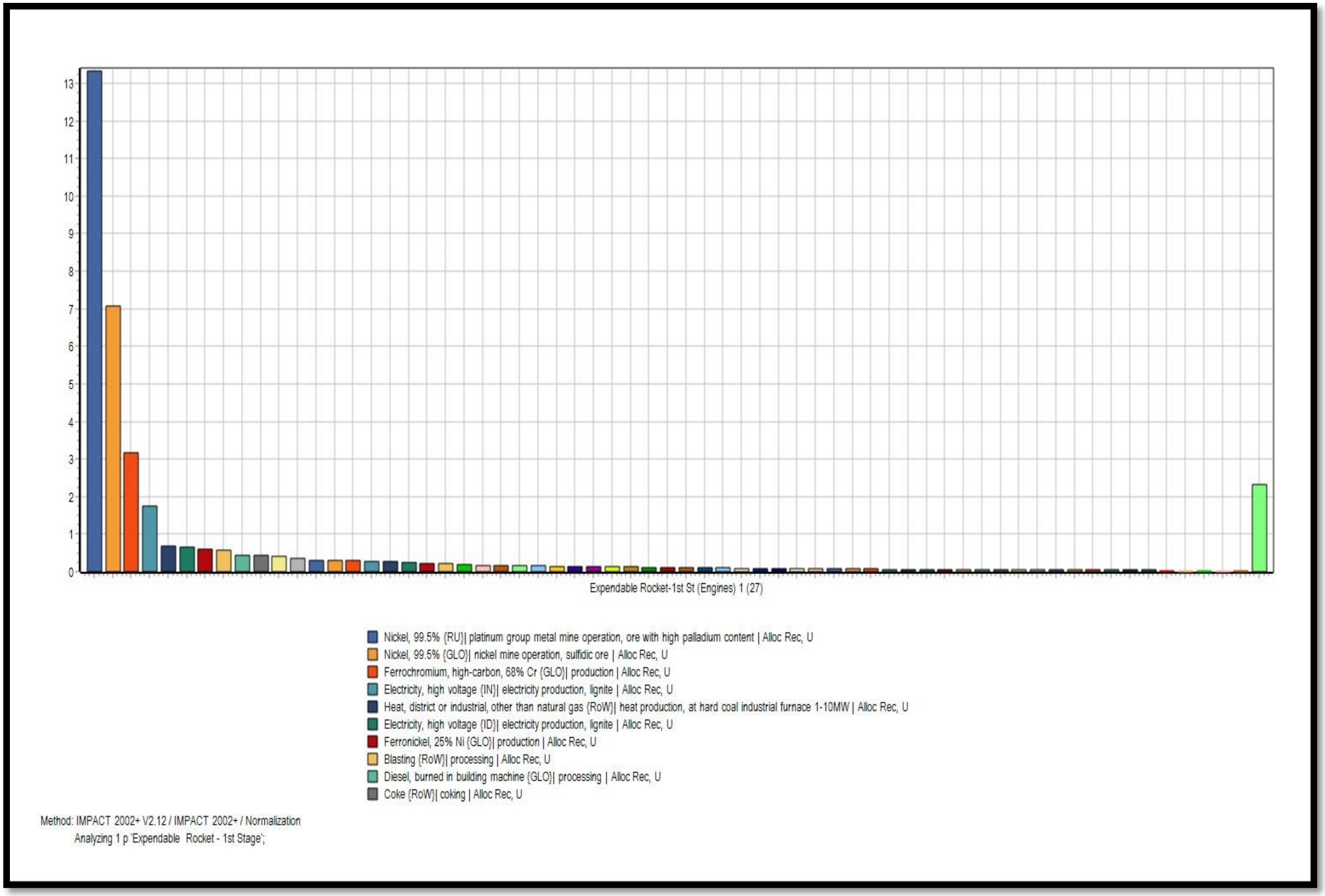


Figure 4-24 Expendable Rocket, 1st Stage Engines Damage Assessment – Normalization, Human Health Constituents at 10% Cutoff (SimaPro Software)

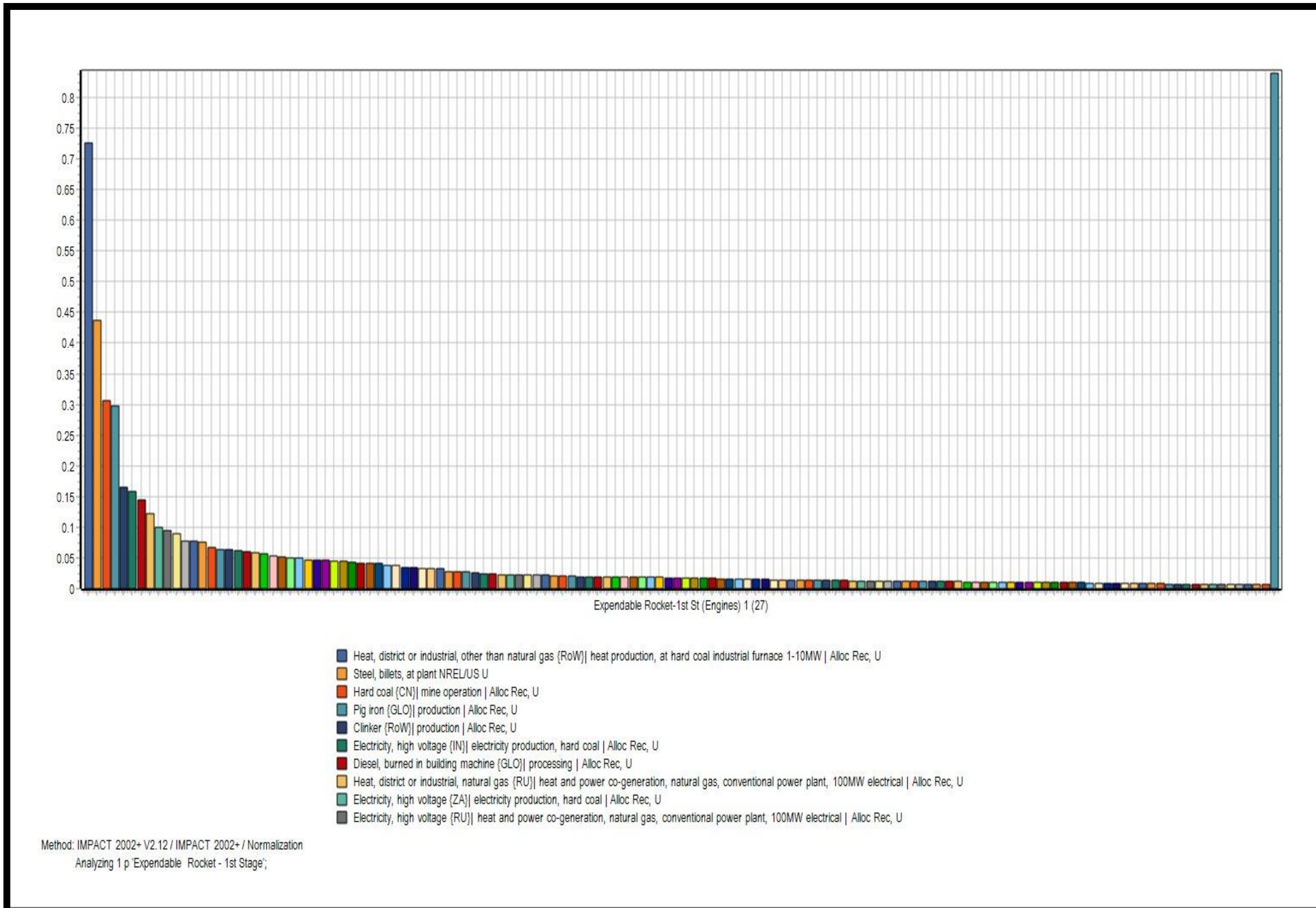


Figure 4-25 Expendable Rocket, 1st Stage Engines Damage Assessment – Normalization, Climate Change Constituents at 10% Cutoff (SimaPro Software)

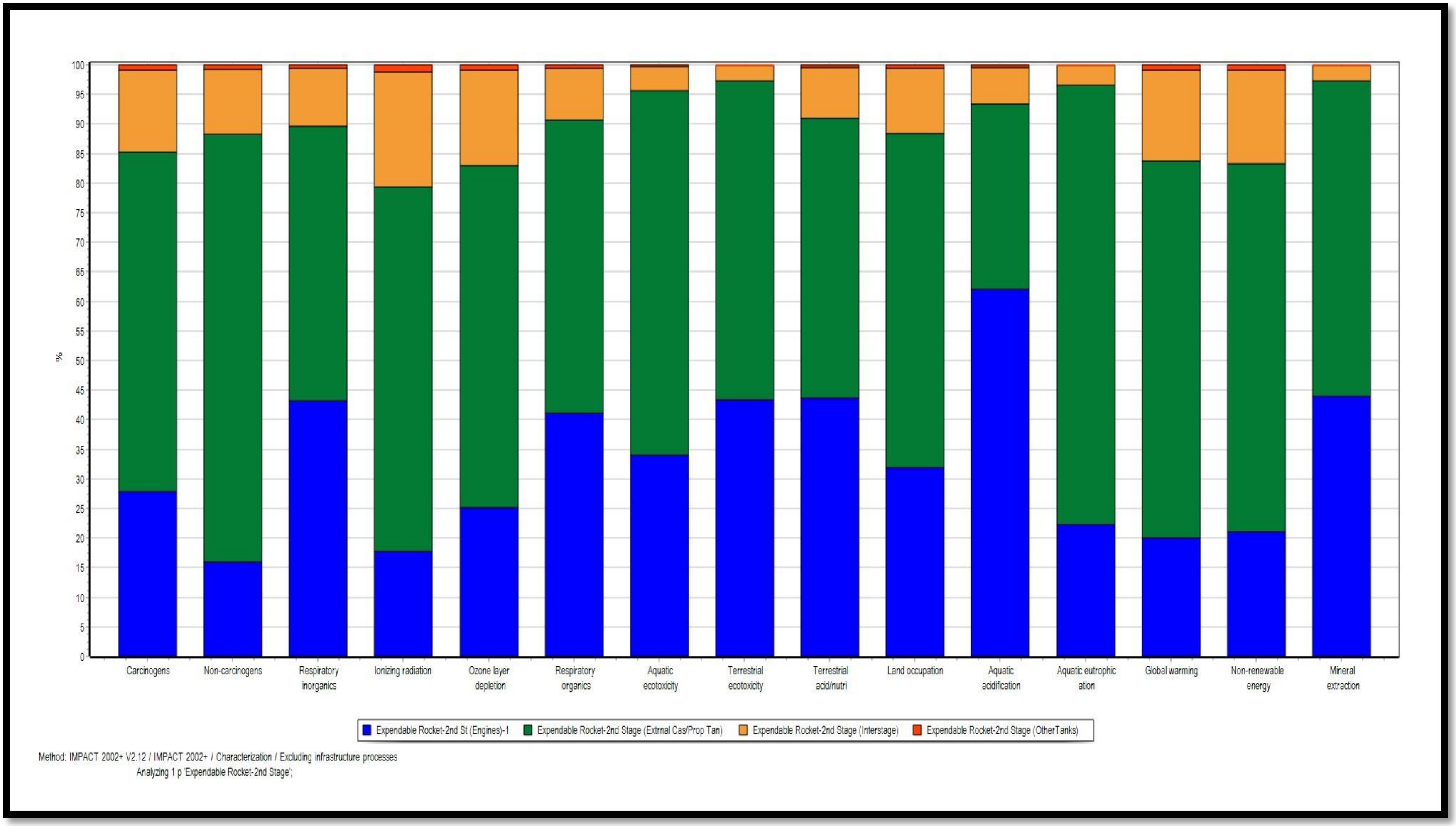


Figure 4-26 Expendable Rocket, 2nd Stage Characterization Categories (SimaPro Software)

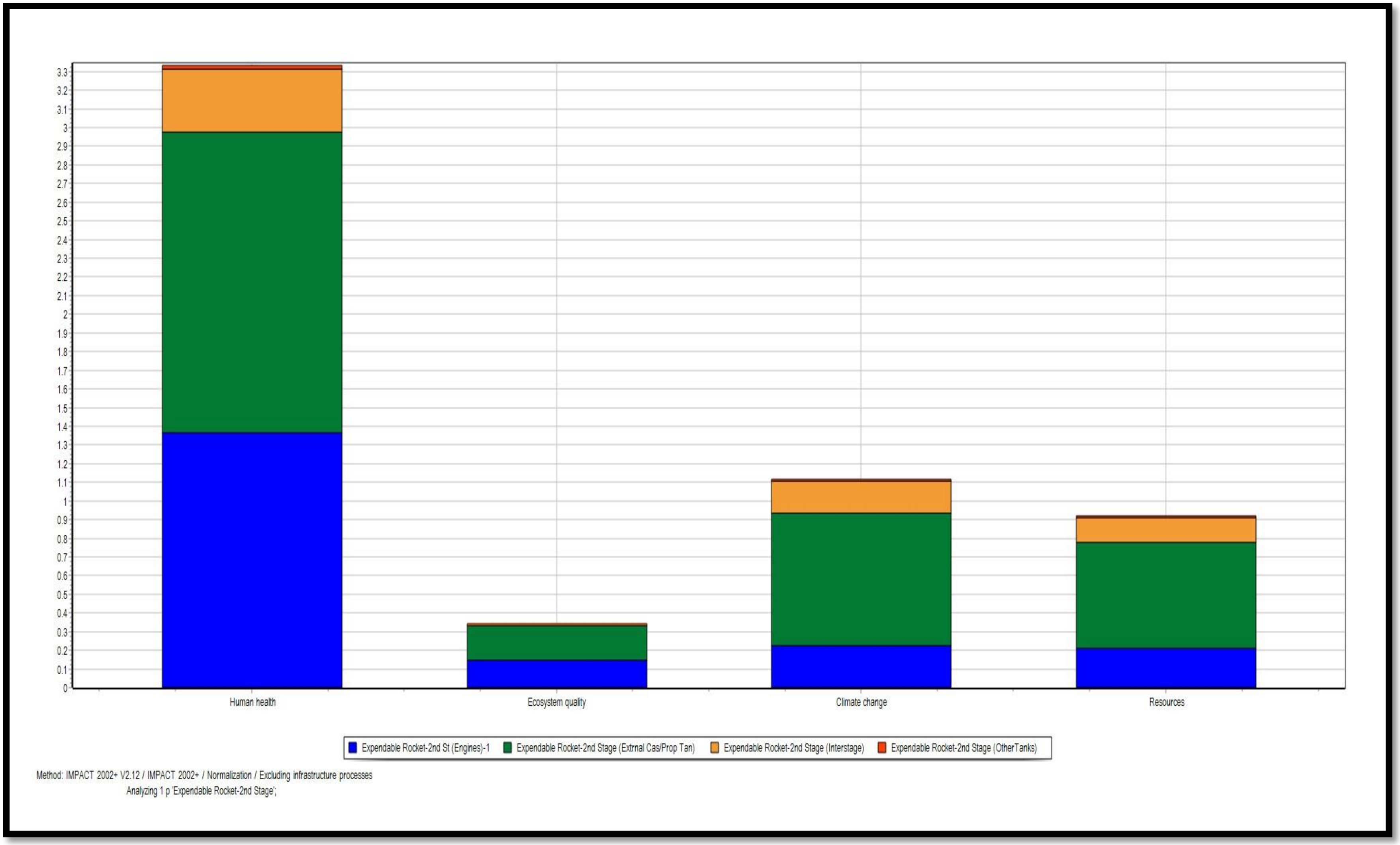


Figure 4-27 Expendable Rocket, 2nd Stage Damage Assessment Normalization (SimaPro Software)

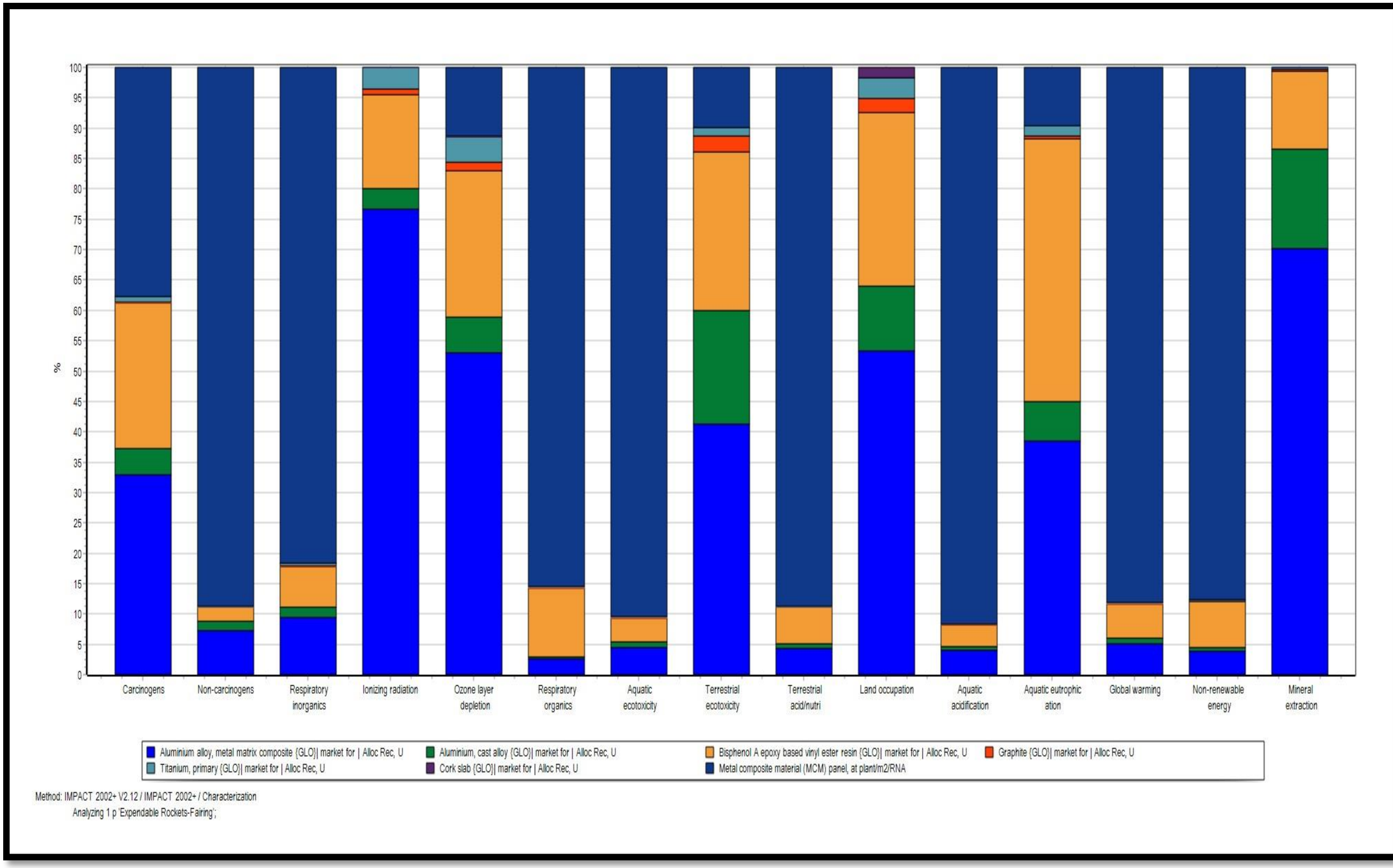


Figure 4-28 Expendable Rocket, Fairing Characterization Categories (SimaPro Software)

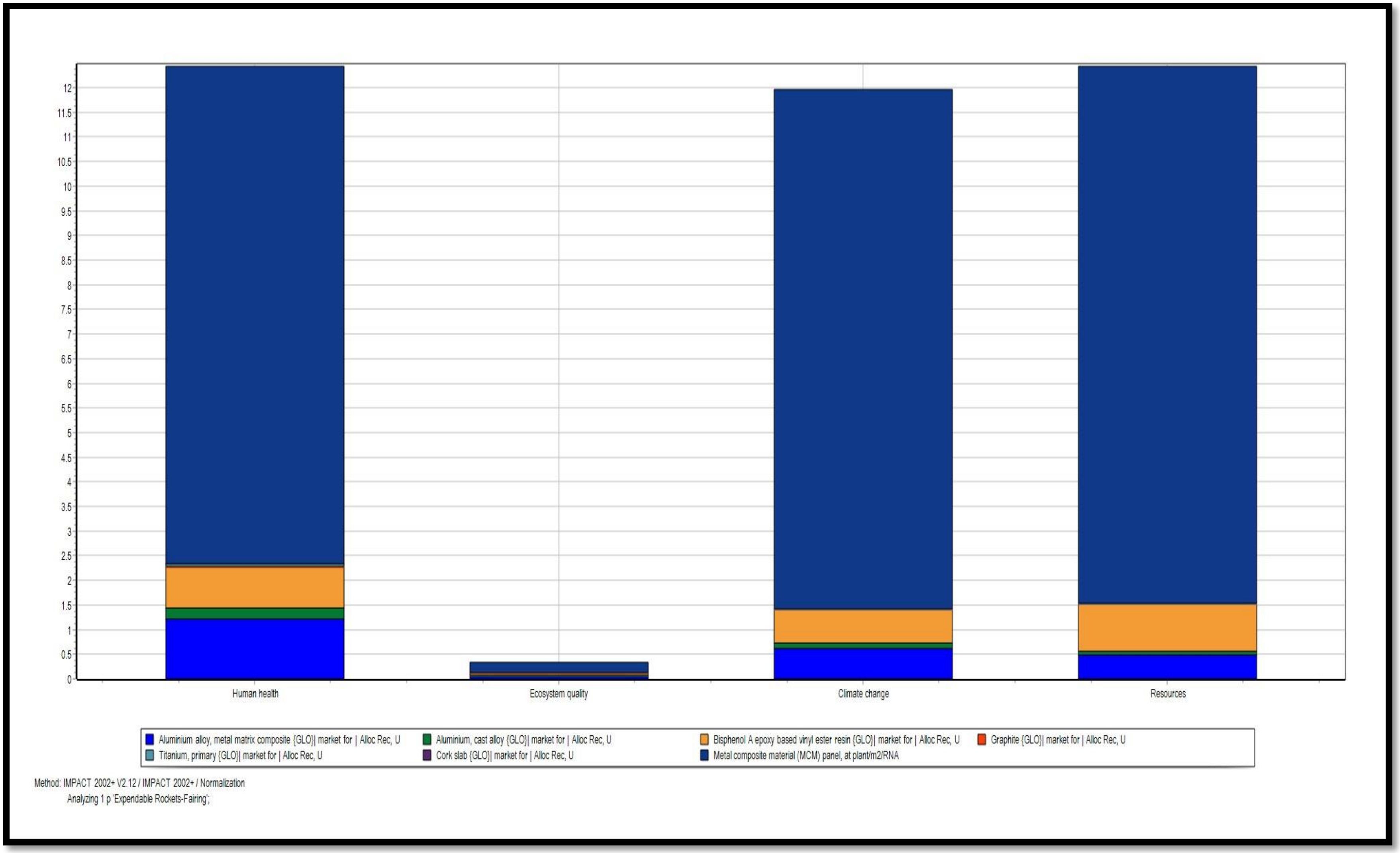


Figure 4-29 Expendable Rocket, Fairing Damage Assessment Normalization (SimaPro Software)

4.1.2.3 Chemicals (Generic) Per Launch

The Characterization of the chemicals as shown in Figure 4-30 reveals that hydrazine and diesel contribute to all categories and influence each category the most. The top three categories are: mineral extraction, ozone layer depletion, and land occupation. The next greatest influencer in each category is liquid nitrogen. The Normalization of the Damage Assessment shows Human Health is the most affected by these chemicals, with hydrazine and diesel as the greatest influencers. Diesel is also a key influencer of the four damage assessment areas and impacts Resources equally with hydrazine. The Damage Assessment Normalization shown in Figure 4-31 indicates that these chemicals impact Human Health and Resources the most. Climate change is affected next. The Network, Figure 4-32, calculated for Climate Change in Normalization at the 10% cutoff of contribution showed hydrazine, liquid nitrogen and diesel as those chemicals contributing most to this damage area.

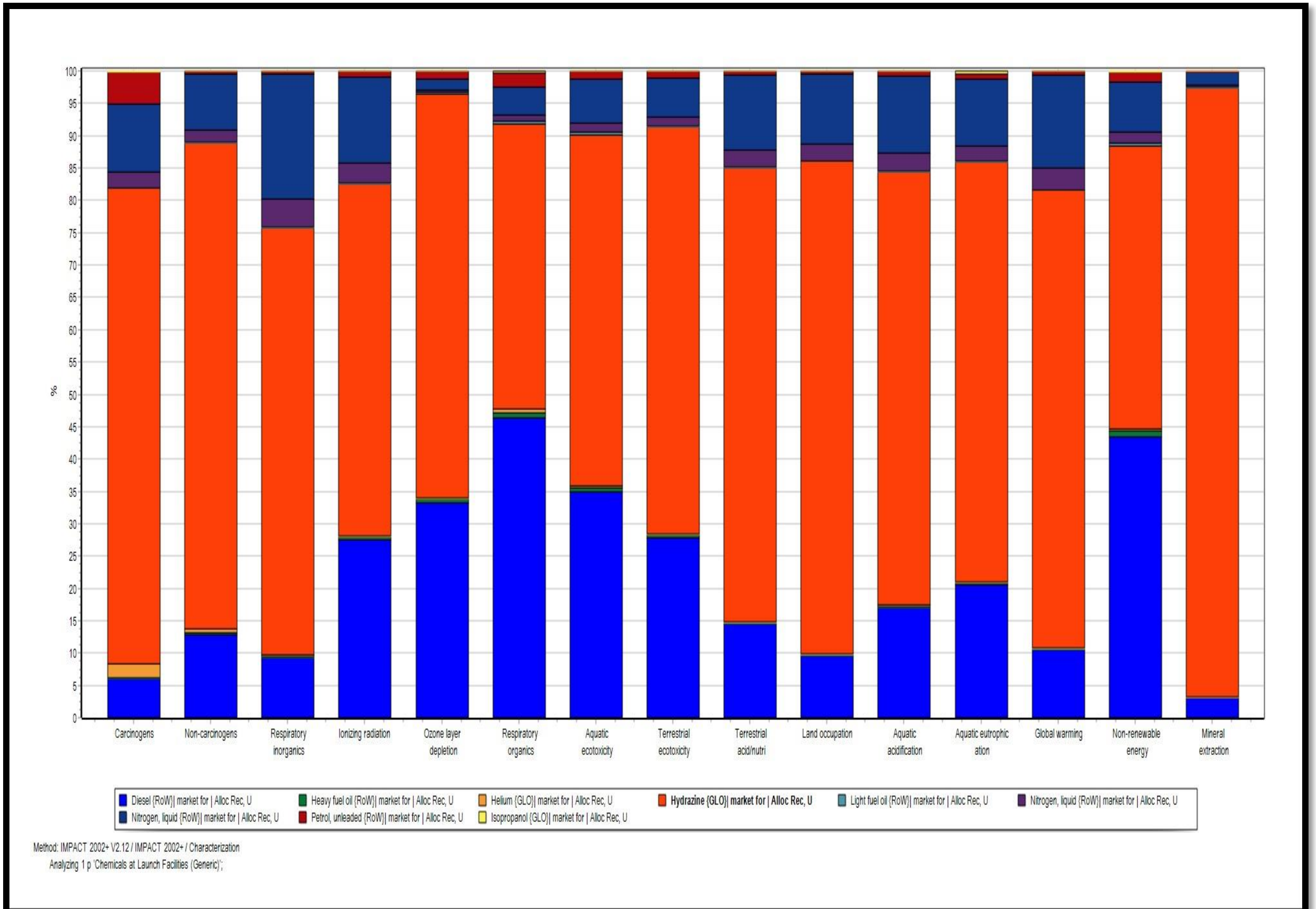


Figure 4-30 Chemicals (Generic) Characterization Per Launch

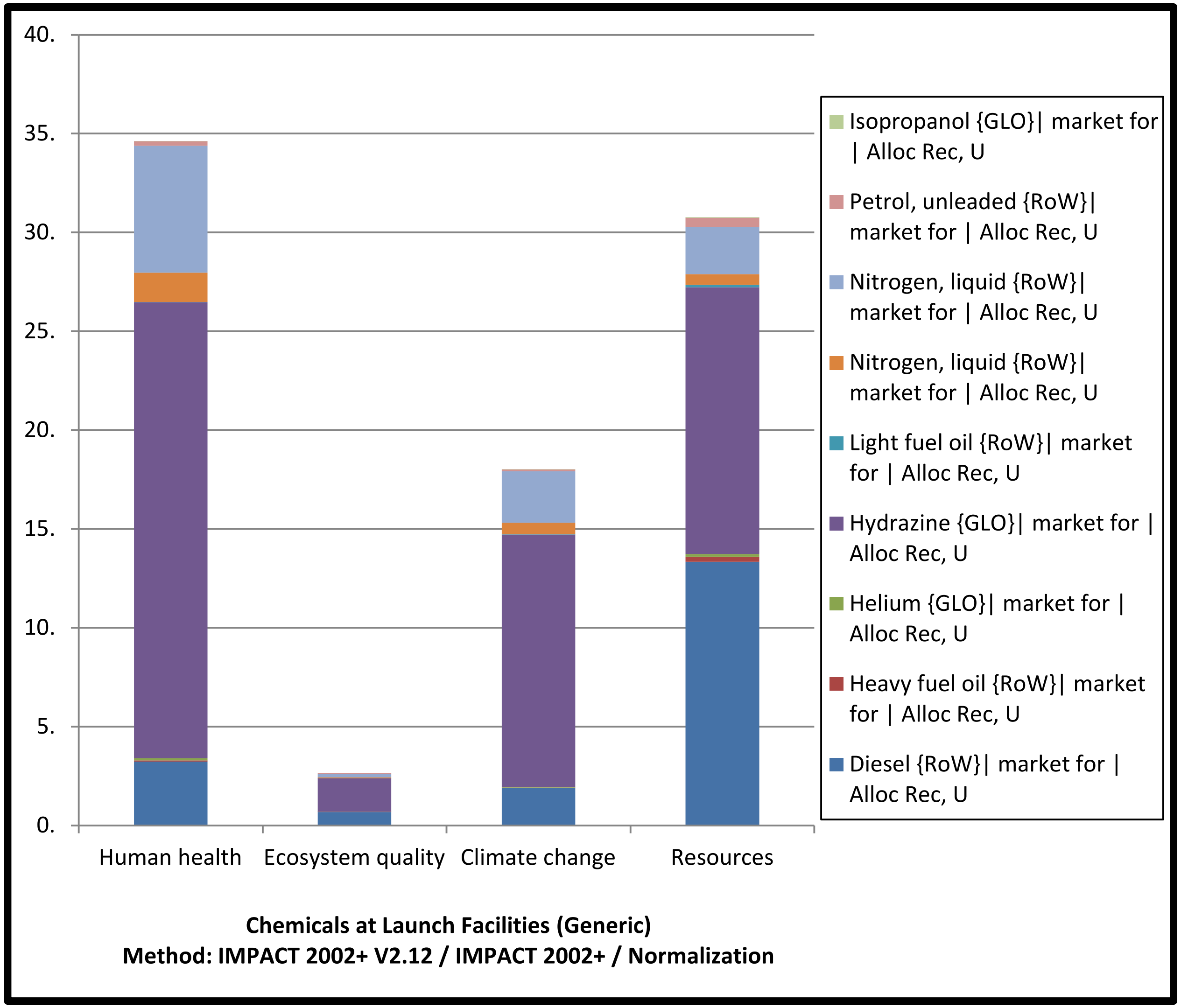


Figure 4-31 Chemicals Damage Assessment Normalization Per Launch

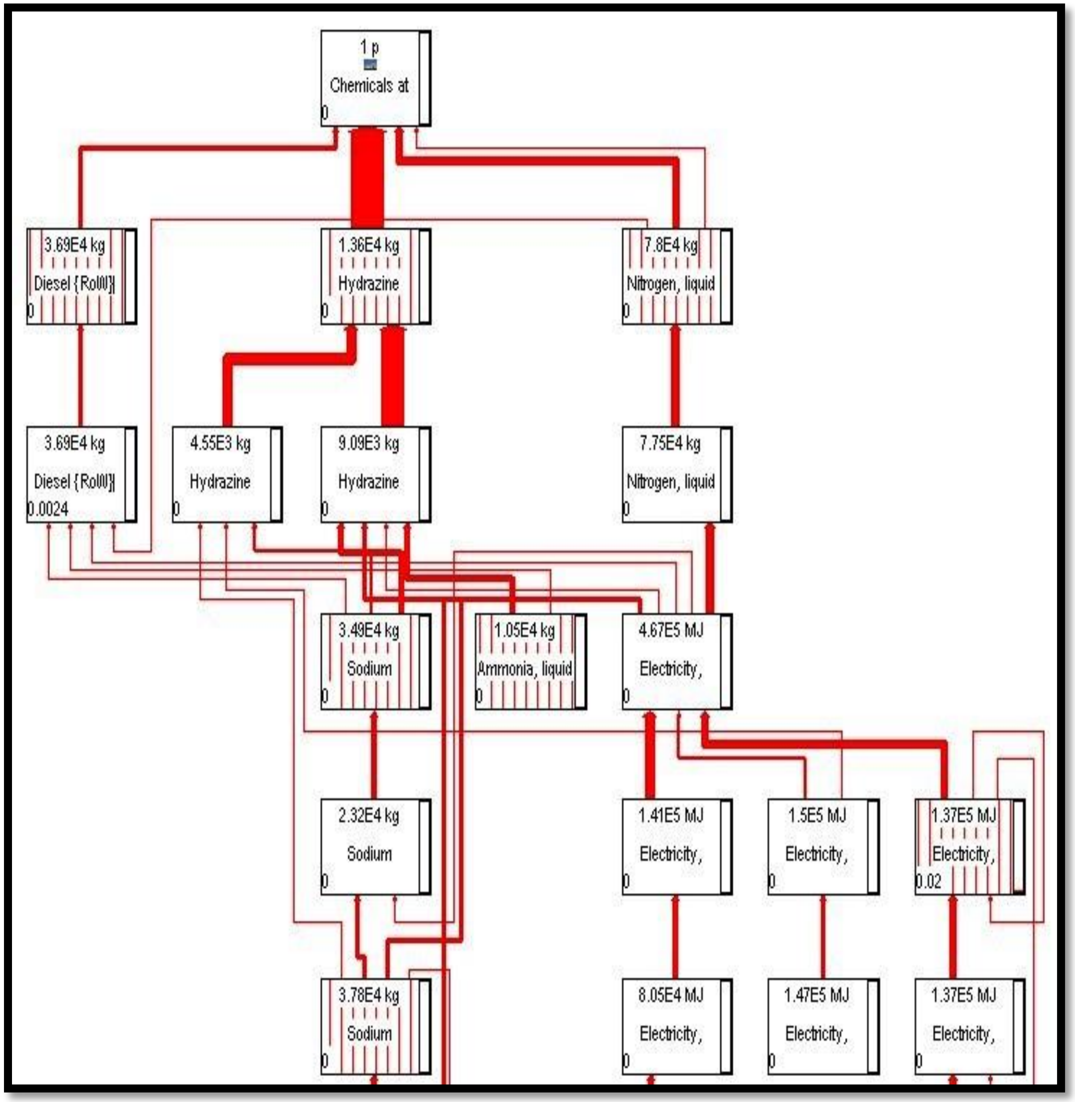


Figure 4-32 Chemicals Network Damage Assessment Normalization Climate Change at 10% Cutoff Per Launch (SimaPro Software)

4.1.2.4 Water Per Launch

The water characterization results, shown in Figure 4-33, revealed deluge water influenced all of these categories, most likely based on volume of use. Figure 4-34 shows the damage assessment that showed the tap water required for personnel and deluge water per launch primarily had highest impact on Resources and then Climate Change, as indicated in the Damage Assessment, Normalization results. Those constituents contributing most to Resource Damage are coal, natural gas, Uranium and crude oil as raw materials contributing to producing the water. The water used per launch contributed to the Climate change damage area from these emissions into the air: carbon dioxide from fossil fuel, methane from fossil fuel, and sulfur hexafluoride, and carbon monoxide from fossil fuel found in the production and transmission to the user. The transportation of the deluge water to the launch facility contributed inputs from crude oil, natural gas and coal in small amounts.

4.1.2.5 Electricity Per Launch

The Characterization categories, Figure 4-35, showed Electricity impacted the following categories more than the diesel generator: carcinogens, non-carcinogens, ionizing radiation, and land occupation. The diesel generators influenced all of the damage areas slightly more than the electricity as shown in Figure 4-36. Diesel generators contributed to Climate change damage area primarily in air emissions from carbon dioxide from fossil fuels, as shown in Figure 4-37. Diesel generator vapors at point of use have health exposure limits regulated by Occupational Health and Safety Administration (OSHA) regulations. The calculated Damage area of Human health identifies the highest contribution is nitrogen oxides, air particulates <2.5 µm, sulfur dioxide, dioxin, aromatic hydrocarbons from diesel generators. Opportunities to find ways to minimize diesel generators used during the launch campaign with green technology alternatives will be discussed later in Objective 3.

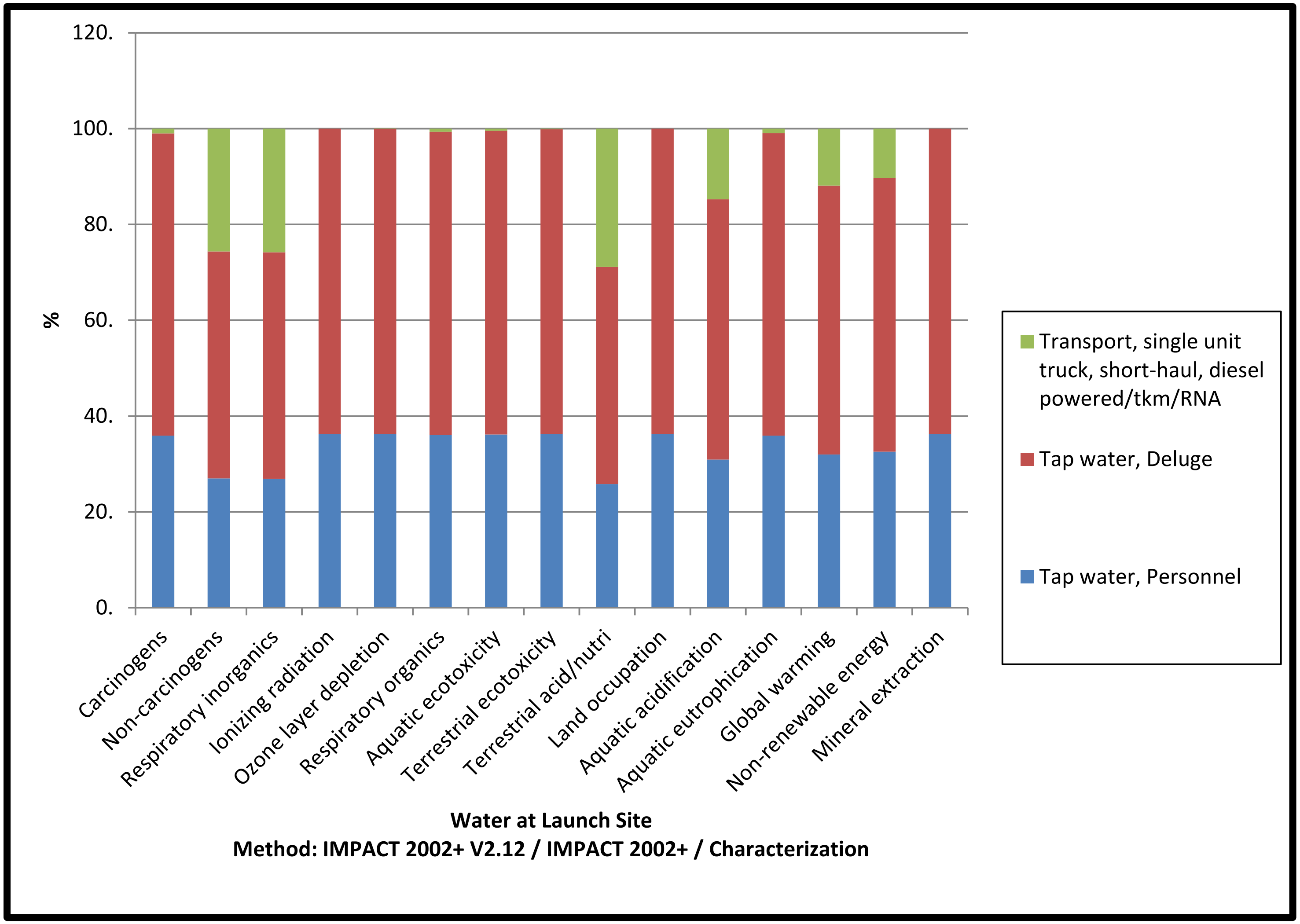


Figure 4-33 Water Characterization Categories Per Launch

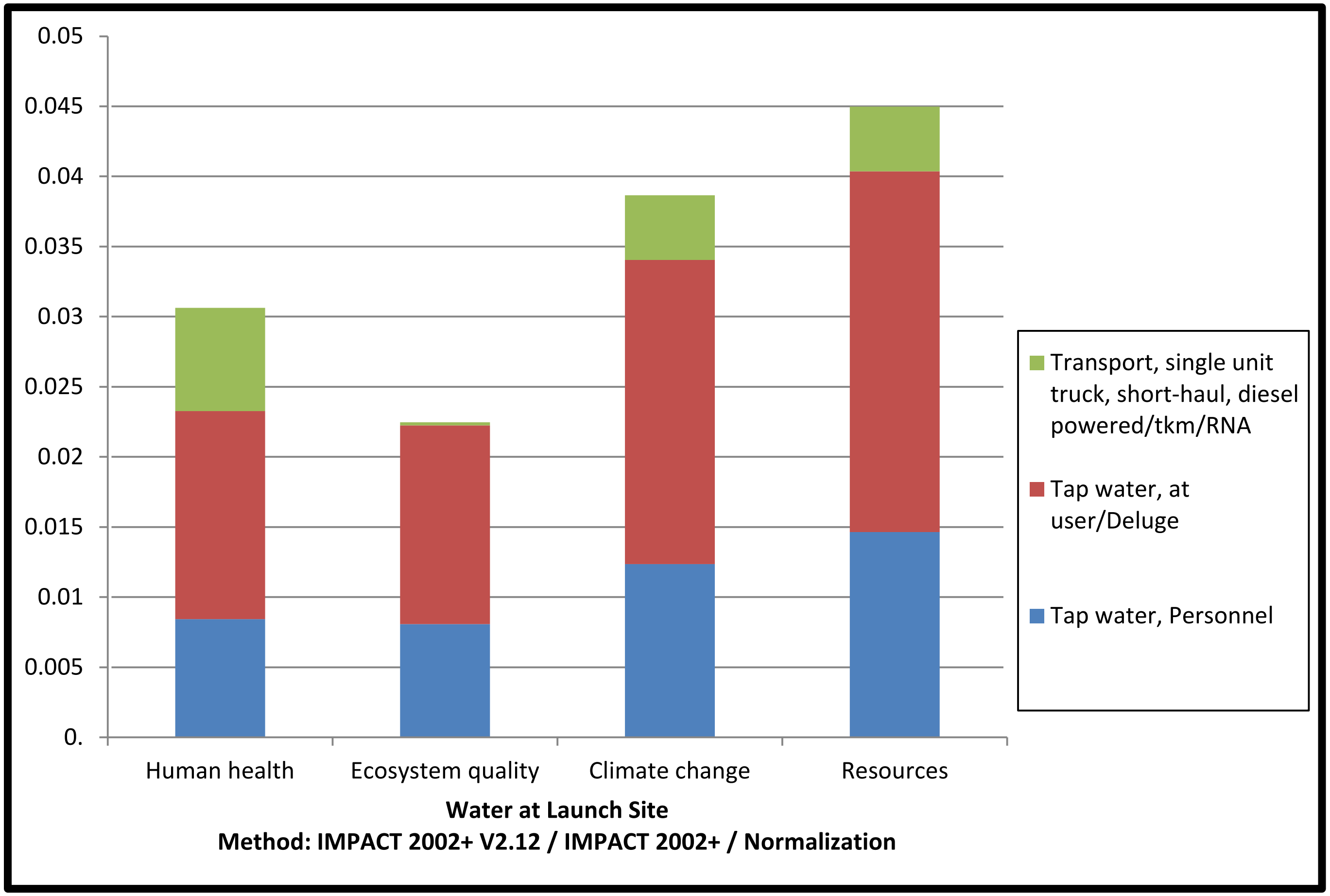


Figure 4-34 Water Damage Assessment Normalization Per Launch

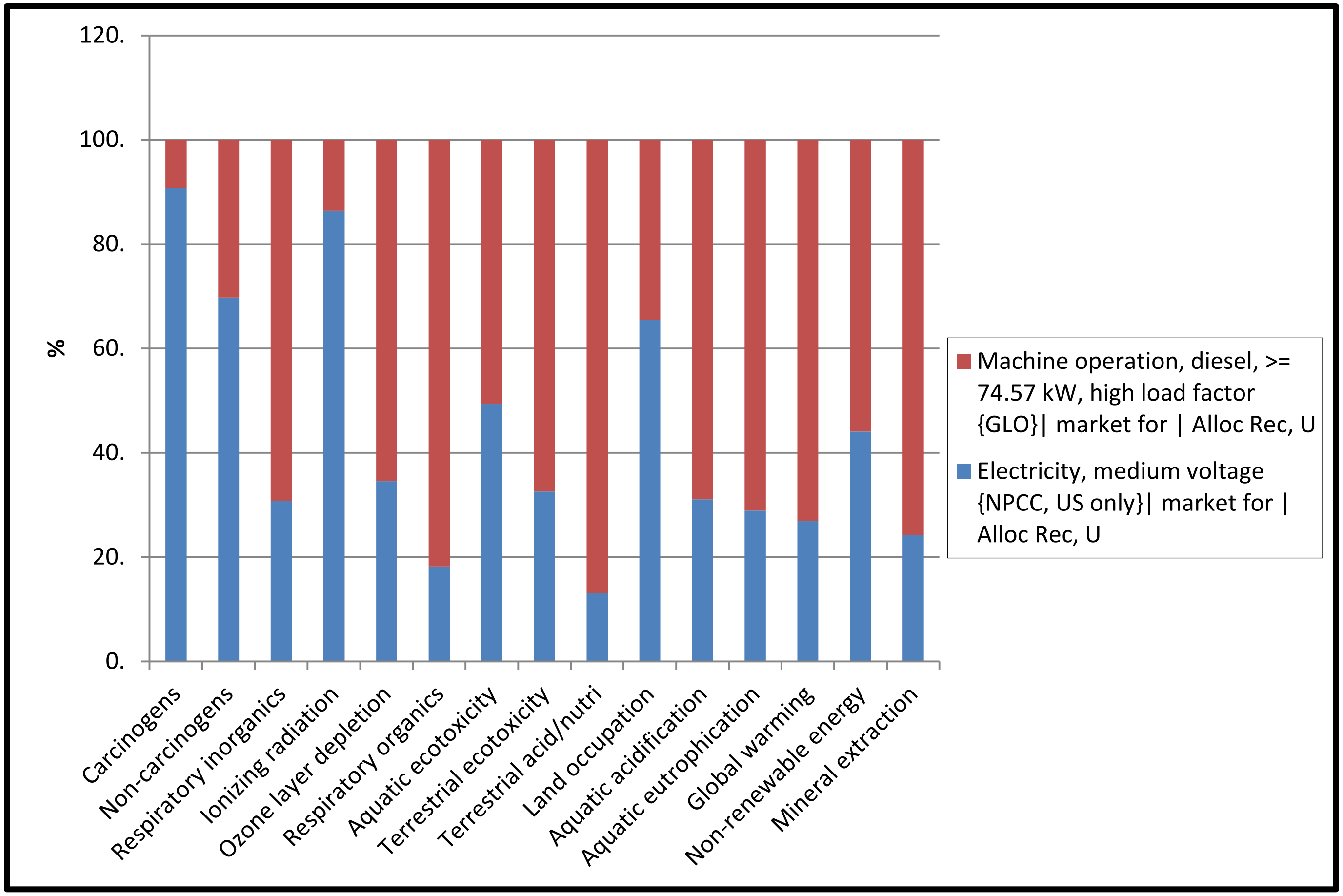


Figure 4-35 Electricity Characterization Categories Per Launch

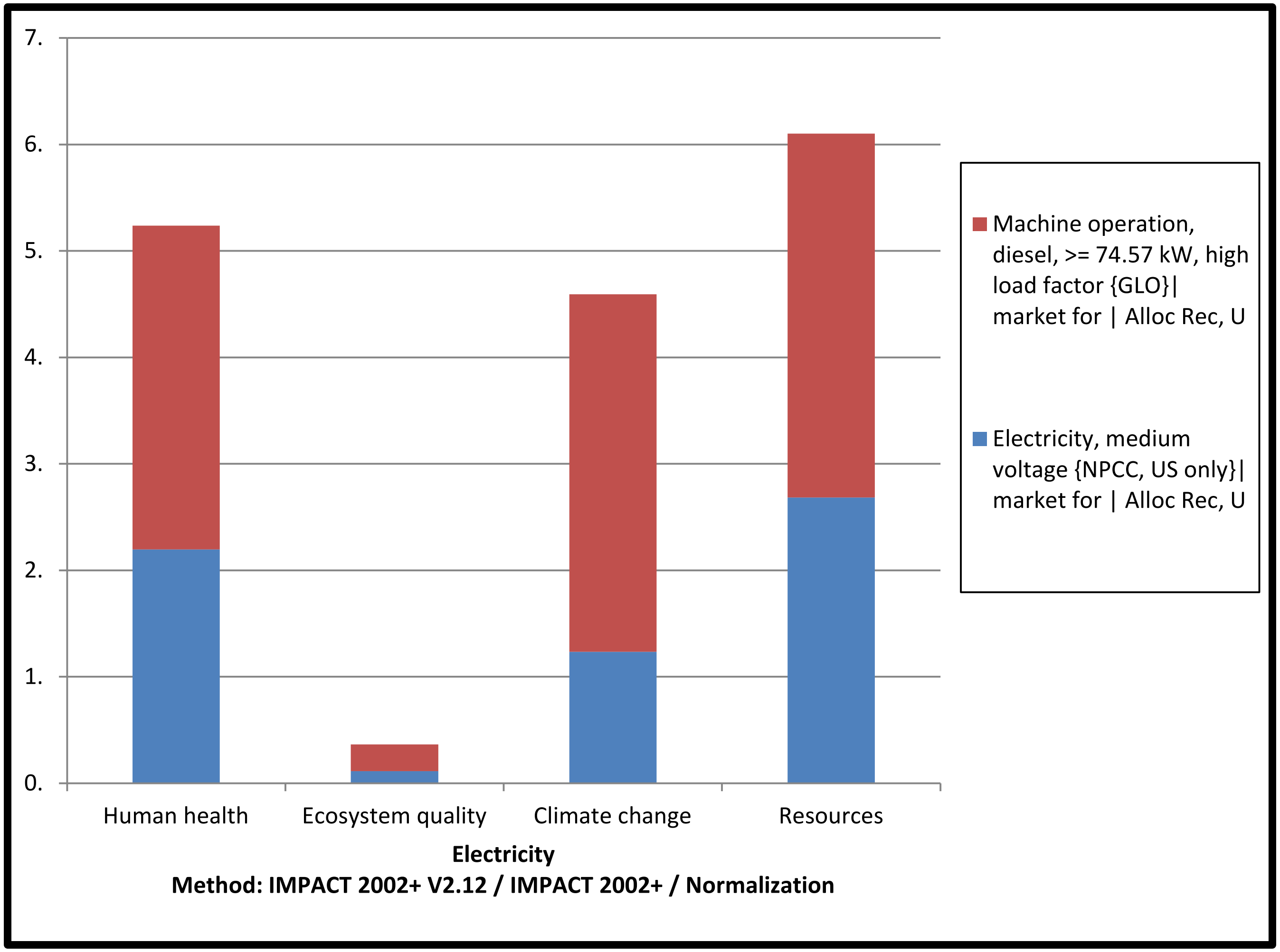


Figure 4-36 Electricity Damage Assessment Normalization Per Launch (SimaPro Software)

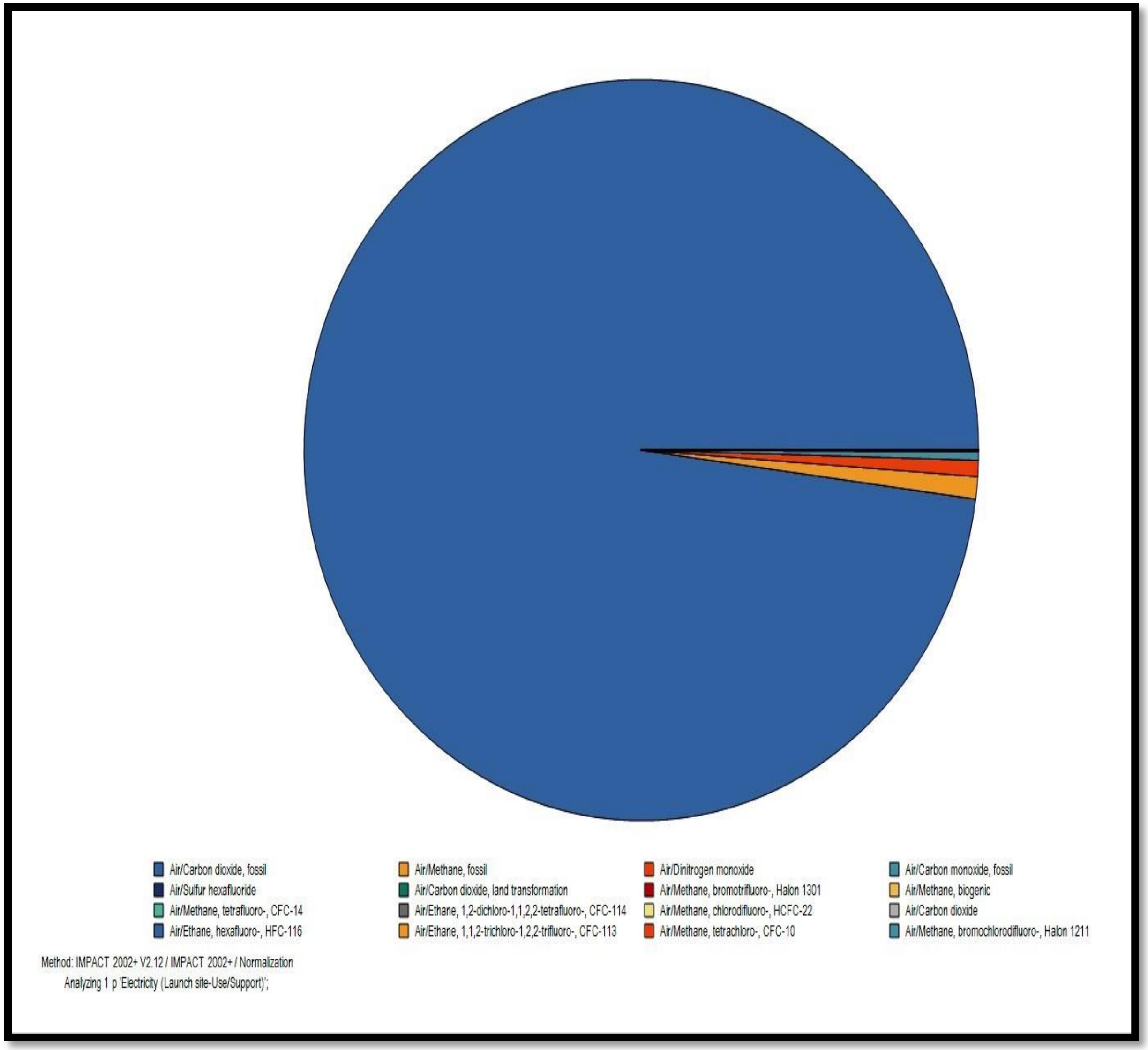


Figure 4-37 Electricity – Diesel Damage Assessment Normalization - Climate Change Per Launch (SimaPro Software)

4.1.2.6 Liquid Propellants Per Launch

4.1.2.6.1 Liquid Oxygen and Liquid Hydrogen Propellant Per Launch

The propellant LOx/LH_2 is used in rocket launchers such as Delta IV Heavy and was modeled using the amount of propellant identified for this launcher. The total propellant was evaluated and calculated results identified in the Damage area, Normalization graph showed Human health was the most impacted from LOx/$LH_{2.}$ When investigating a little more closely into the Human health damage area, particulates <2.5 µm, nitrogen oxides, sulfur dioxide, and aromatic hydrocarbons contributed the most.

Overall, the transportation needed for the additional propellant prior to actual launch did not influence the damage assessment areas to any great extent. Figure 4-38 shows the characterization categories impacted as expected. Figure 4-39 revealed Human health was the most impacted by the LOx and LH_2 propellant with Resources and Climate change as the next impacted, respectively. When evaluating the Network graphic, Figure 4-40, the LOx is the main contributor to the overall damage assessment areas. Electricity is shown to be the key as to why LOx, a cryogenic liquid, is a main environmental impact as a propellant.

When investigating more into contribution from LOx using the Damage Assessment for the 1st Stage propellant, the Single Score shows how it is the greatest contributor to all the damage areas, Figure 4-41. **Overall, LOx appears to be the main contributor to environmental impacts from this propellant.**

4.1.2.6.2 Liquid Oxygen and Liquefied Natural Gas Propellant Per Launch

The propellant LOx and liquefied natural gas (LNG) is used in various rocket launchers such as the Blue Origin with the BE-4 engine and was modeled using the propellant amount identified for this launcher. Figure 4-42 shows, as expected, this propellant impacts all areas based on quantity used. For instance, the test firings are equal in amount to 1st Stage propellant. The total propellant was evaluated similar to the LOx/LH_2 and the calculated damage assessment, Figure 4-43, revealed Human health was impacted and then Resources and Climate change, respectively. **The Ecosystem quality seems to be the least impacted from propellants**. When we compare the Network at 10% cutoff, the Human health damage area results indicated the LOx and the electricity inputs were the main contributors. Natural gas does have some influence, but even in the Network at 10% cutoff showing Climate change damage area, the LOx and its electricity requirement is the greatest influencer.

4.1.2.6.3 Liquid Oxygen and Kerosene (RP-1) Propellant Per Launch

The propellant LOx/RP-1 is used in space launchers such as SpaceX Falcon Heavy and was modeled using the propellant amount identified for this launcher. Figure 4-44 shows a similar result of impact to each of the categories as the other propellants. The Damage Assessment, Normalization results, shown in Figure 4-45, revealed Human Health was impacted more slightly than Resources and Climate change was about half of Human health impact. Ecosystem quality was influenced less than 3% by this propellant. The Network graphic of the Normalization, **Human health**, at the 10% cutoff shows LOx influences more than the RP-1 on this damage area. The main constituents influencing this impact are found in air from the particulates <2.5 µm sulfur dioxide, nitrogen oxides, and aromatic hydrocarbons. When evaluating the Normalization, Climate change Network at 10% cutoff, LOx contributes the most, however, now the RP-1 fuel is more of an influencer to this damage area. The main constituents influencing this impact area are found in air: carbon dioxide and methane from fossil fuel, and sulfur hexafluoride.

A comparison of the three liquid propellants is shown in Section 4.1.4.

4.1.2.7 Transportation Per Launch

The transportation of all of the consumables impact to the characterization categories is shown in Figure 4-46. This figure shows that mineral extraction, ionizing radiation, and land occupation are totally impacted by diesel-powered truck, using U.S. data from National Renewable Energy Laboratory (NREL). The west coast diesel-powered truck contributes 5- 10% more than southeast diesel-powered truck. Overall, the transportation contribution as identified in this study did not have significant impact on the damage areas relative to the six consumables examined. Both coasts were identified for transportation and the West coast diesel for 100 miles was slightly higher impact than the Southeast diesel. One reason this difference might occur would be due to the composition of the fuels and its manufacturing processes. The Damage Assessment, Normalization revealed Human health was impacted the most and Climate

Change impacted slightly higher than Resources. Figure 4-47 shows the relative contributions of each of the types of transportation and coast areas. Figure 4-48 provides the single score damage assessment confirms the diesel-truck on the west coast contributes slightly more than the east coast.

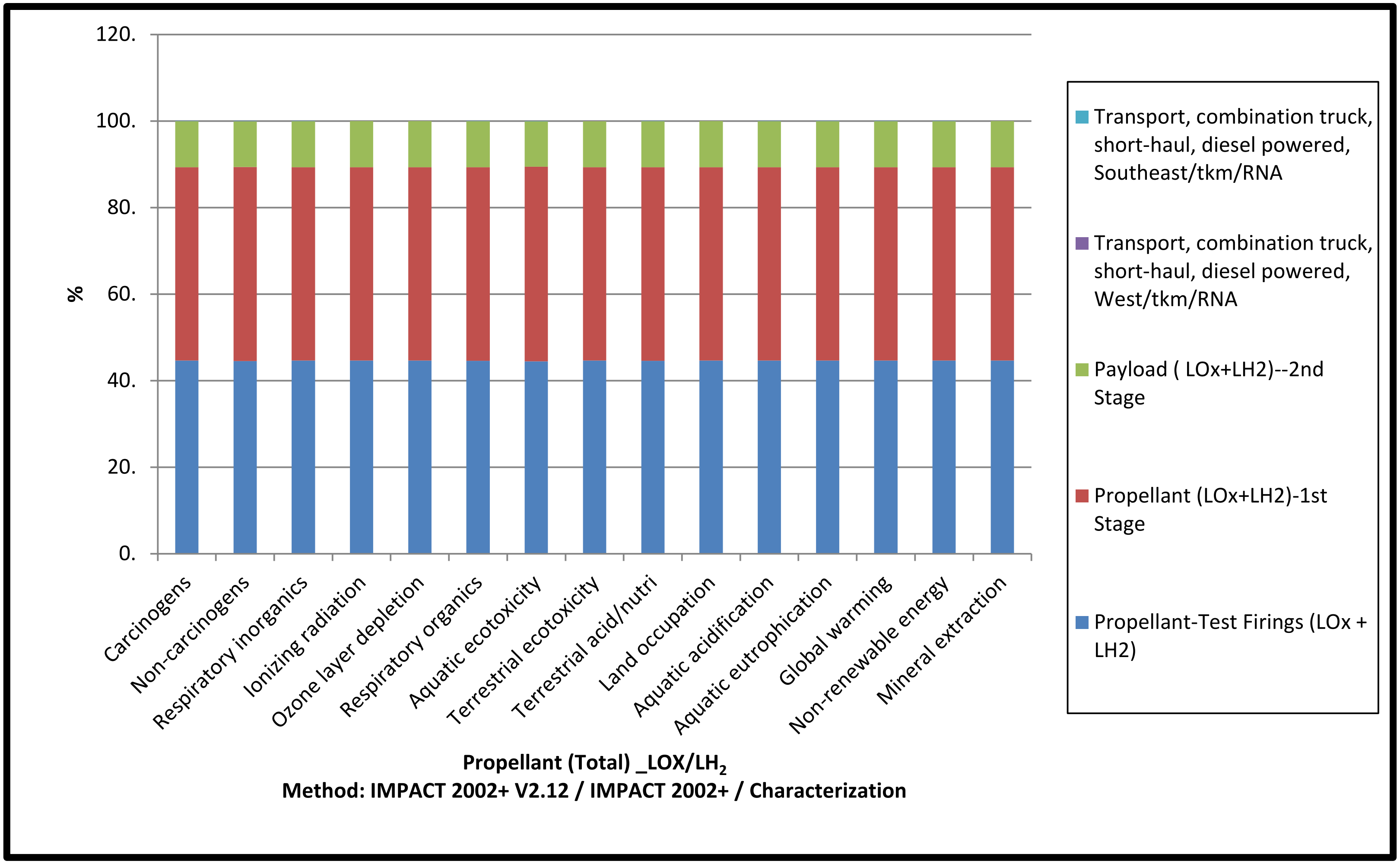


Figure 4-38 Propellant LOx/LH$_2$ Characterization Categories (SimaPro Software)

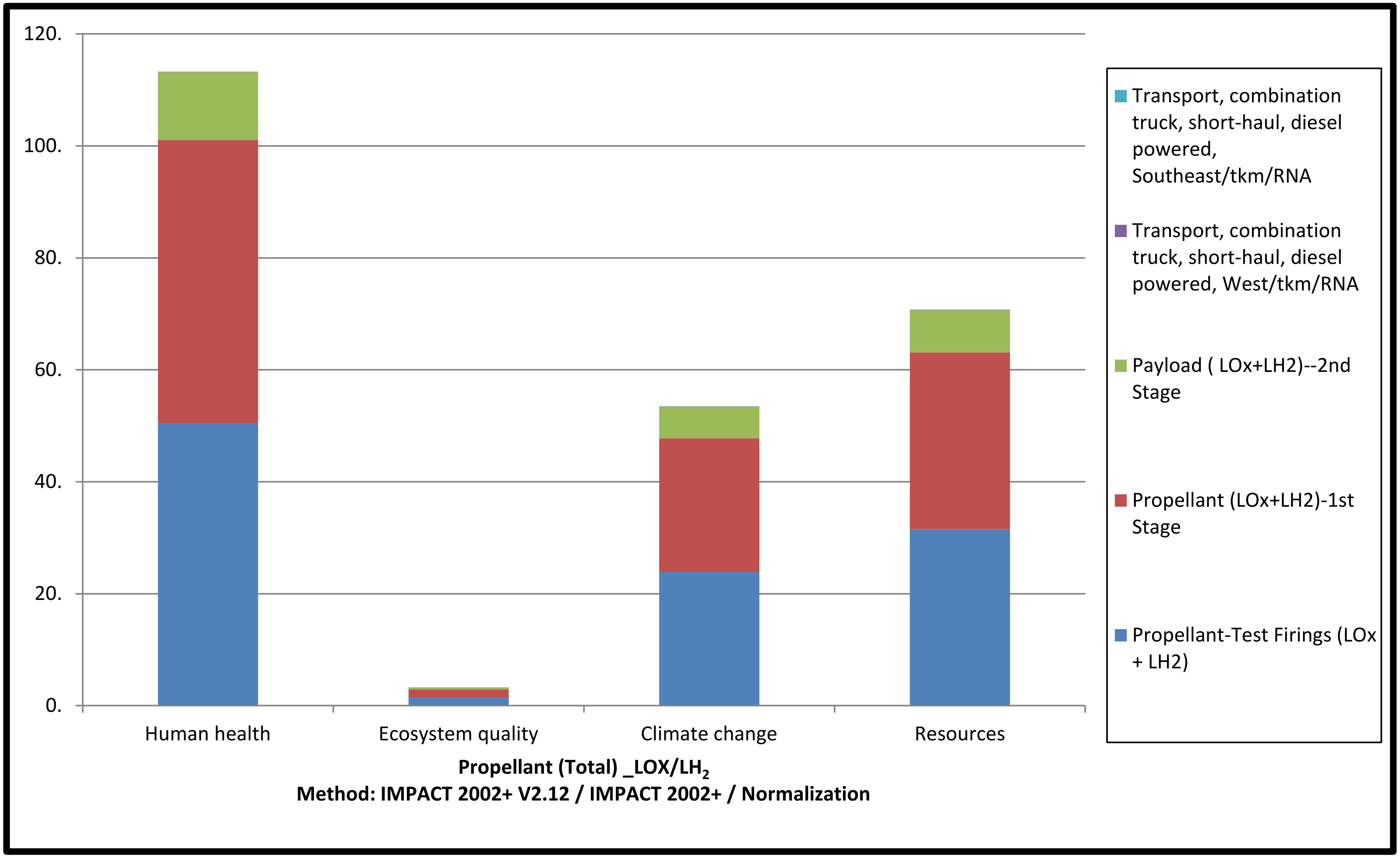


Figure 4-39 Propellant LOx/LH_2 Damage Assessment (SimaPro Software)

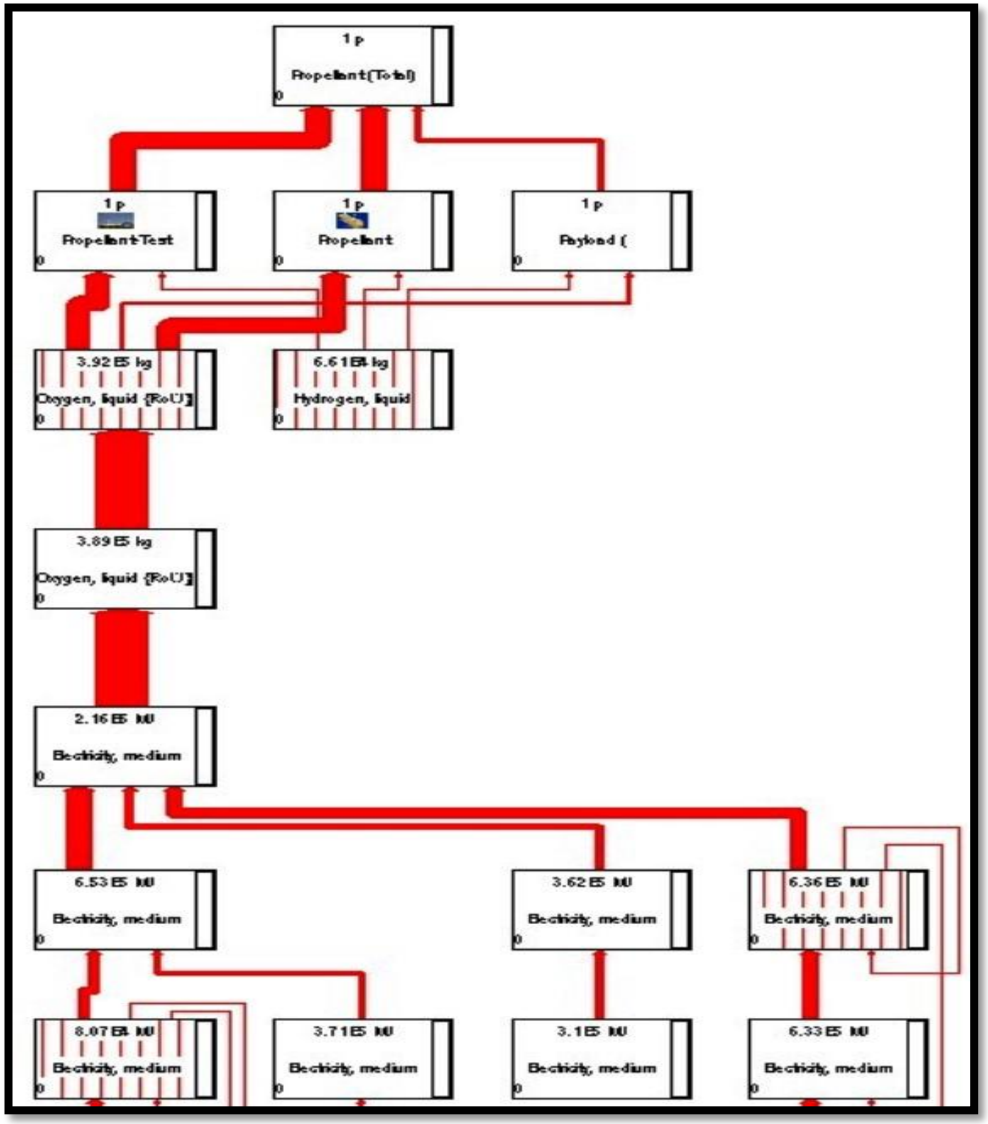


Figure 4-40 Propellant (LOx/LH_2) Network Damage Assessment Normalization - Human Health at 10% Cutoff Per Launch (SimaPro Software)

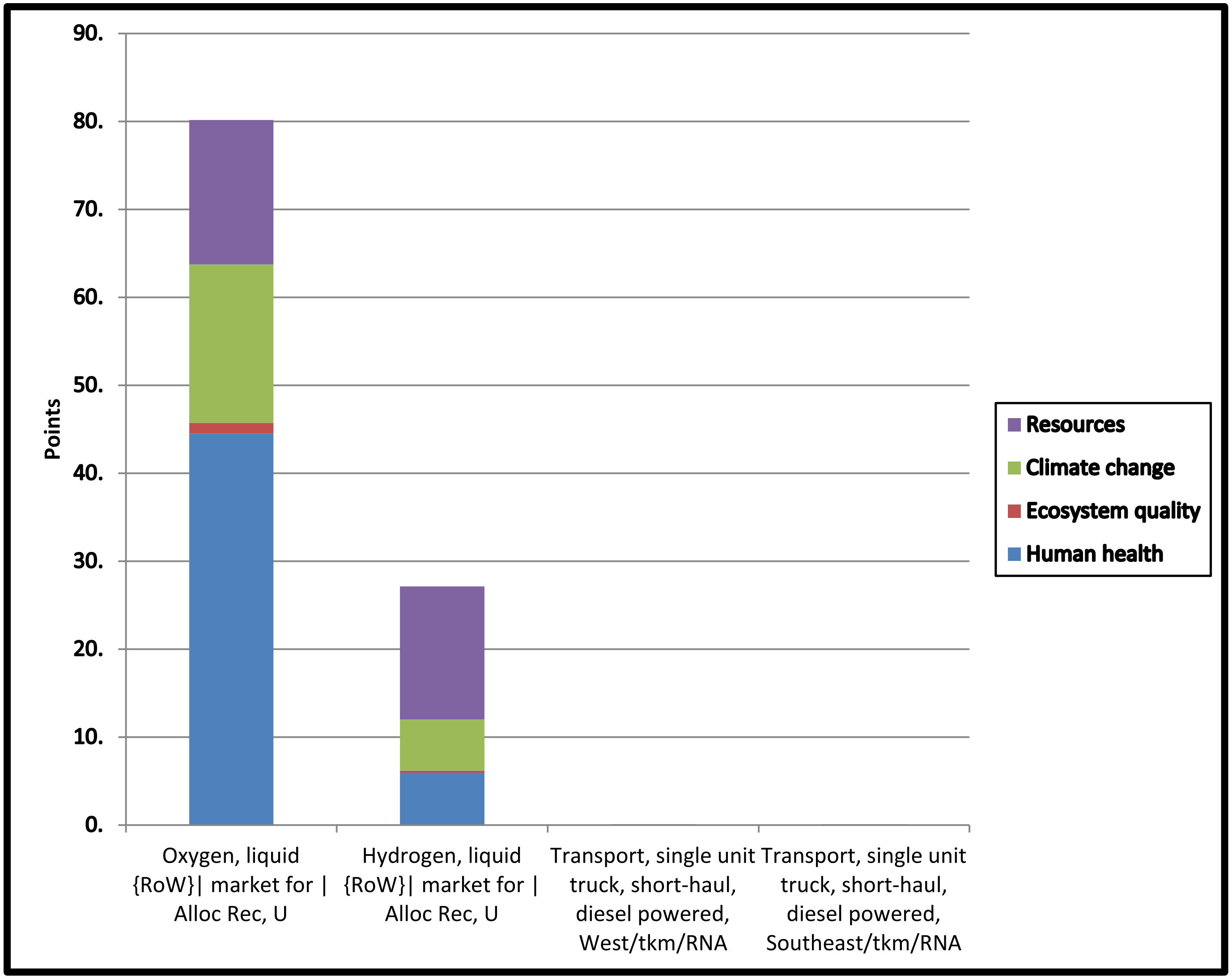


Figure 4-41 Propellant (LOx/LH$_2$) Damage Assessment Single Score (SimaPro Software)

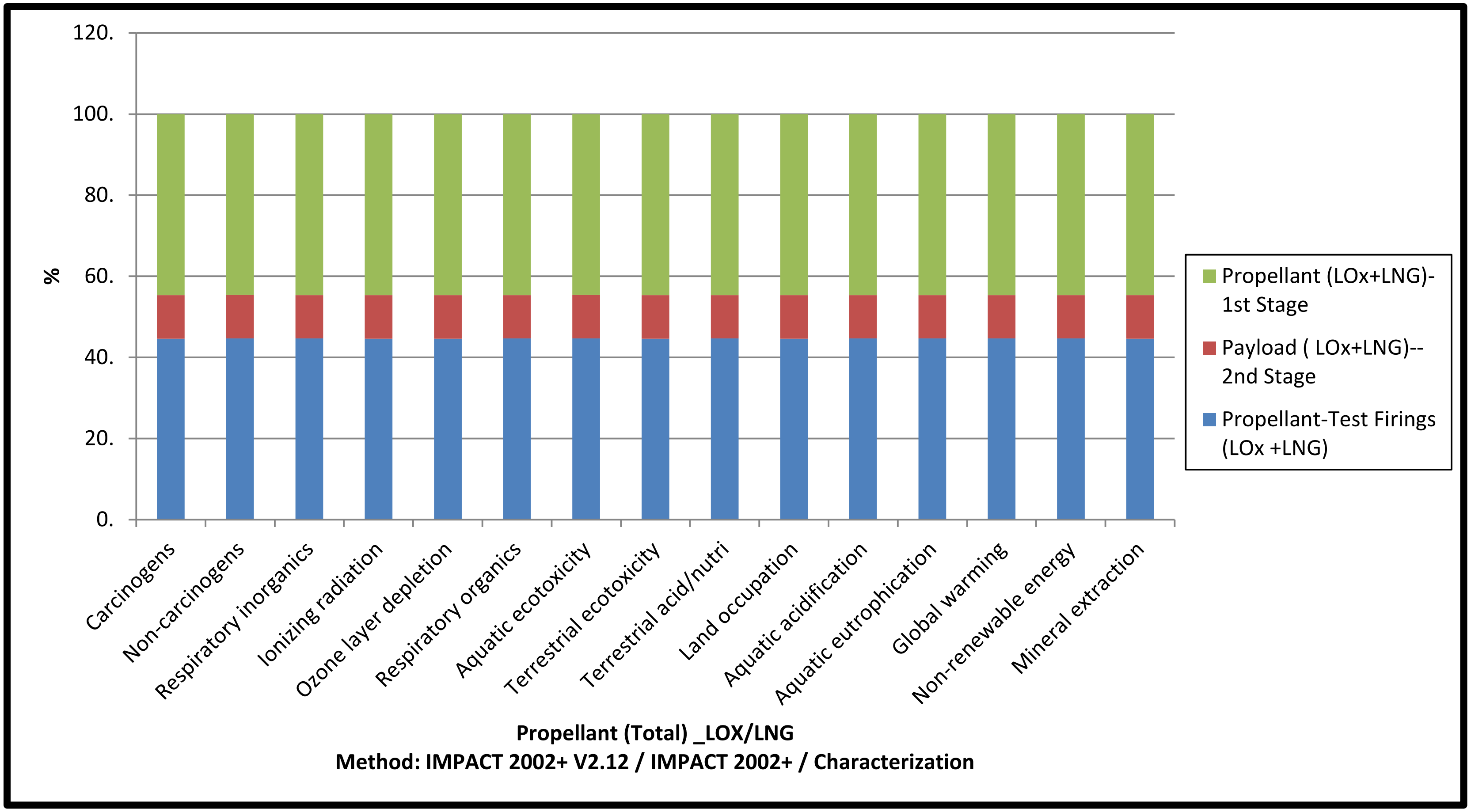


Figure 4-42 Propellant LOx/LNG Characterization Categories (SimaPro Software)

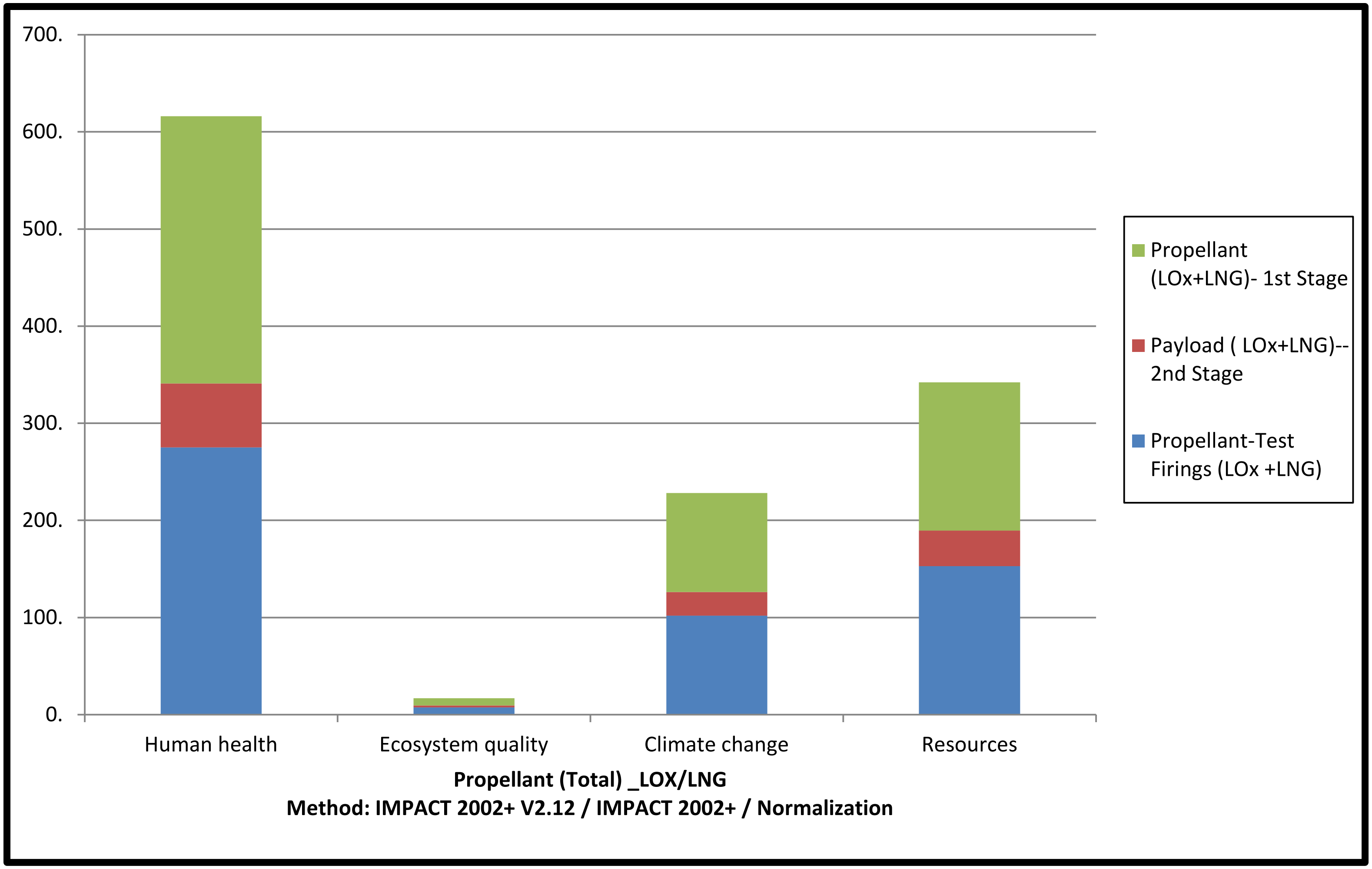


Figure 4-43 Propellant LOx/LNG Damage Assessment Normalization (SimaPro Software)

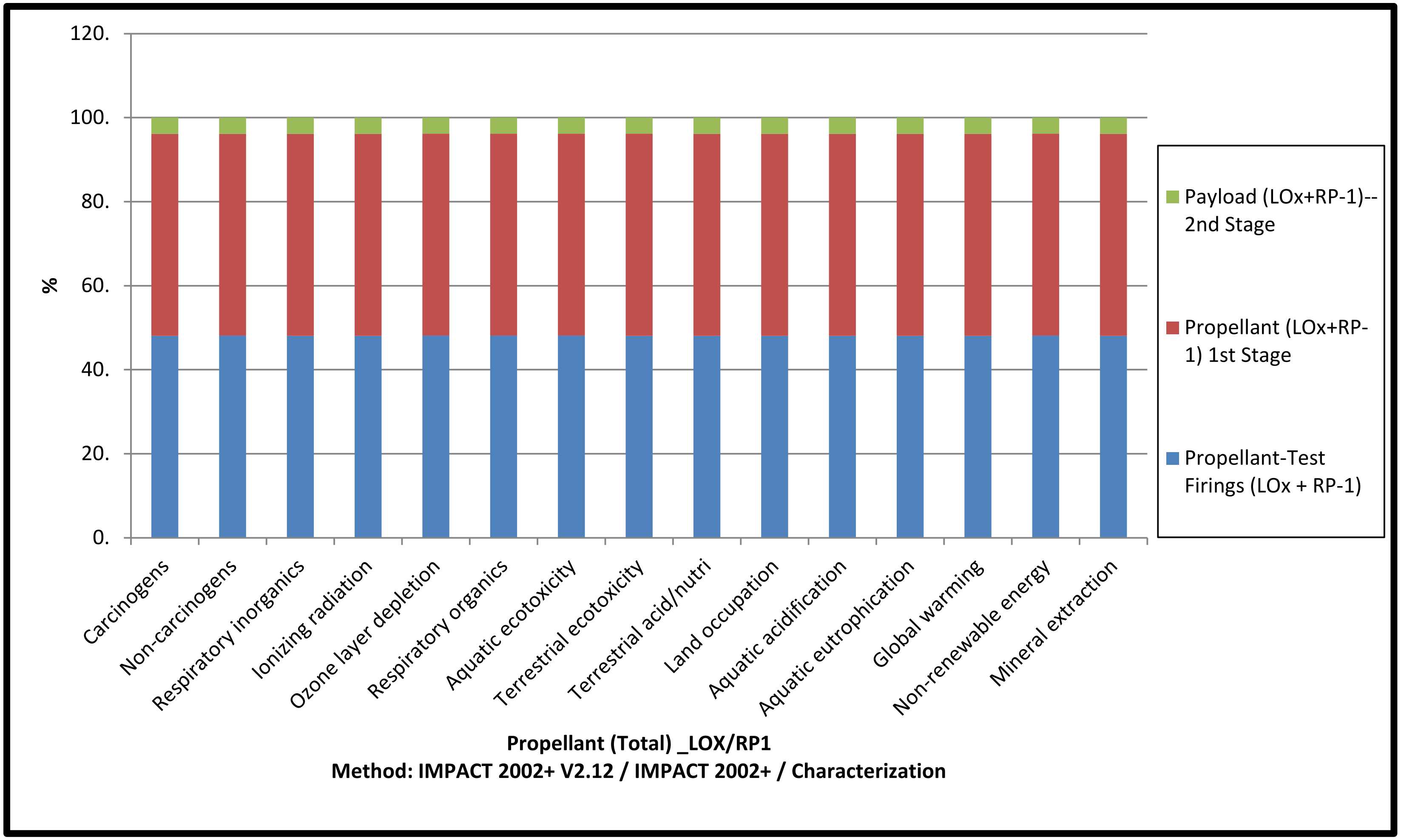


Figure 4-44 Propellant LOx/RP-1 Characterization Categories (SimaPro Software)

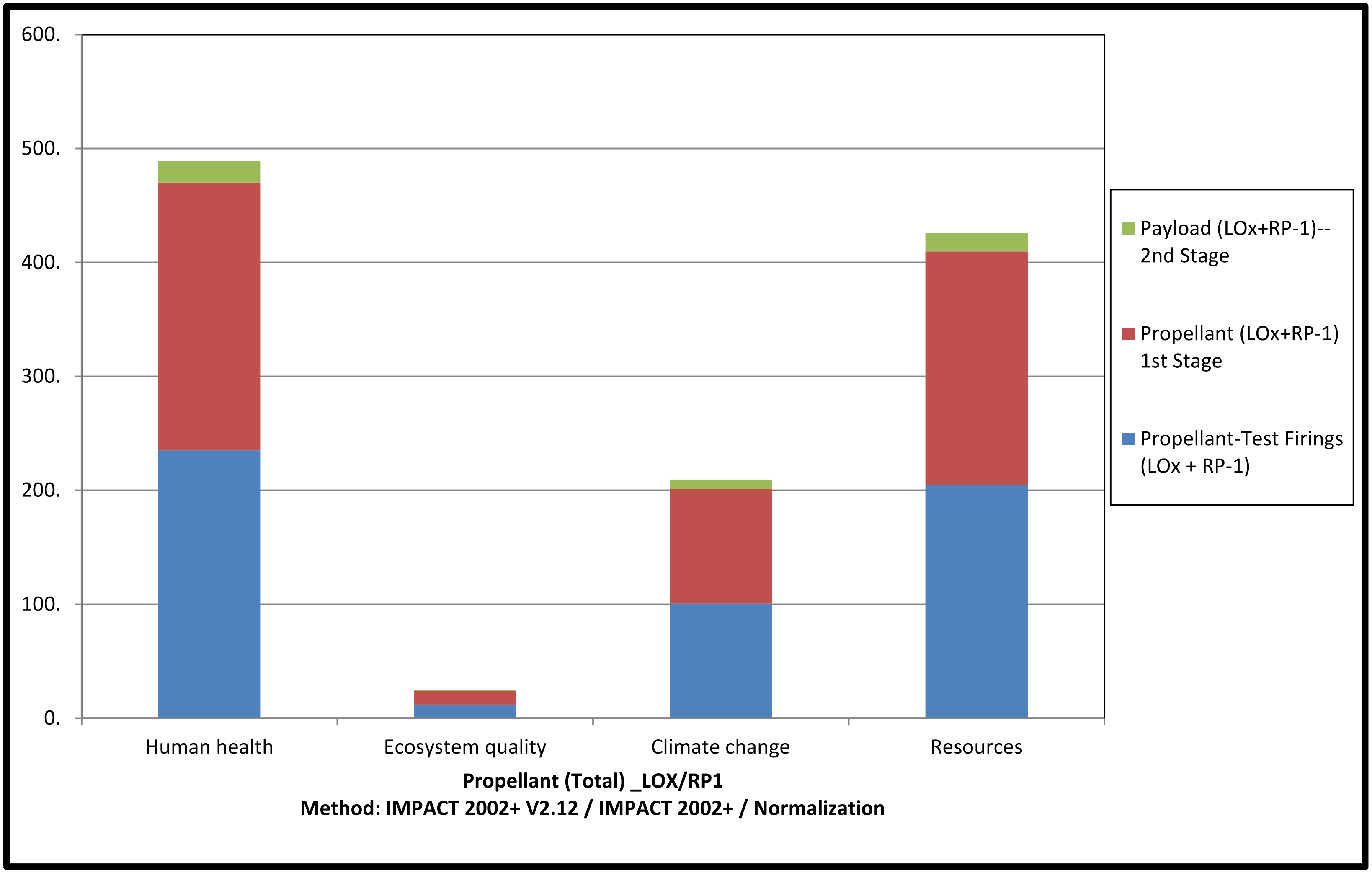


Figure 4-45 Propellant LOx/RP-1 Damage Assessment Normalization (SimaPro Software)

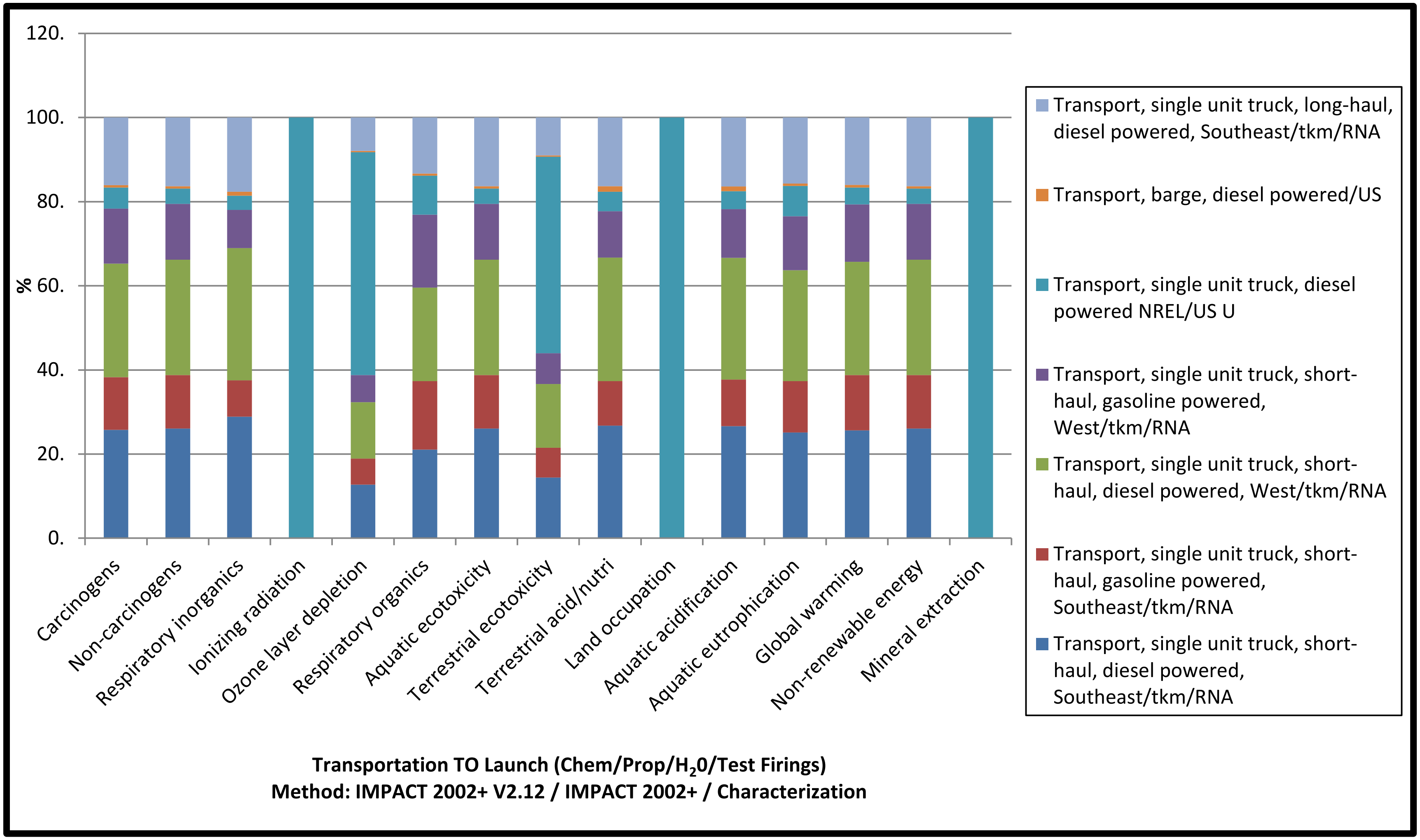


Figure 4-46 Transportation Characterization Categories (SimaPro Software)

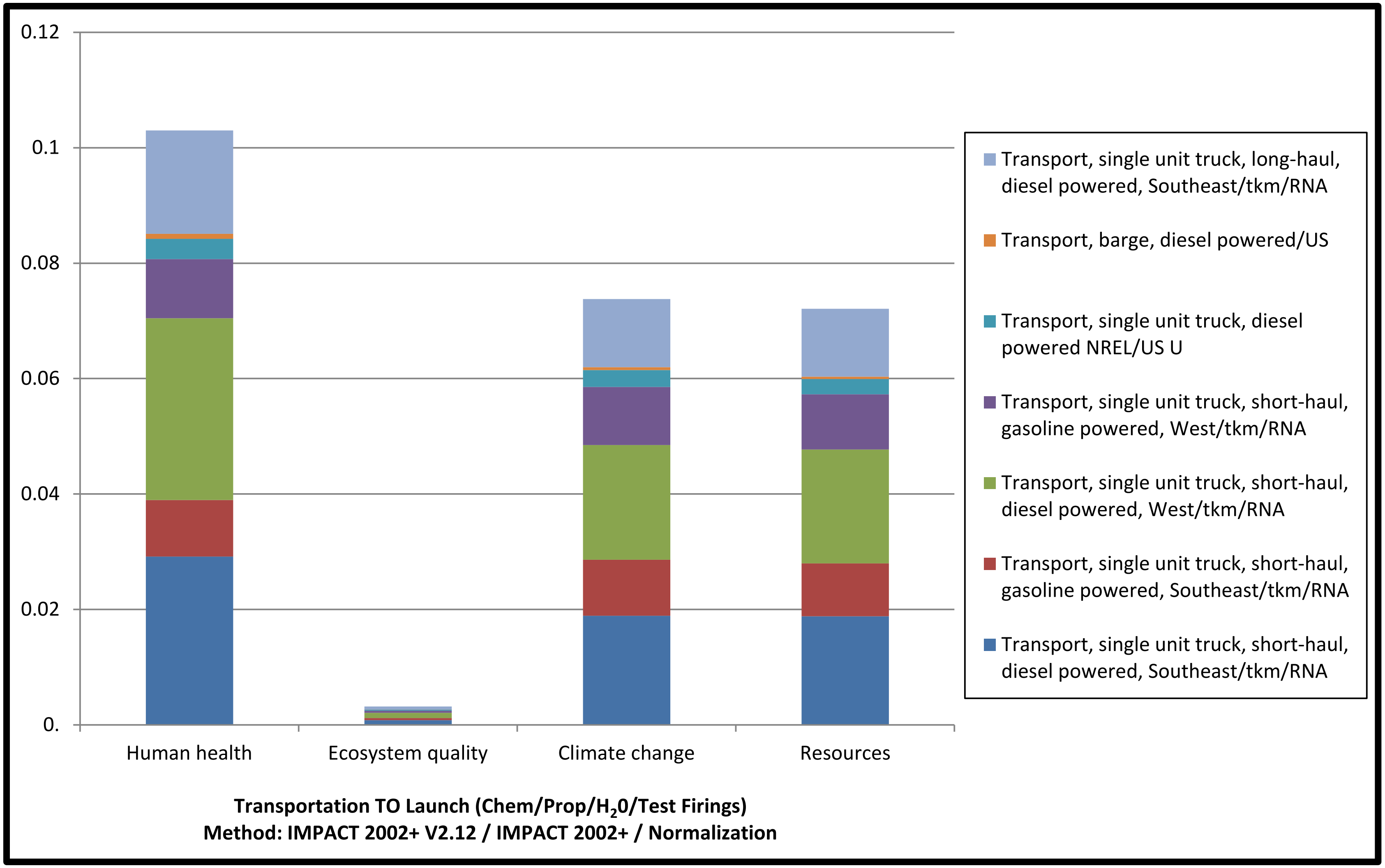


Figure 4-47 Transportation Damage Assessment Normalization (SimaPro Software)

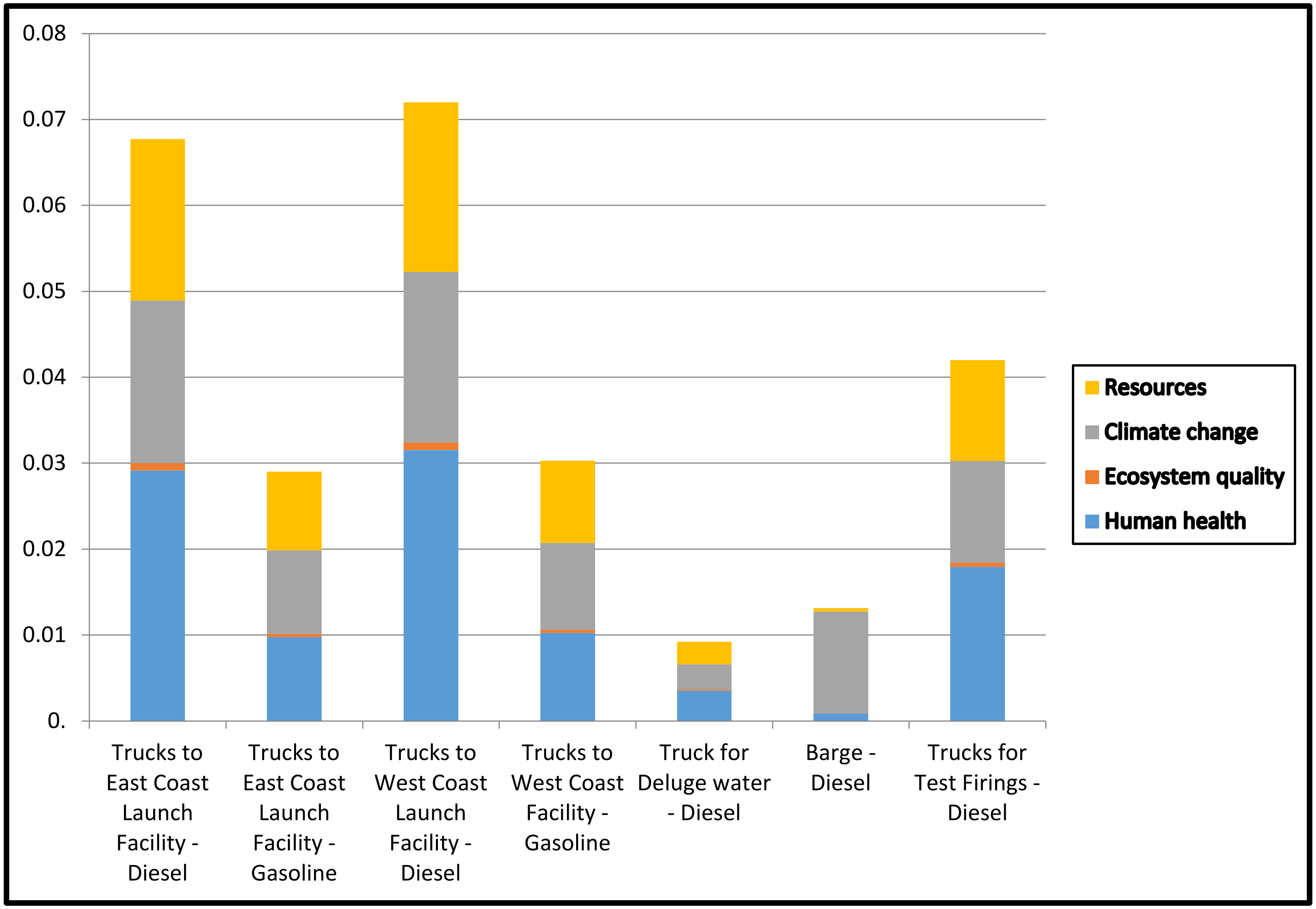


Figure 4-48 Transportation Damage Assessment Single Score Per Launch

4.1.3 Comparison of Reusable and Expendable Rocket Booster Per Launch

As mentioned previously, reusable and expendable rocket boosters have a few differences identified in this study. Other studies may know of other specific differences that were not included. This additional understanding of the differences can aid in refining the model for each of these boosters. A comparison of these boosters with the liquid propellants allows the decision maker to know which might be more eco-friendly if the space mission would have the flexibility to choose their launch vehicle and propellant. So, this comparison builds upon the base-case results.

4.1.3.1 Reusable Rocket Booster with Three Liquid Propellants

The reusable rocket booster SimaPro process was used as the building block and then each of the propellants (1^{st} Stage, 2^{nd} Stage, and Test Firings) was added to show a complete launcher system.

The reusable rocket booster with the three liquid propellants was compared as shown in Figure 4-49 for the Characterization categories. Each propellant influences the damage categories differently, however, the propellants, as seen previously in this chapter, influence Human health most. In the Characterization categories, LNG appears be the greatest influence of the propellants in eight categories; whereas, RP-1 impacts Ionizing radiation, ozone layer depletion, respiratory organics, aquatic and terrestrial ecotoxicity, aquatic eutrophication, and non-renewable energy categories. For propellant, LOX/LH_2 has the minimal impact to these categories. For all Characterization categories except mineral extraction, the impact of LH_2 is less than 30% of the impact of the propellant with the greatest impact (either LNG or RP-1, depending on the category). In other words, LH_2 reduces impacts by over 70% in all categories except mineral extraction. For mineral extraction, LH_2 reduces impacts by over 40%

The environmental burden found by the use of one reusable rocket booster with a liquid propellant shows each level of impact to each of these categories. The Damage Assessment, Normalization indicates that the LNG fuel poses the greatest impact to Human health and RP-1 poses the greatest impact to Resources. The comparison of these propellants when added to the reusable rocket launcher shows LNG and RP-1 were the greatest influencers to Climate change damage area with LH_2 as the lowest, as shown in Figure 4-50.

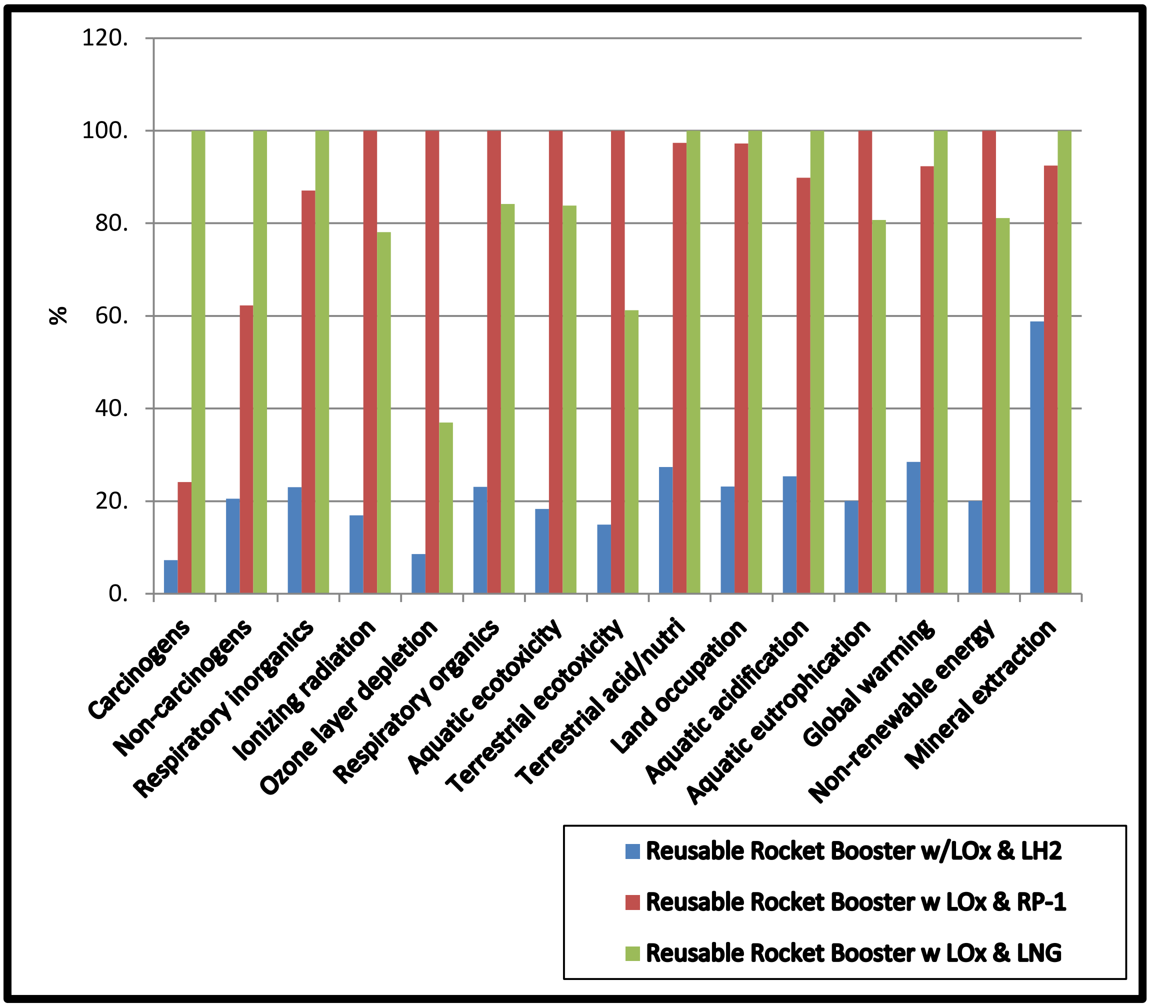


Figure 4-49 Reusable Rocket Booster with Liquid Propellants Comparison Characterization Categories

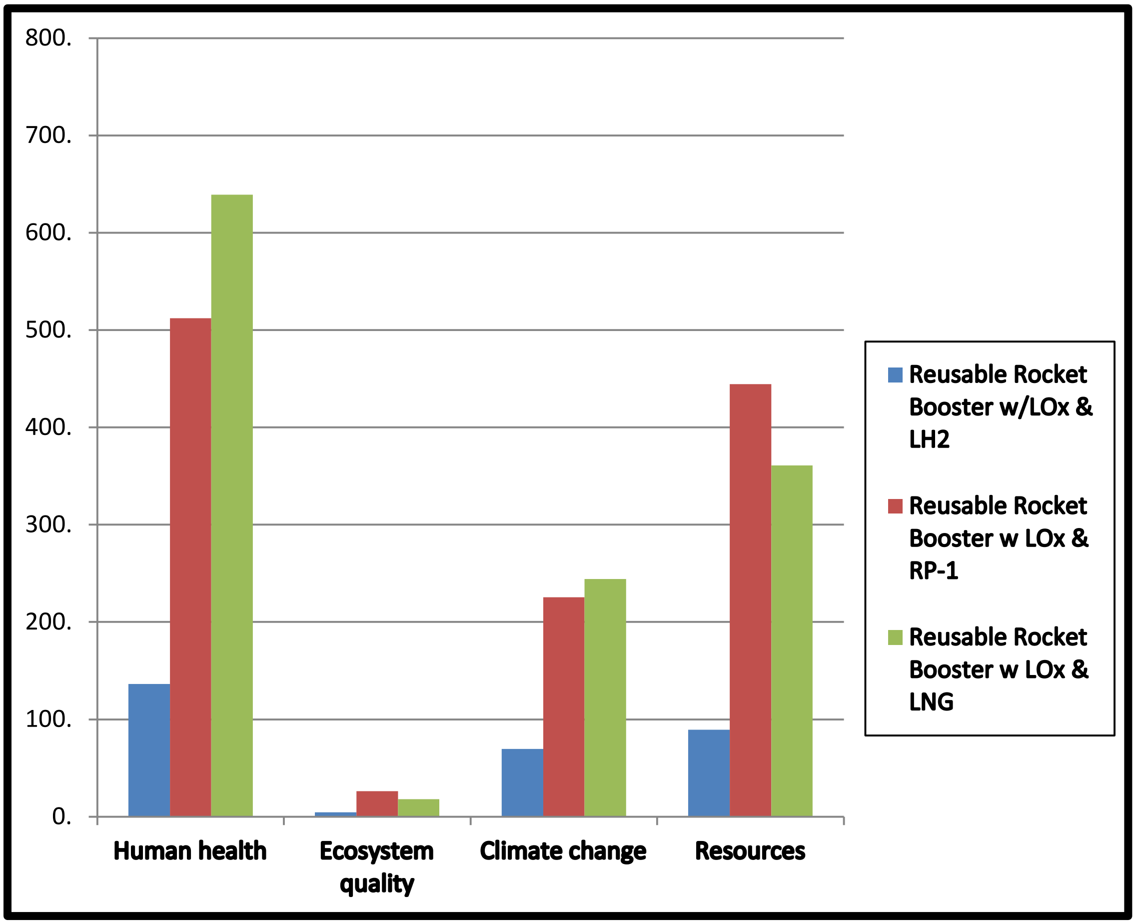


Figure 4-50 Reusable Rocket Booster with Liquid Propellants Comparison Damage Assessment, Normalization

4.1.3.2 Expendable Rocket Booster with Three Liquid Propellants

The SimaPro element for expendable rocket booster added the three propellants individually to make a complete rocket launcher with payload. Characterization results shown in Figure 4-51 reveals LNG is the greatest contributor to eight of the categories of mineral extraction, global warming, aquatic acidification, land occupation, terrestrial acid/nutrification, respiratory inorganics, carcinogens and non-carcinogens. RP-1 impacts the other categories not mentioned. For all Characterization categories except mineral extraction, the impact of LH_2 is less than 40% of the impact of the propellant with the greatest impact (either LNG or RP-1, depending on the category). In other words, LH_2 reduces impacts by over 60% in all categories except mineral extraction. For mineral extraction, LH_2 reduces impacts by 8.4%. The expendable rocket booster with propellant of LOx and LH_2 impact assessment characterization revealed that the 1st Stage influenced the Aquatic ecotoxicity, Aquatic acidification, Aquatic eutrophication and Mineral extraction as much or more than the propellant.

Figure 4-52 shows the damage assessment comparison of the expendable rockets with the specific propellant added per launch. Human Health is the most impacted by integration of the expendable rocket and the propellant. The expendable rocket booster with LNG fuel is the greatest contributor to the Human health damage area, whereas, the integrated expendable rocket with RP-1 most impacts Resource damage area. Climate Change is the third impacted from all the integrations of the expendable rocket booster with propellant.

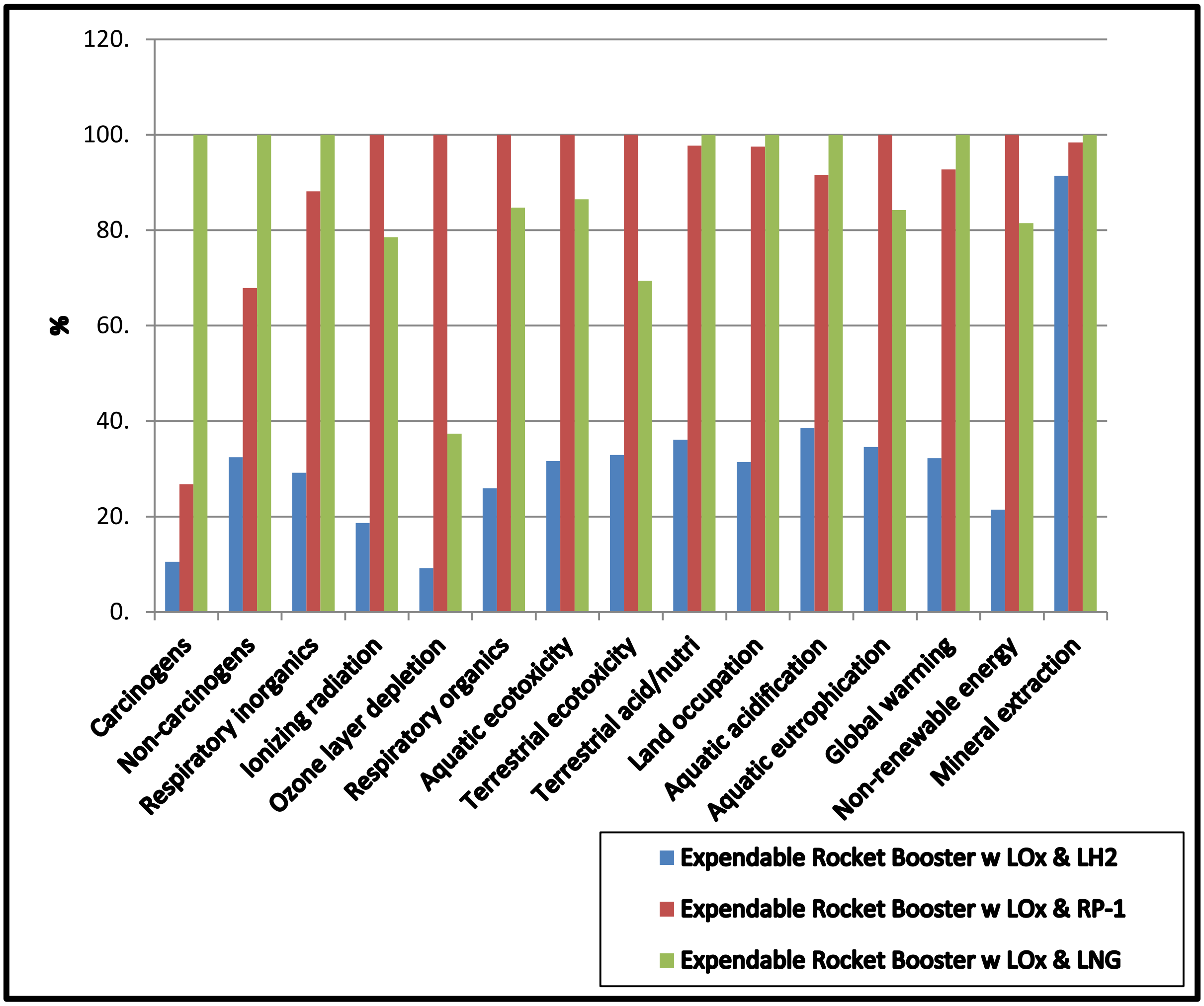


Figure 4-51 Expendable Rocket Booster with Propellants Comparison, Characterization Categories

185

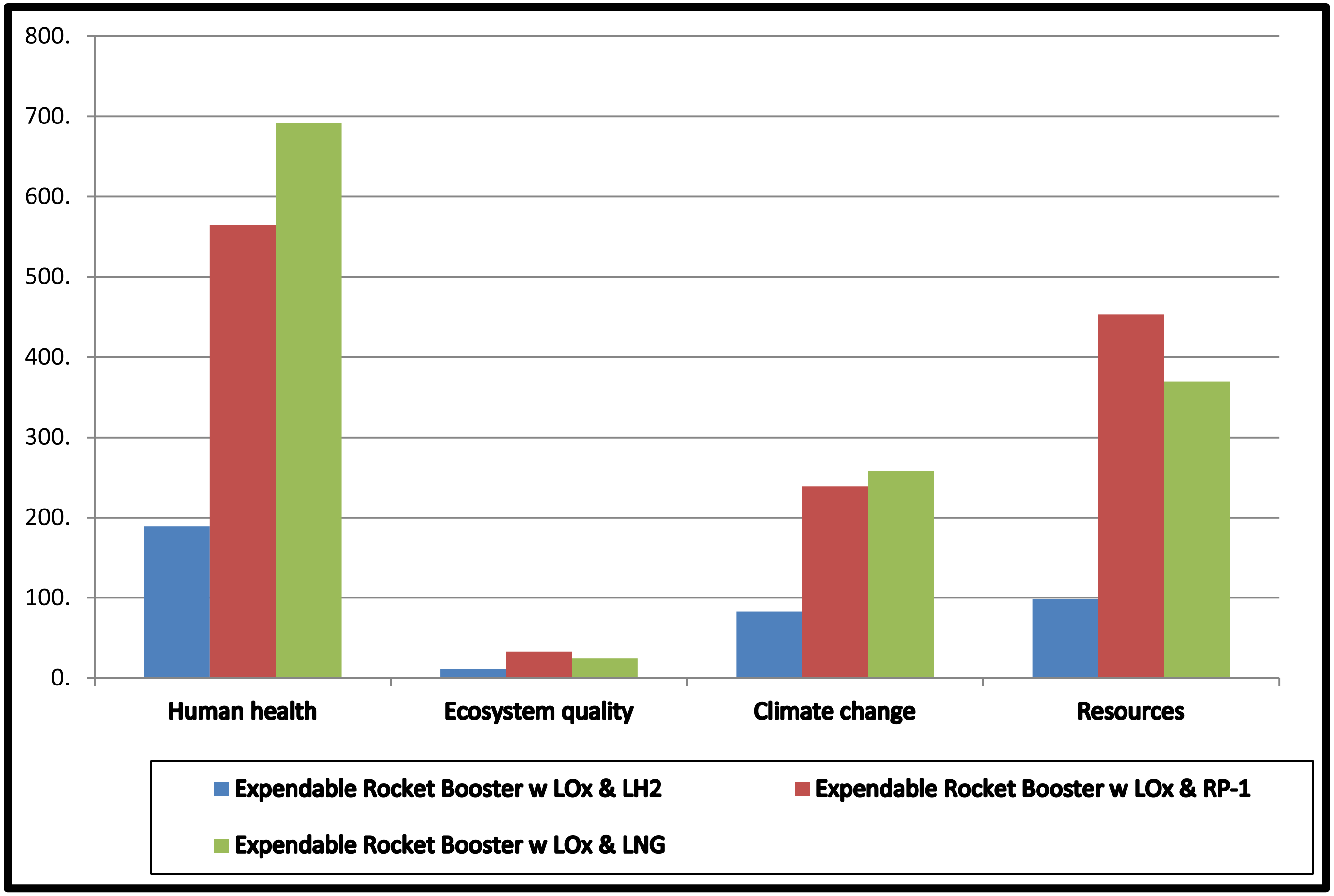


Figure 4-52 Expendable Rocket Booster with Propellant Comparison Damage Assessment Normalization

4.1.3.3 Side-by-side Rocket Booster Comparison

One comparison would be the reusable versus the expendable rocket booster as the CST activities continue to mature and decisions on mission types and frequency of launches will become more important. For this study, the reusable rocket booster was used on both LEO and GTO missions for 20 times. The expendable rocket booster supporting both LEO and GTO missions was used for one time with no recovery. The propellants would be used one time for each of these rocket boosters. So, for this comparison only the boosters will be compared using the SimaPro software to determine the environmental burden or consequences. The 1st Stage of the reusable rocket will have the additional 2% propellant included. Again, the more refined the data for each booster – reusable and expendable - the better the environmental burden or analysis will become.

Figures 4-53 and 4-54 compare the results for the reusable rocket booster versus the expendable rocket booster in the characterization and damage assessment. The Characterization results indicate the expendable rocket booster alone impacts all categories more than the reusable rocket booster. The reusable booster reduces impacts from 30% minimum (for non-renewable energy) to 89% maximum (for mineral extraction). This result is to be expected due to the reusability of the 1st Stage portion of the booster. Since even the engines are assumed to be reused at least 20 times, this would account for this result. Human health is the damage area most affected by both of the rocket boosters with the expendable rocket influencing this damage area the most. The climate change is affected next highest and this impact is mostly due to the expendable rocket booster.

When comparing these two rocket boosters, of course, the least impact to the environmental burden in the life cycle would come from the reusable rocket booster. Most of the environmental burden would occur in upstream life cycle phases such as raw material acquisition and manufacturing. For this base-case characterization of CST activities in the United States, the reusable rocket booster generates the least environmental burden as expected.

4.1.4 Comparison of Liquid Propellants Per Launch

The three liquid propellants used in this study were compared using the amount of oxidizer and fuel needed for a liquid rocket engine in the 1st Stage, 2nd Stage supporting LEO and GTO payloads and test firings as part of the launch campaign. The mass amount of propellant for each liquid propellant type was modeled after real world launchers. Figures 4-55 and 4-56 show the Characterization and the Damage Assessment, respectively, of the three liquid propellants. The comparison built upon the SimaPro results from the base-case analysis.

The Characterization reveals the LNG impacts the following categories the most: carcinogens, non-carcinogens, respiratory inorganics, terrestrial acid/nutrification, land occupation, aquatic acidification, global warming and mineral extraction. The RP-1 impacts the following categories the most: ionizing radiation; ozone layer depletion; respiratory organics; aquatic ecotoxicity; aquatic eutrophication; and non-renewable energy.

The Damage Assessment using Normalization comparing the three propellants reveals **Human Health is most impacted by all three propellants**. The LNG fuel impacts Human health damage area the most and RP-1 fuel impacts almost as much. Resources are impacted next and RP-1 fuel impacts this area the most. Climate change is impacted third of the overall four damage areas. The LNG fuel impacts Climate change slightly more than RP-1.

Overall, **the propellant with the highest environmental impact is LOx and LNG fuel.** The top five constituents causing the most consequence from the propellant LOx/LNG to the Human health damage area is particulates < 2.5 µm, sulfur dioxide, aromatic hydrocarbons, nitrogen oxides, and dioxin. The propellant LOx/LNG has these top four constituents that impact the Climate change damage area: carbon dioxide, fossil; methane; fossil; sulfur hexafluoride; and dinitrogen monoxide. Resources are impacted most from the LOx/RP-1 propellant from these five constituents used as raw materials – crude oil; hard and brown coal; natural gas; and Uranium. The propellant, LOx/LH_2 has the least impact because the quantities of both LOx and LH_2 modeled using Delta IV Heavy rocket booster data is less than the amount for the other two propellants modeled. For Delta IV Heavy used as the model for this propellant, less amount of propellant is needed to achieve the performance and thrust designed for this launcher. On a per-kg basis calculated from the sensitivity analysis, the LOx/LH_2 propellant has more influence across all four damage areas. However, on an equivalent launch performance basis, LOx/LH_2 propellant has less impact than RP-1 in all four damage areas because less LOx/LH_2 is required to achieve the same performance. **For this base-case ELCA, LOx/LH$_2$ has the least impact to the environment and LOx/LNG has the greatest impact to the environment in areas of Human health and Climate Change.**

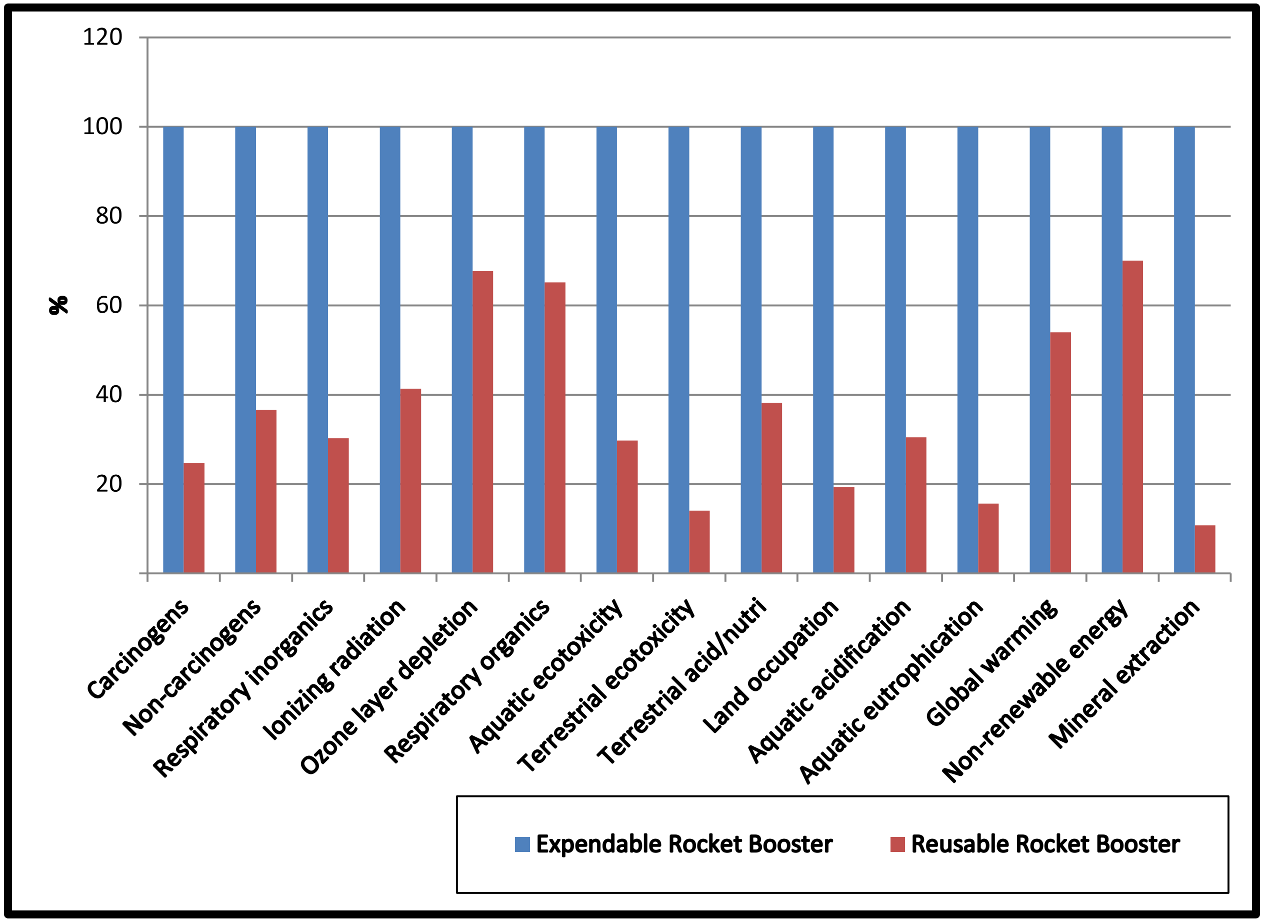


Figure 4-53 Comparison of Reusable versus Expendable Rocket Booster in Characterization Impacts

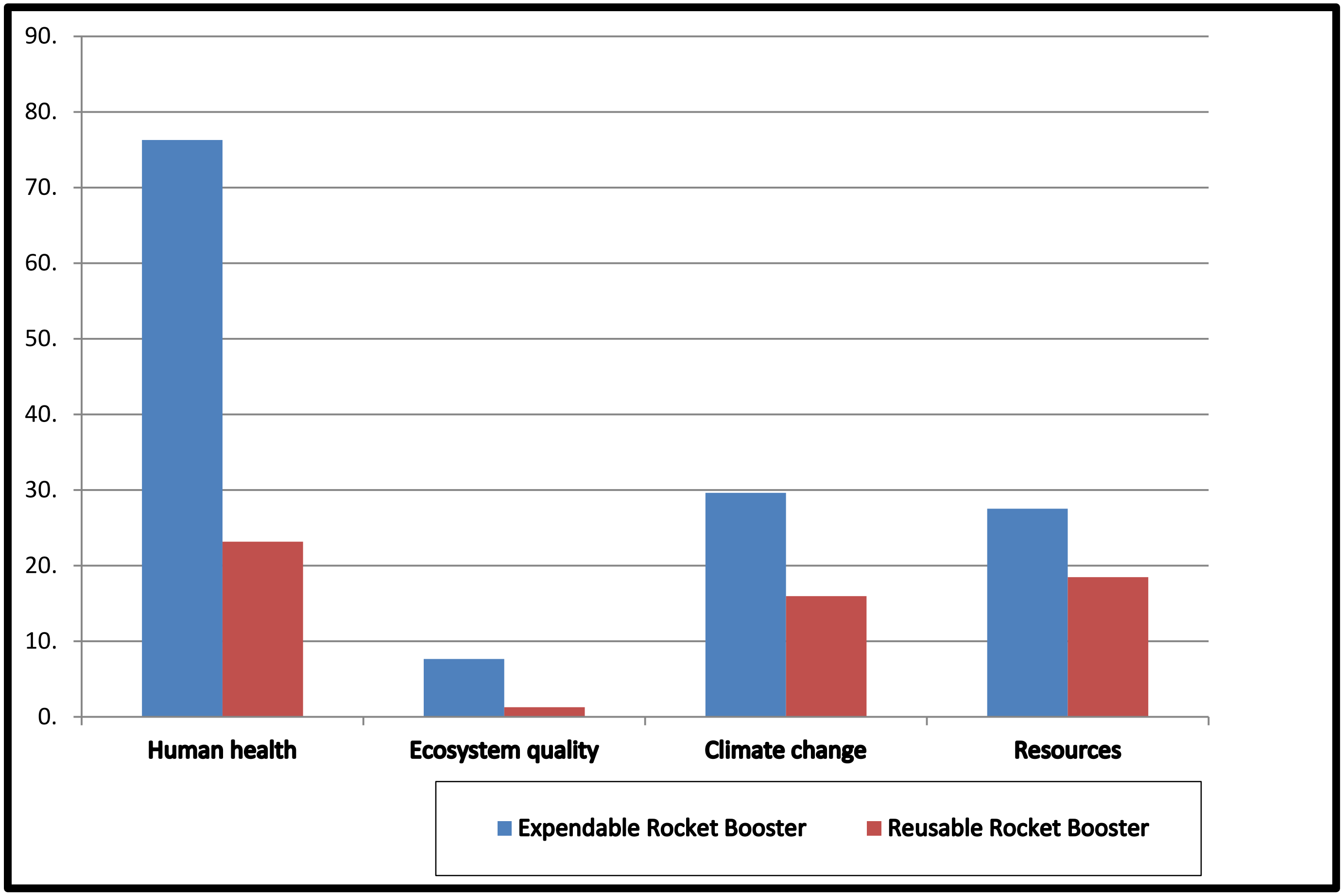


Figure 4-54 Comparison of Reusable and Expendable Rocket Boosters Damage Assessment Normalization

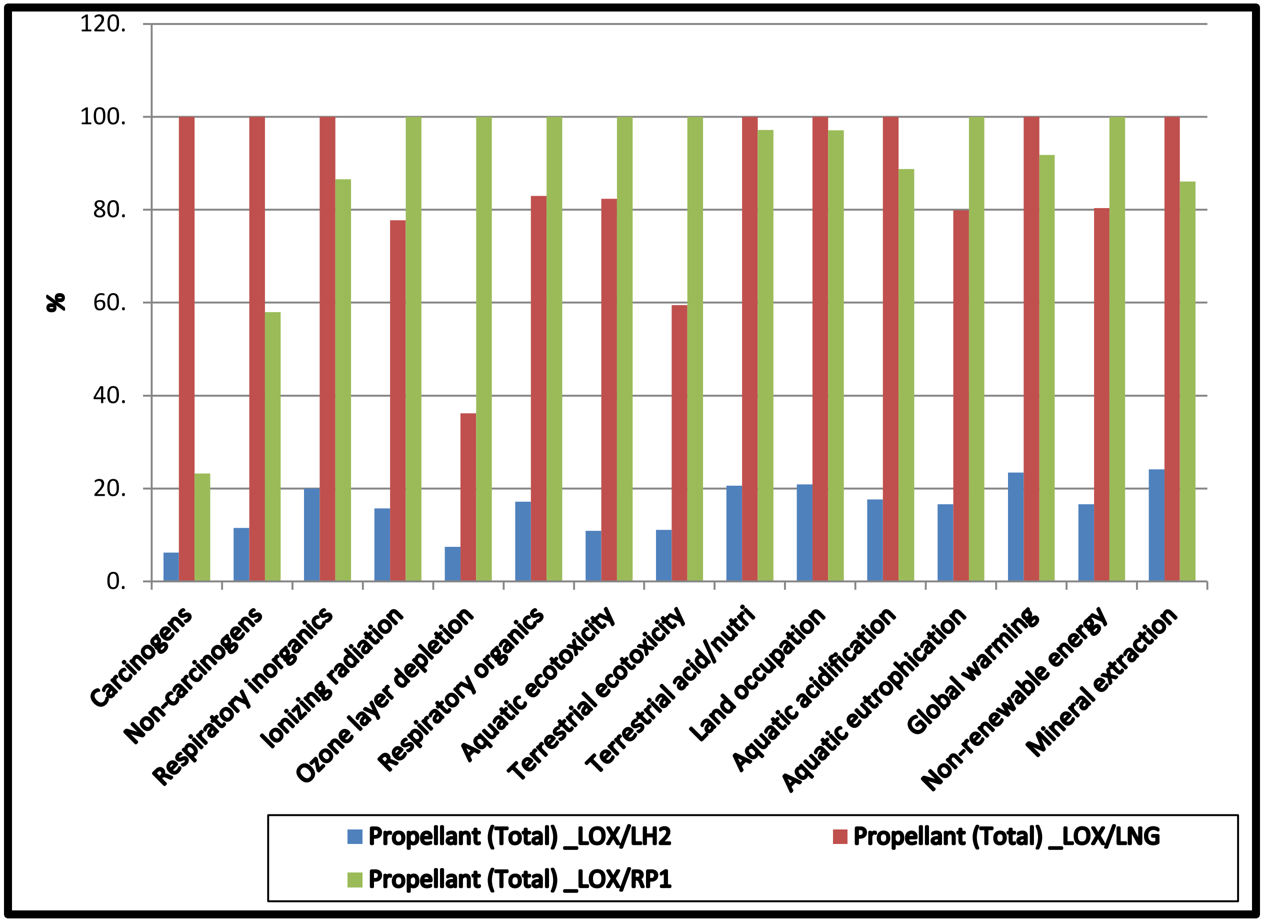


Figure 4-55 Comparison of Liquid Propellants Characterization Impact Categories

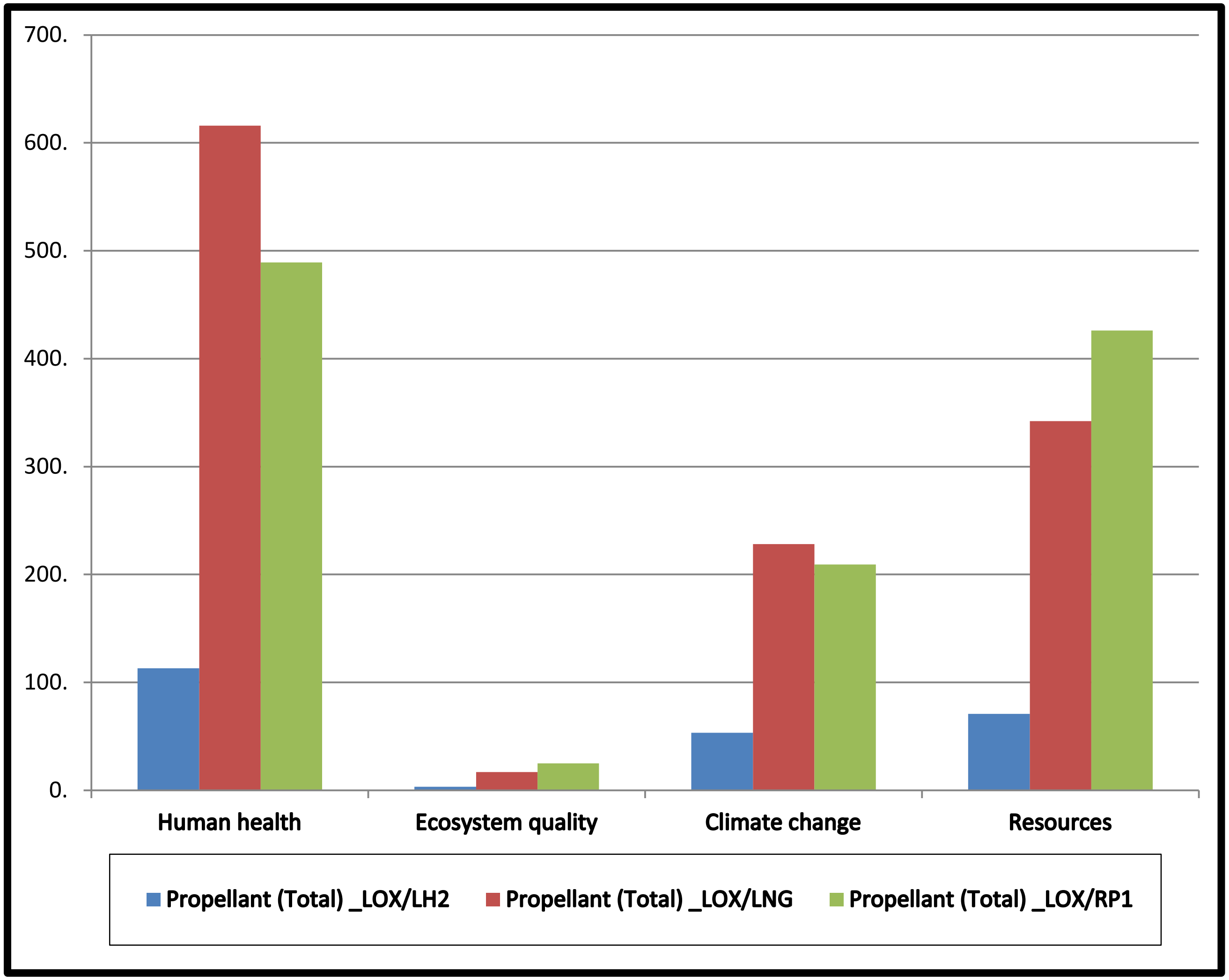


Figure 4-56 Comparison of Liquid Propellants Damage Assessment Normalization

4.1.5 Delphi Method Applied to Rocket Boosters and Propellants Per Launch

Table 4-29 shows the Delphi Method (annotated as “1”) results compared to the SimaPro results (annotated as “2”) for five consumables: reusable rocket booster, expendable rocket booster, LOx/LH_2, LOx/LNG, LOx/RP-1. The table shows the top two of the four damage areas impacted. Both the expert panel and SimaPro agree that Human health is the most impacted by the reusable rocket booster. For the expendable rocket booster, both agree that Climate change is the most impacted. For LOx/LH_2, both agree Human health and Resources damage areas are most impacted. For LOx/LNG and LOx/RP-1, the results from expert panel and SimaPro agree that Resources are impacted.

Figure 4-57 shows the Delphi Method mean value results of 18 participants. This figure also shows the level of concern for the five consumables. Figure 4-58 provides the SimaPro results for the five consumables. A direct value comparison cannot be made but general agreement is shown in the top two highest damage areas affected for Delphi Method and SimaPro results for these consumables. When visually comparing these results, the expert panel and the SimaPro results agree on the LOx/LH_2, whereas the other consumables a difference in which damage area impact is seen as the greatest. Also, a difference is seen in the two results on which consumable poses the greatest impact to the damage areas. From the Delphi Method, LOx/RP-1 is greatest overall in the damage areas. From the SimaPro results, LOx/LNG is greatest overall in the damage areas. One other observation is the Ecosystem quality is of more concern to the expert panel from these consumables, whereas, the SimaPro results show minimal impact to this damage area from these consumables. SimaPro results for Ecosystem quality is most likely due to the impact method’s priority placed on each of the damage areas and Ecosystem quality is the lowest.

So, the use of a Delphi Method allows the key stakeholders an opportunity to decide on what is the most important impact or damage areas (end-points) in their decision making. By using experts to inform the LCA results, another perspective emerged showing how various end-points are seen as most impacted from CST activities in the United States.

Table 4-29 Comparison of Delphi Results and SimaPro Results[41]

CONSUMABLE	HUMAN HEALTH	ECOSYSTEM QUALITY	CLIMATE CHANGE	RESOURCES
REUSABLE ROCKET	1, 2		1	2
EXPENDABLE ROCKET	2		1, 2	1
LOx/LH_2	1, 2			1, 2
LOX/LNG	2	1		1, 2
LOX/RP-1	2	1		1, 2

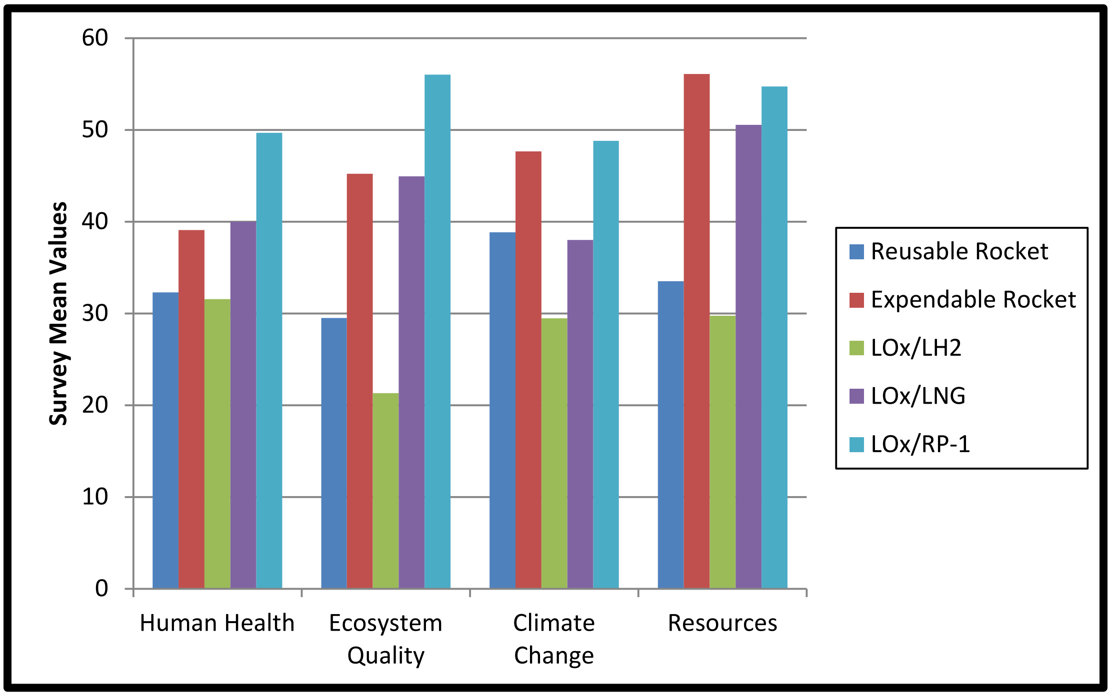


Figure 4-57 Delphi Method Participant Results[42]

[41] 1 = Panel of Experts Input, 2 = SimaPro Results

[42] The Delphi Method survey results reflect the mean value of survey participant responses from 0-100 for each of the consumables in each of the damage areas.

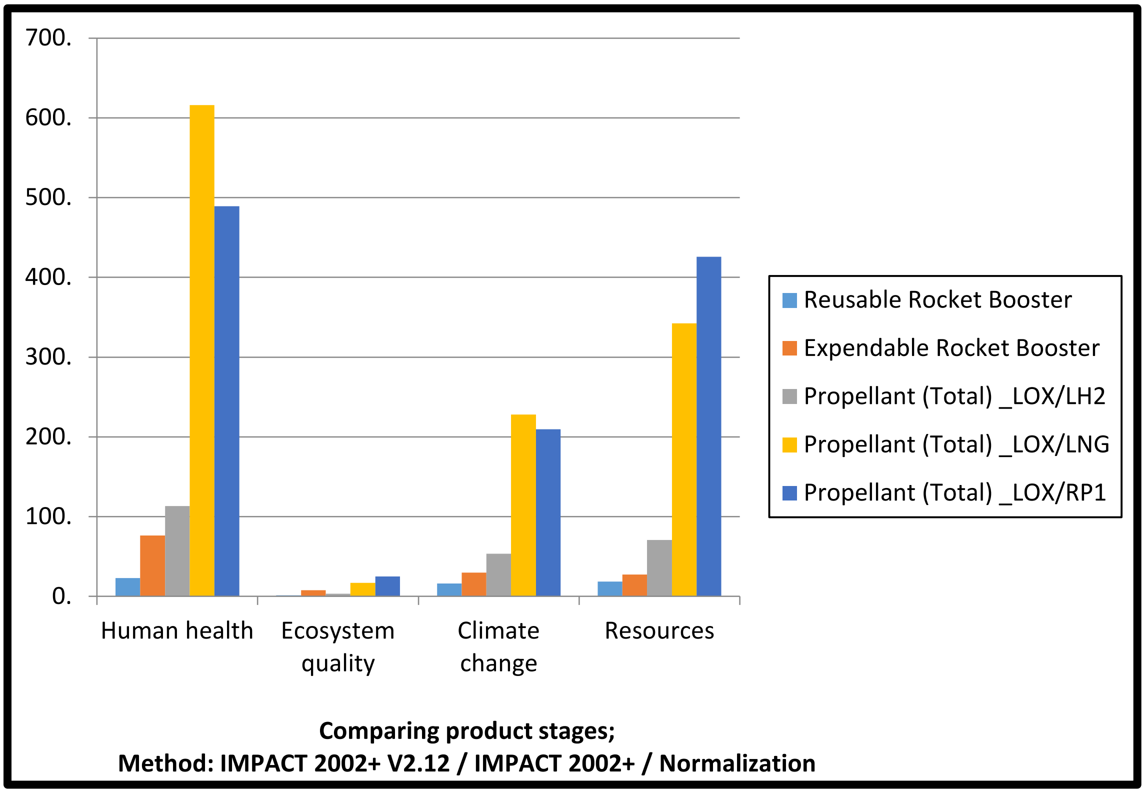


Figure 4-58 SimaPro Results for Five Consumables

These Delphi Method results provide the perspective of the diverse panel and show that stakeholders for the space launches will most likely have these differing perspectives when deciding on what is most important in their decision making about environmental impacts from a launch of a space vehicle.

4.1.6 Space Transportation Environmental Profiles Per Launch Derived From Base-Case

The LCA methodology provides insight into the environmental impacts associated with CST activities in the United States. Space transportation environmental profiles to Launch (STEP-L) were developed using inventory and impact assessment results for this study.

For this base-case, six scenario-based STEP-Ls were generated to show the Characterization and Damage Assessment Normalization for the reusable rocket and the expendable rocket with each propellant and the other consumables of water, electricity and chemicals as a launch system. Characterization and Damage Assessments were shown for each consumable individually in Section

4.1.2. .All of these consumable results will generate the STEP-L for each rocket launcher type assessed in this study.

The standard SimaPro charts **were not** used for the STEP-Ls. Instead, radar charts were used to represent the reusable or expendable rocket boosters combined with each of the propellants and the other consumables for a per launch and whole system perspective. Radar charts display where the most impact occurs holistically and from where these impacts are generated within the launch of one space vehicle into orbit. These STEP-Ls will readily allow for accounting for cumulative environmental implications as part of the operational decision-making.

4.1.6.1 Modules for Reusable Rocket Booster Space Transportation Environmental Profiles (STEP) Per Launch.

Figures 4-59 and 4-60 show the STEP-L of the reusable rocket with the propellant of LOx/LH_2 in the Characterization and Damage Assessment Normalization. Figures 4-61 and 4-62 show the STEP-L of the reusable rocket booster with propellant LOx/LNG in the Characterization categories and the Damage Assessment Normalization. Figures 4-63 and 4-64 show the STEP-L of the reusable rocket with propellant of LOx/RP-1 also in the Characterization categories and Damage Assessment Normalization.

The operator from just a glance can review these figures to see the category in the Characterization most affected and which consumable contributes most to that category and damage area. Now this combination of **per Launch** of a reusable rocket booster and all of the consumables offers a system perspective into the launch campaign of these consumable inputs. When a reusable rocket booster is used with one of the propellants this study examined, then this STEP-L would represent the per Launch contribution to the environmental impact in those damage areas and those characterization categories. This environmental-related information allows the decision maker to begin to evaluate options where substitutions might be considered without compromising efficiencies in the mission of launching one space vehicle with payload.

4.1.6.2 Modules for Expendable Rocket Booster Environmental Mission Profiles Per Launch

The expendable rocket booster varies from the reusable rocket booster by not having the grid fins, landing legs or extra propellant for landing in this study. Also, the reusable is used for 20 launches and the expendable is used for one launch.

Figures 4-65 and 4-66 show the STEP-L of the expendable rocket with the propellant of LOx/LH_2 in the Characterization and Damage Assessment Normalization. Figures 4-67 and 4-68 show the STEP-L of the expendable rocket booster with propellant LOx/LNG in the Characterization categories and the Damage Assessment Normalization. Figures 4-69 and 4-70 show the STEP-L of the expendable rocket with propellant of LOx/RP-1 Characterization categories and Damage Assessment Normalization.

When selecting the reusable rocket booster with those consumables examined in this study, then this STEP-L would be the mission environmental contributions from launching one space vehicle into orbit per Launch.

From examining these radar charts for the expendable rocket booster, the chemicals, propellant and the 1st Stage become more obvious as those consumables impacting many or all areas or even one significantly. This environmental-related information again allows a decision maker to begin to think about impacts from using the expendable rocket booster and possibly act on opportunities for minimizing future environmental effects.

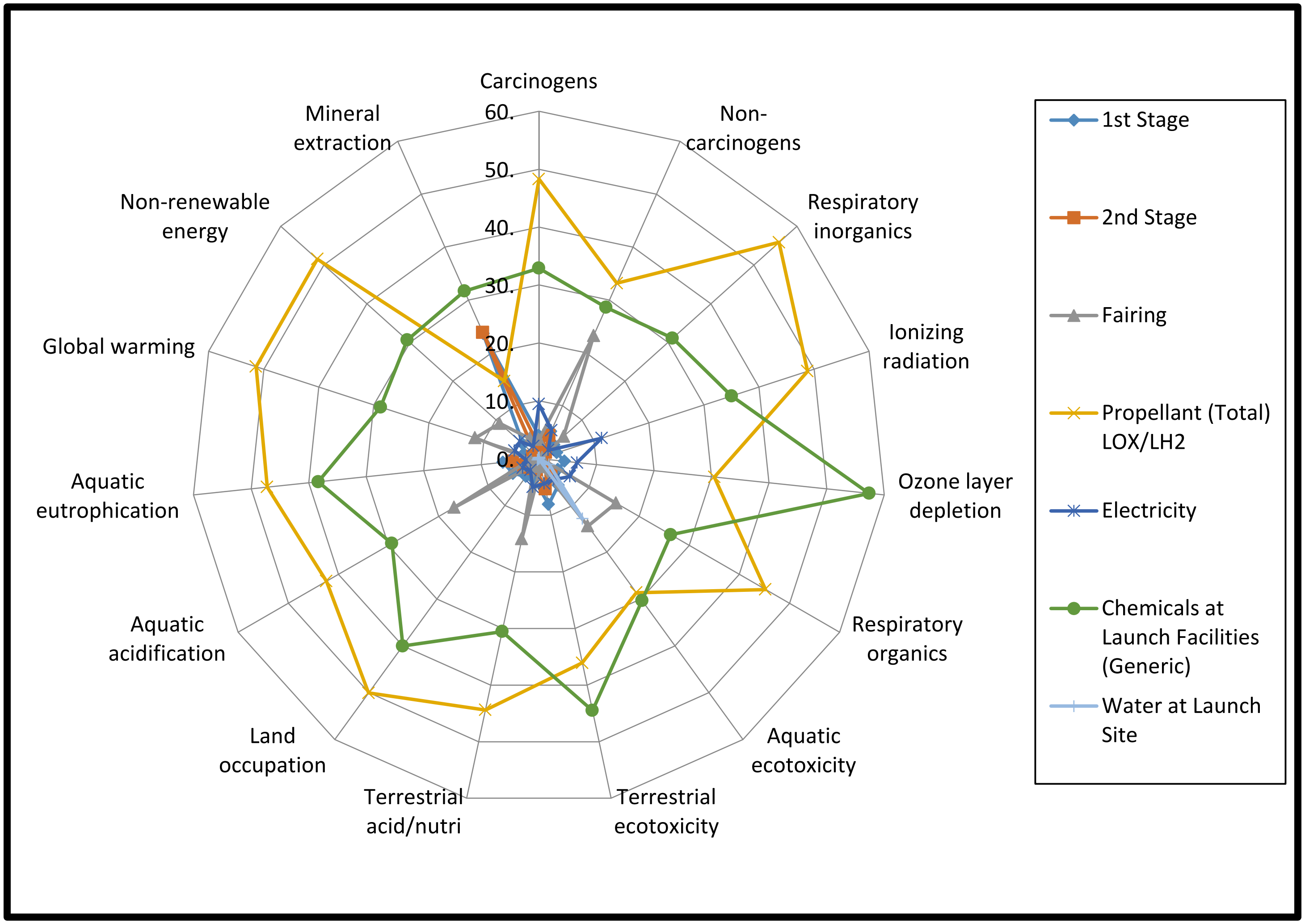


Figure 4-59 STEP- L for Reusable Rocket Booster with LOx/LH$_2$ Characterization Categories

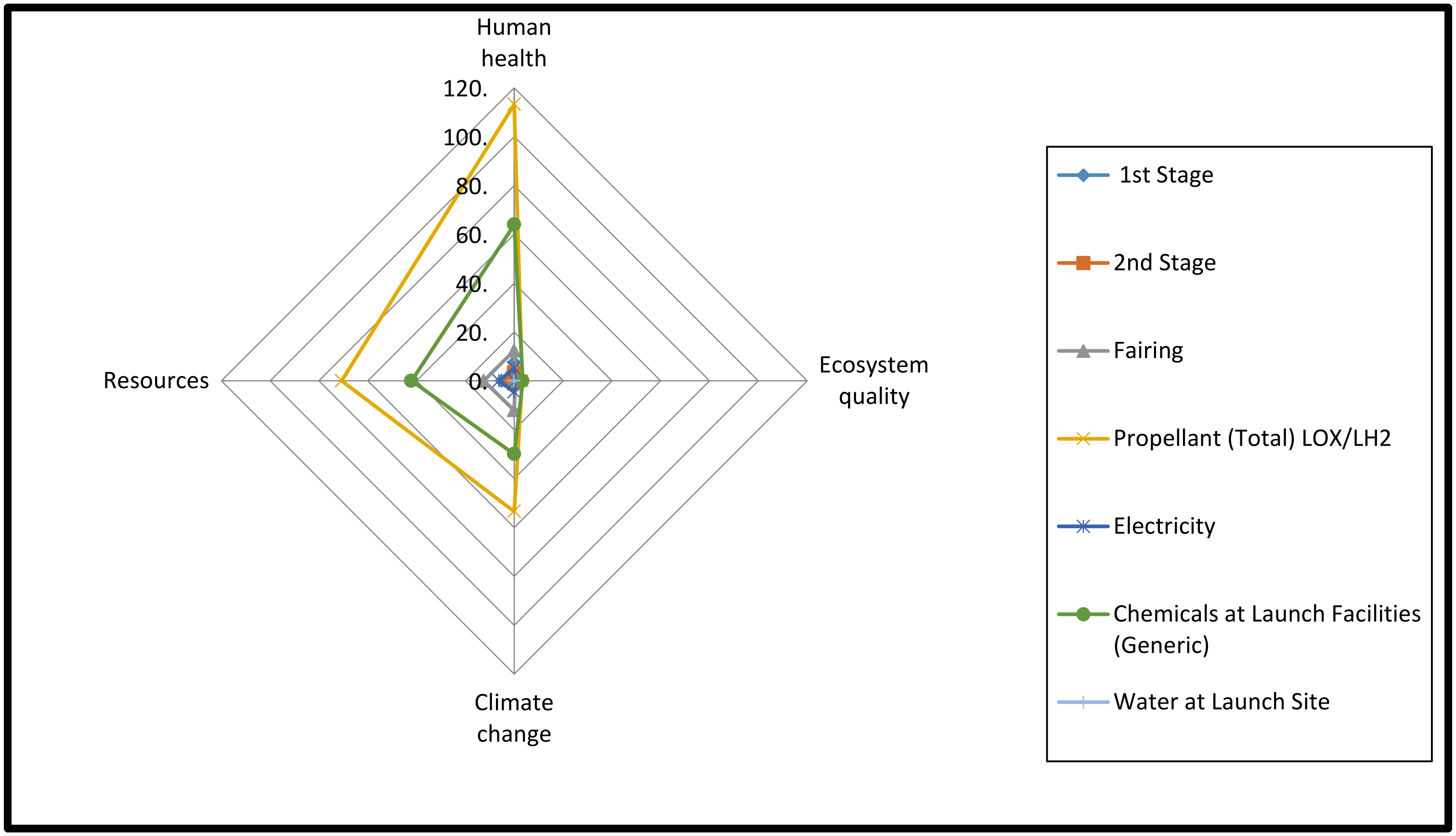


Figure 4-60 STEP- L for Reusable Rocket Booster with Propellant LOx/LH_2 Damage Assessment Normalization

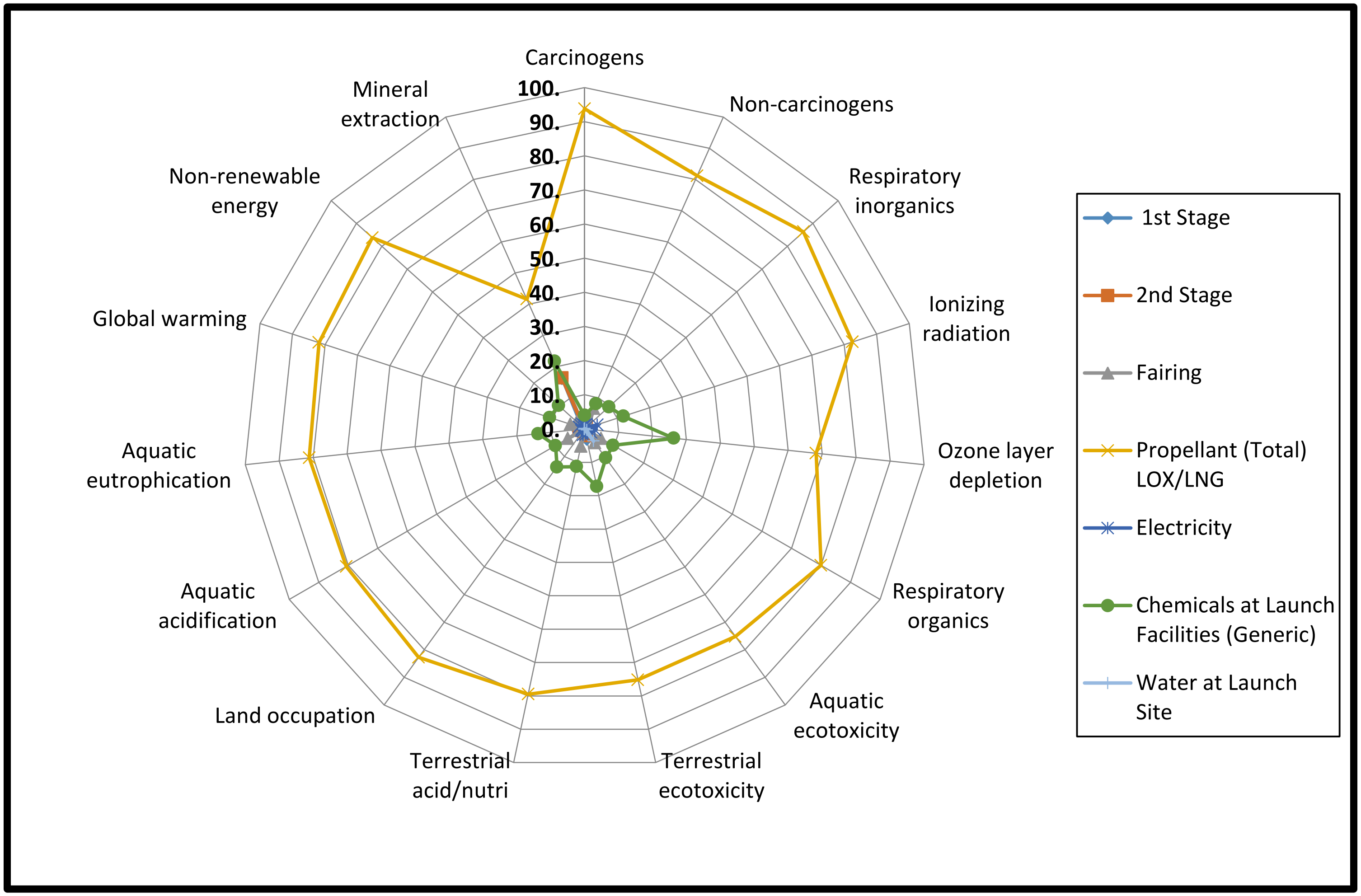


Figure 4-61 STEP- L for Reusable Rocket Booster with Propellant LOx/LNG Characterization Categories

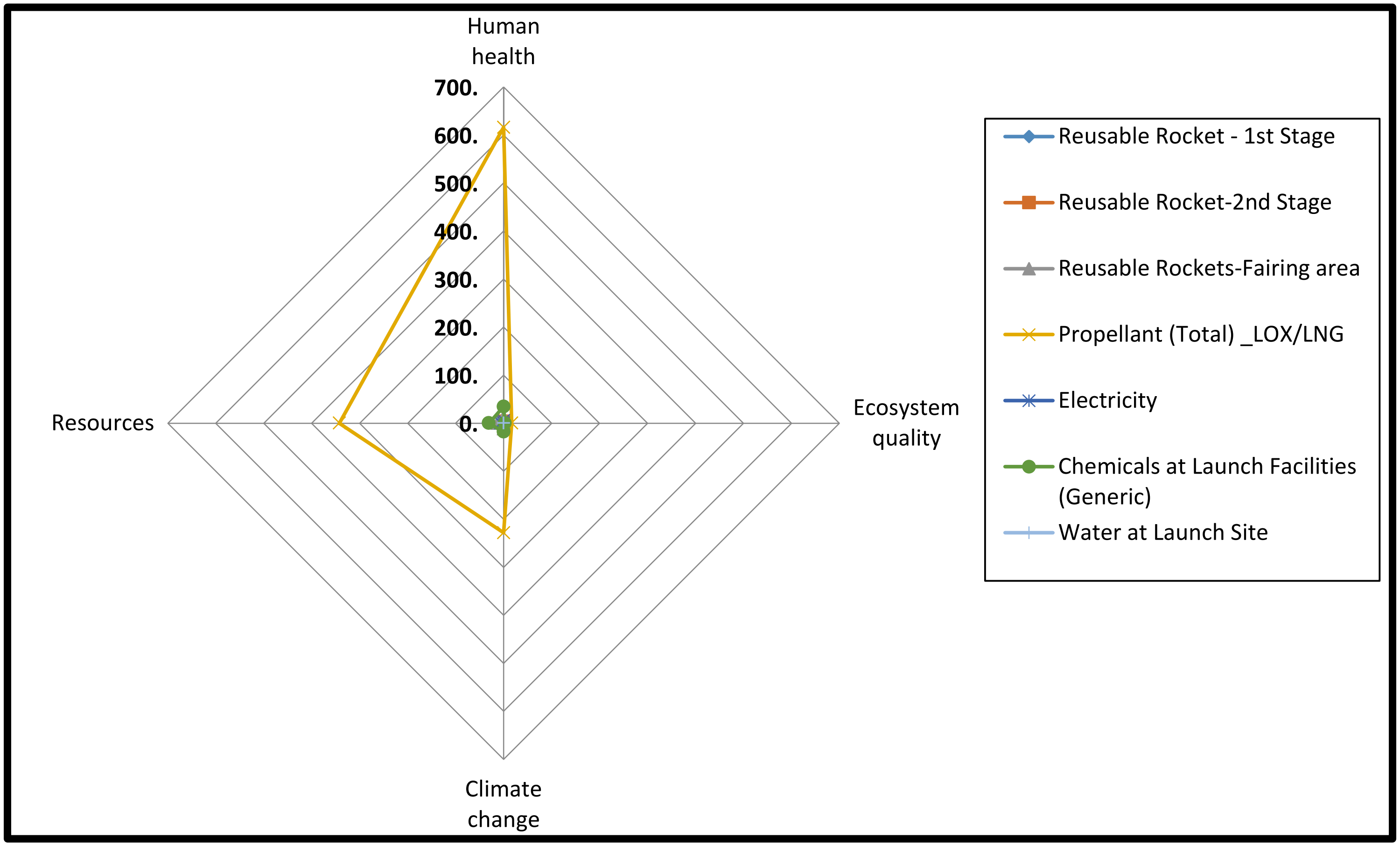


Figure 4-62 STEP- L for Reusable Rocket Booster with Propellant LOx/LNG Damage Assessment Normalization

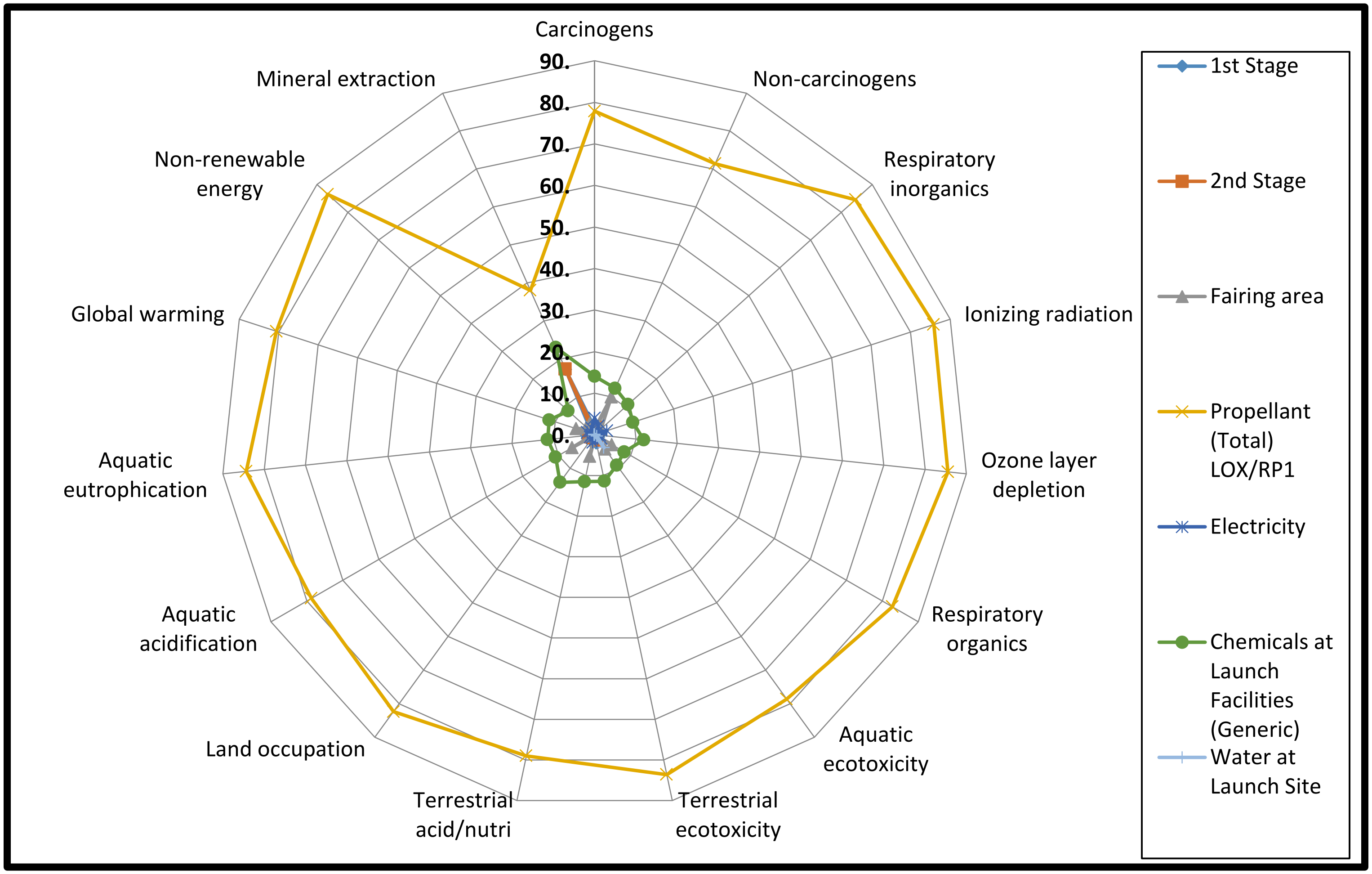


Figure 4-63 STEP- L for Reusable Rocket with Propellant LOx/RP-1 Characterization Categories

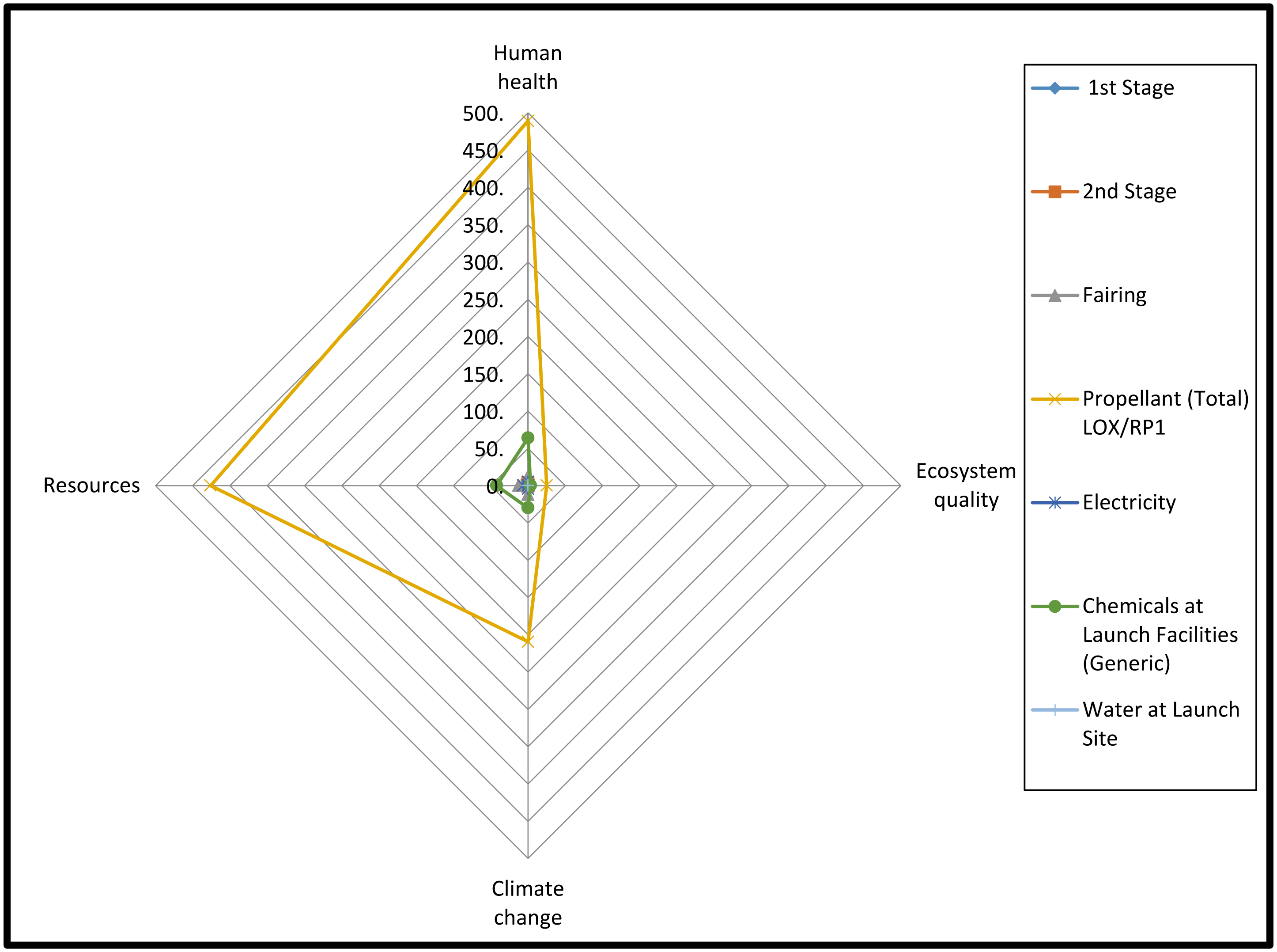


Figure 4-64 STEP- L for Reusable Rocket with Propellant LOx/RP-1 Damage Assessment Normalization

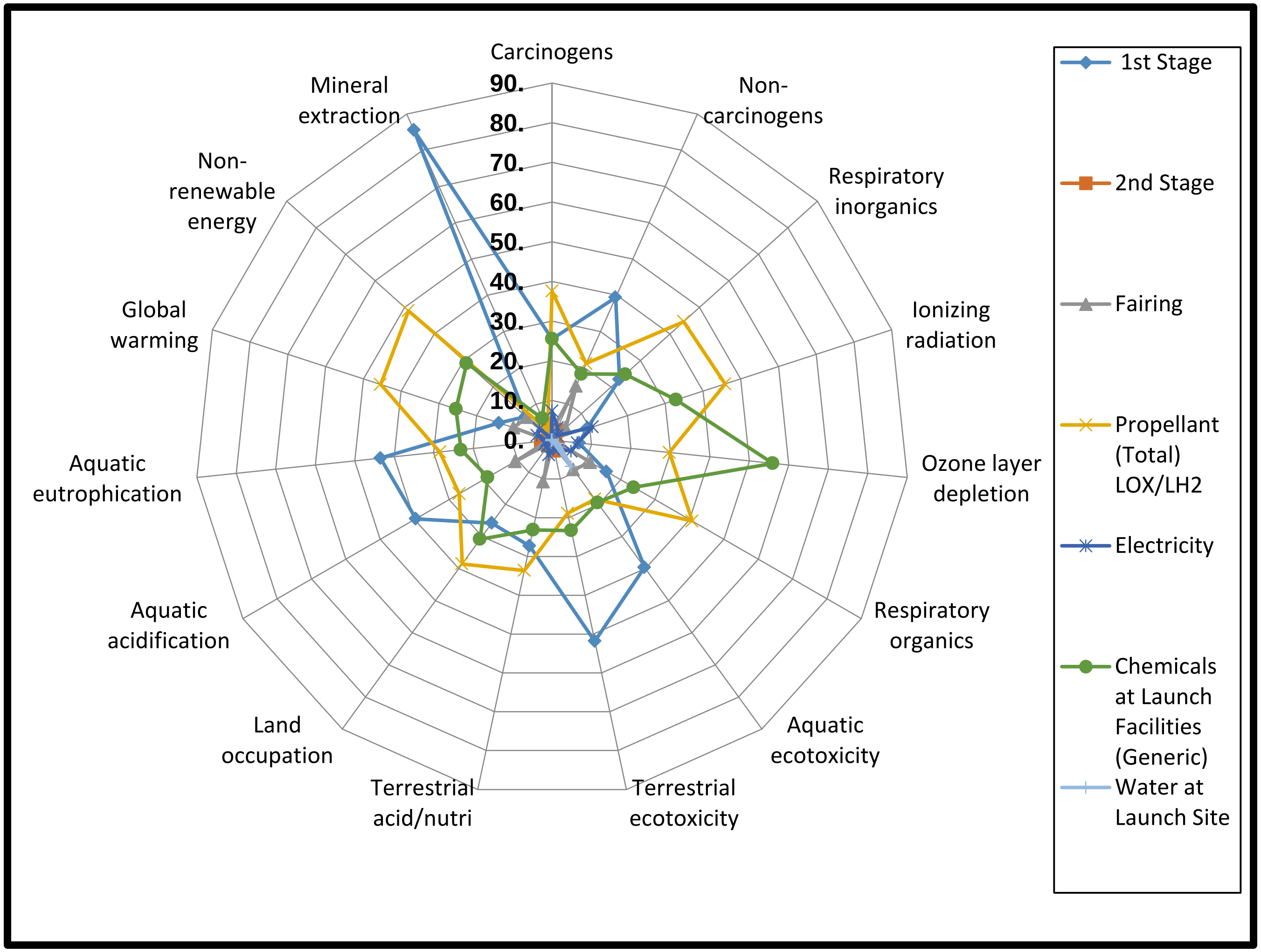


Figure 4-65 STEP- L for Expendable Rocket Booster with Propellant LOx/LH$_2$ Characterization Categories

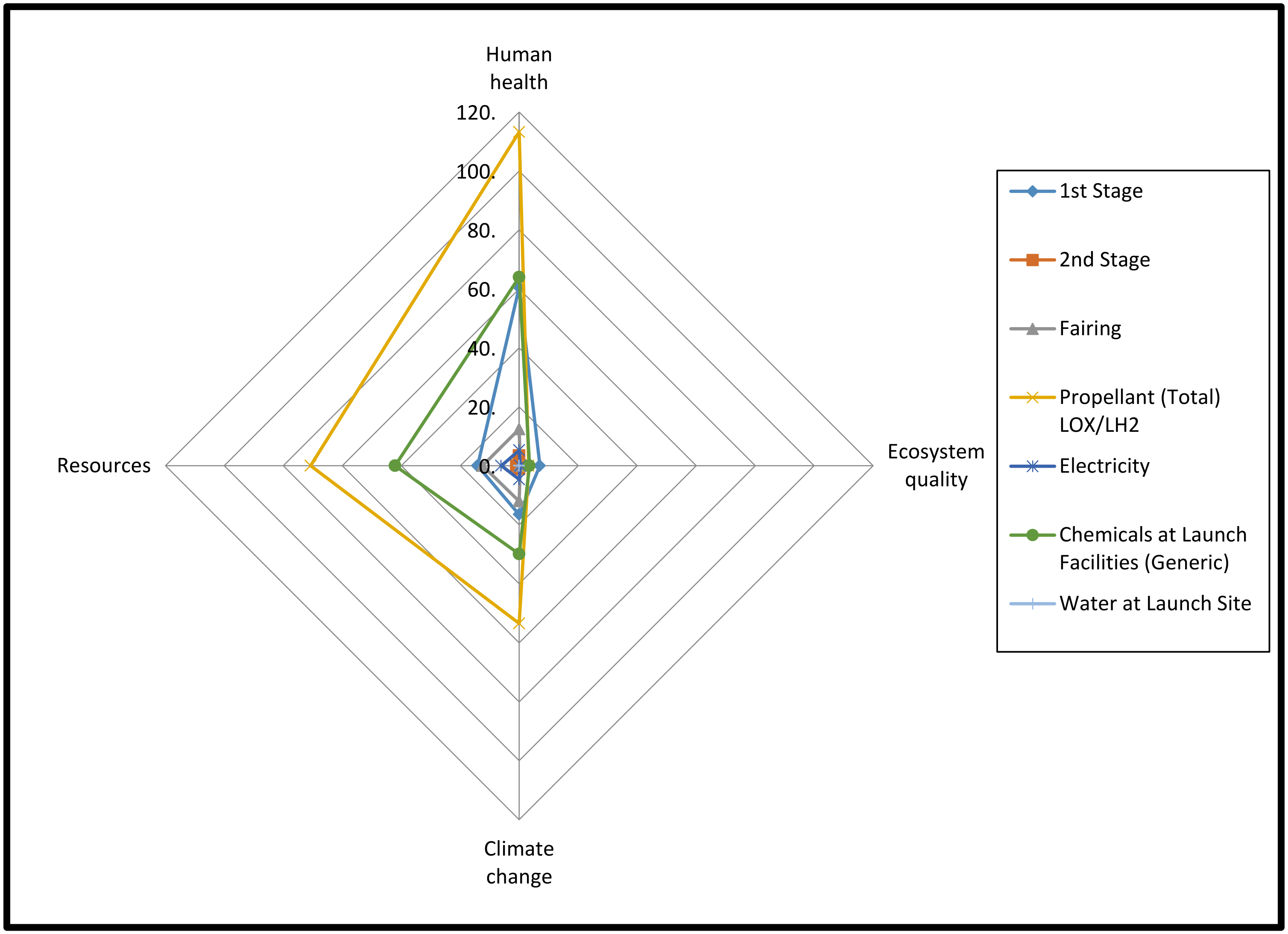


Figure 4-66 STEP- L for Expendable Rocket Booster with Propellant LOx/LH_2 Damage Assessment Normalization

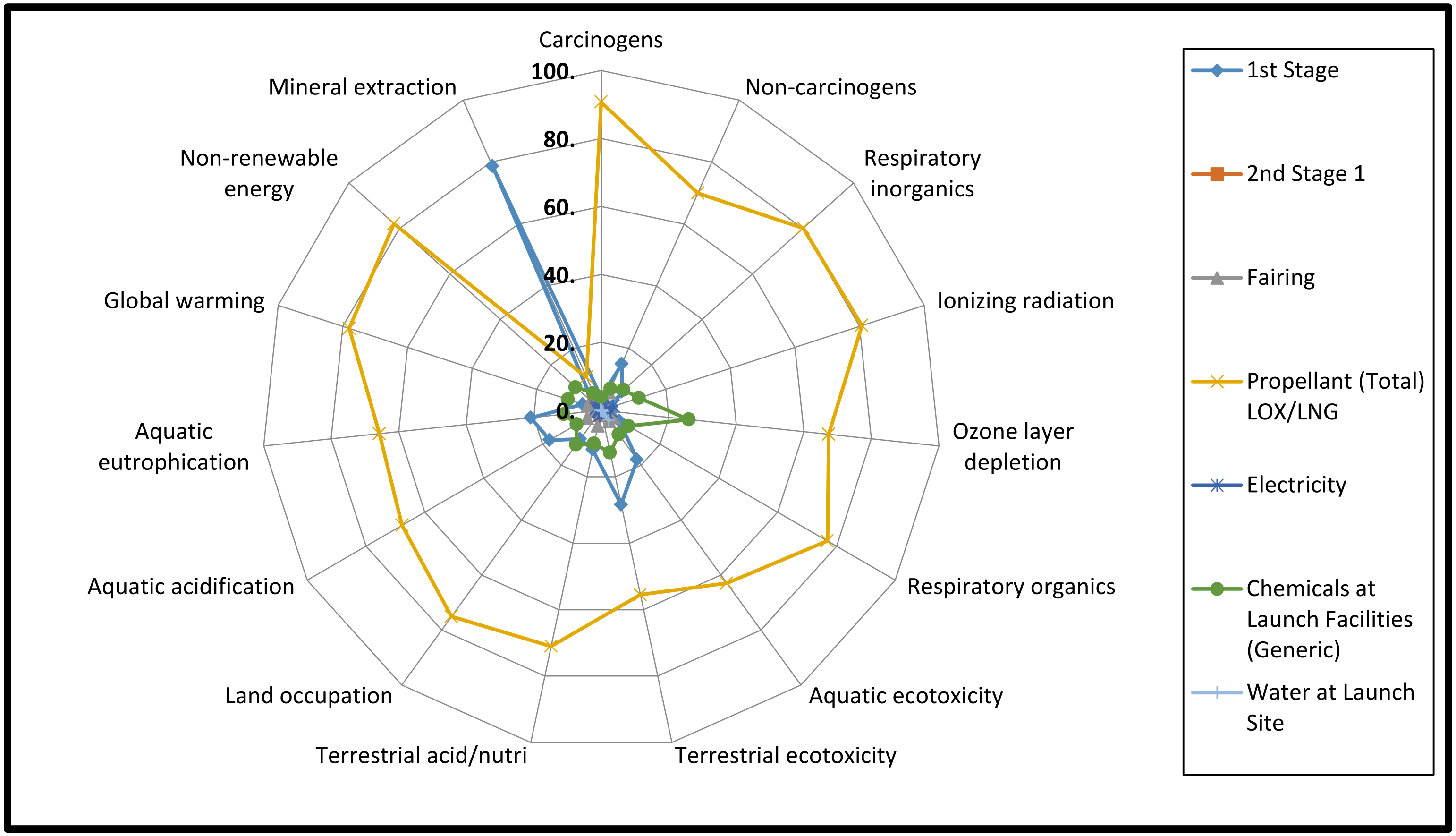


Figure 4-67 STEP- L for Expendable Rocket Booster with Propellant LOx/LNG Characterization Categories

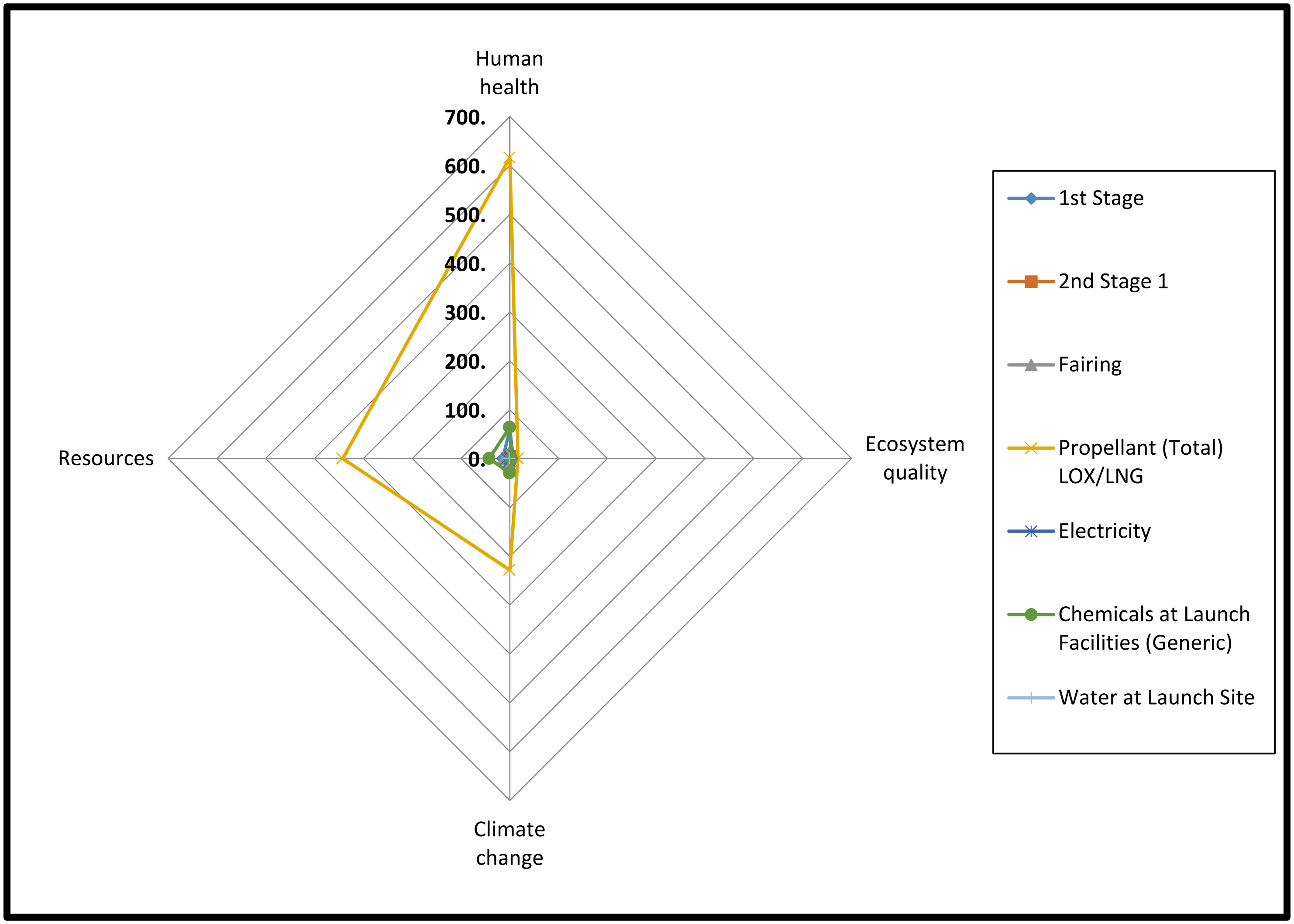


Figure 4-68 STEP- L for Expendable Rocket Booster with Propellant LOx/LNG Damage Assessment Normalization

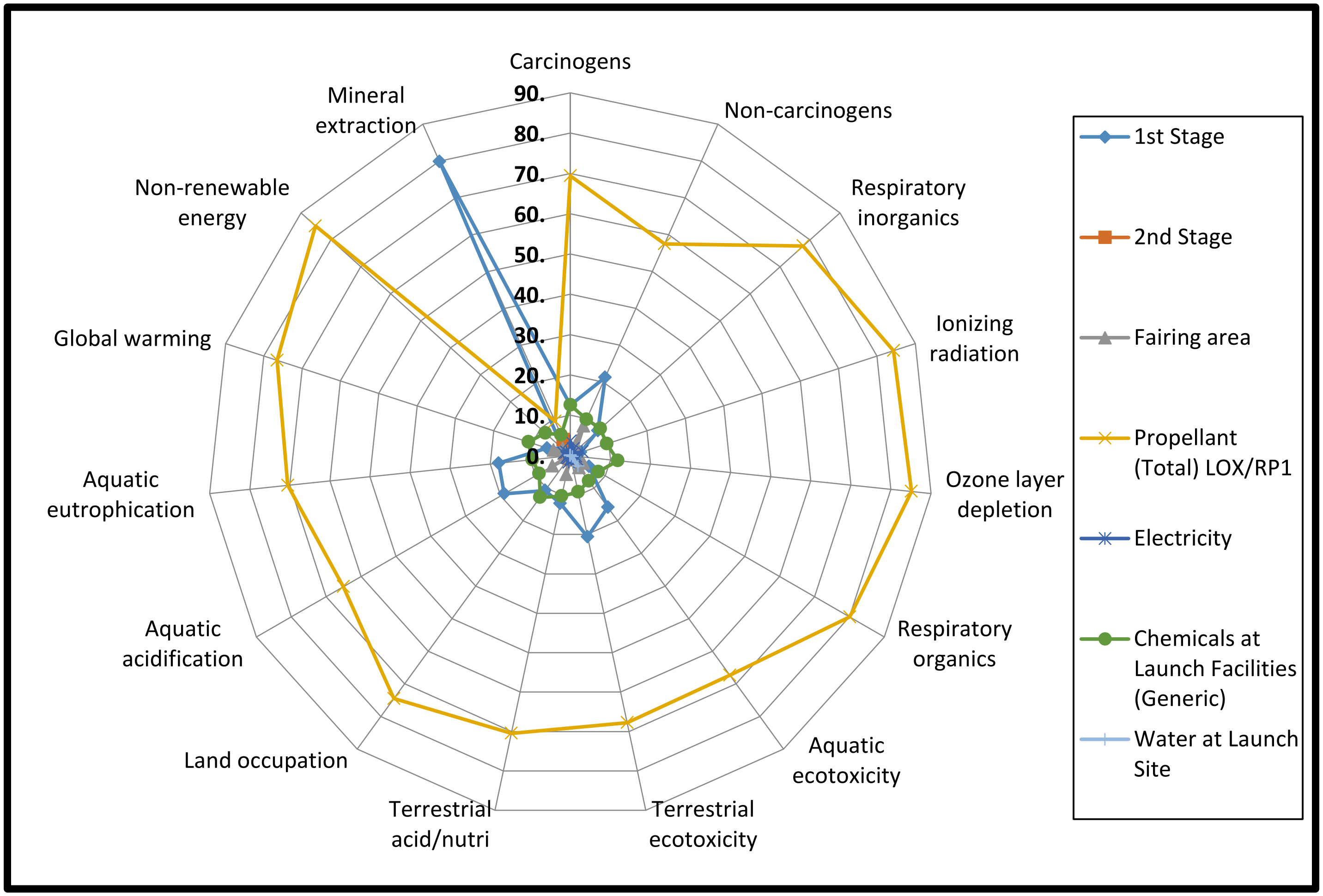


Figure 4-69 STEP- L for Expendable Rocket Booster with Propellant LOx/RP-1 Characterization Categories

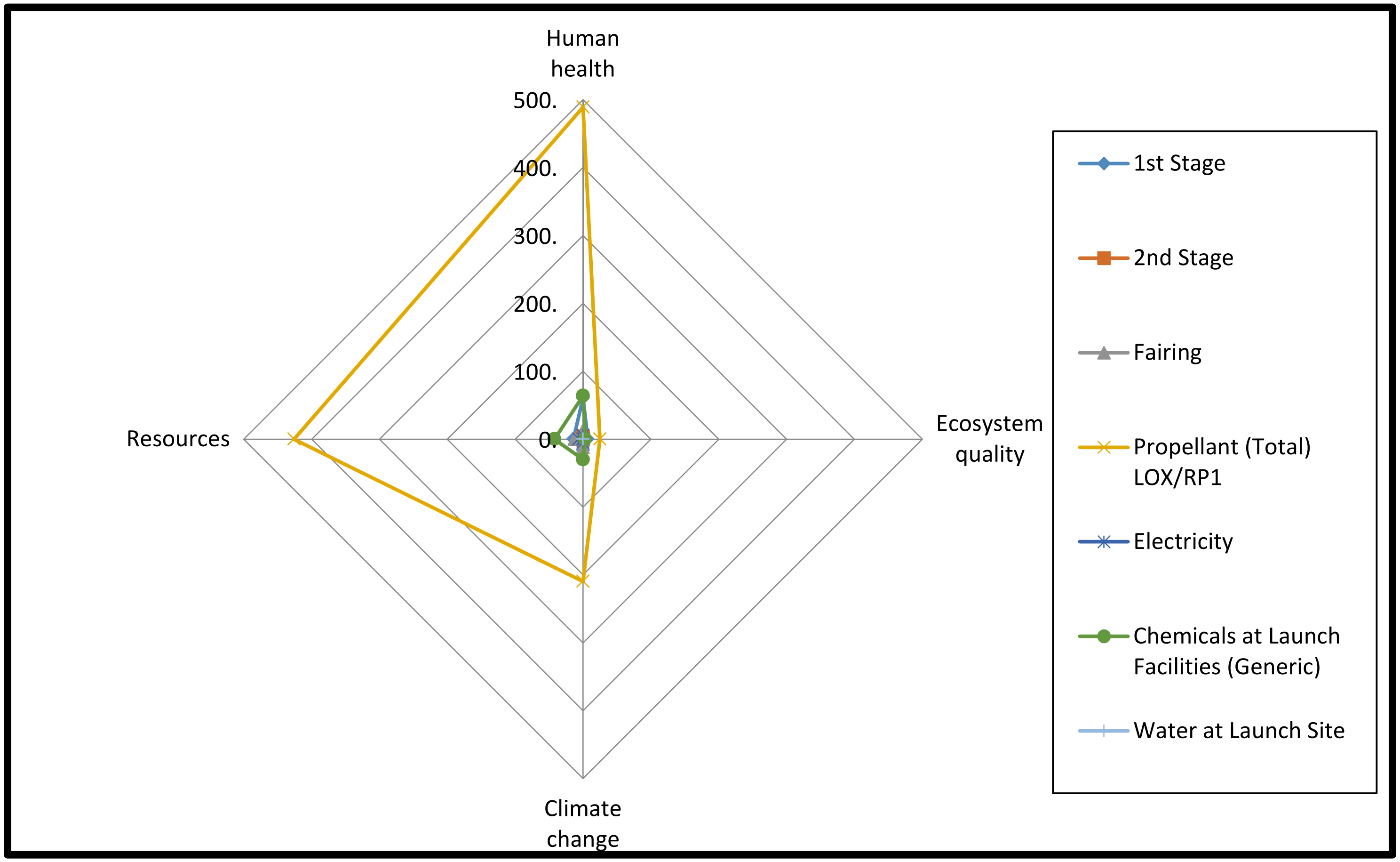


Figure 4-70 STEP - L for Expendable Rocket Booster with Propellant LOx/RP-1 Damage Assessment Normalization

One way to apply this ELCA is to aid the environmental managers, program managers, NEPA authors, launch operators, and other decision-makers on environmental implications or consequences per launch using a STEP-L. These STEP-Ls aided in development of a quick look dashboard (see Section 4.4). This STEP-L dashboard is an interface to allow the operator to build out each mission launch and gain insight into the overall environmental impact of each launch prior to the launch and possibly provides a more cumulative view over time as these STEP-Ls are prepared for each launch mission. The operator can then capture and record these impacts following a launch for future systems and environmental reviews.

Other ways to develop specific STEP-Ls might be to use other LCA tools such as OpenLCA or DoD Scoring Factors from the Sustainability Assessment Methodology can be used for the LCIA phase of the LCA framework. Future studies might use DoD Scoring Factors found in the DoD Sustainability guide to contrast with the SimaPro results.

4.1.7 Summary of Base-Case of CST Activities using LCA Methodology

The LCA methodology provided quantitative values to aid in identifying those highest contributors to the environmental burden or impact areas in the inventory analysis. The propellants, in particular the LOx, and the engine components and their material makeup generate or influence the greatest environmental burden per Launch for a space vehicle launch into orbit. The reusable rocket booster influenced the environmental burdens less than the expendable rocket booster, as expected, due to the ability to reuse materials and other parts more than one time. The various chemicals used and stored at the launch facility can make a difference as to the environmental burden. In this study, eight chemicals were chosen based on NEPA documents references and the operational need for the chemicals. Hydrazine, diesel and liquid nitrogen had the highest impact for the chemicals considered. More fidelity is needed in the Chemicals consumable based on the accuracy of the type and amount of chemicals, the length of storage at the facility, the type of disposal and handling, recycling of materials, and other unique equipment needed for storage. Finally, electricity and water are minimal contributors to the environmental burden. However, the diesel-generator was the largest contributor of impact within the electricity consumable. Finding another source of electricity or power for the crane and other operational needs rather than using the diesel would decrease significantly the environmental impacts.

Figure 4-71 and 4-72 show the characterization and damage assessment for all of the consumables considered in this study. These summary figures allow a direct comparison of all the consumables and their relative contribution to impact on a per launch basis. However, these combination figures of all the consumables do not represent an operational launch scenario. An operational launch scenario would not use both boosters and all three liquid propellants but use one booster and one propellant. Figure 4-73 shows the Damage Assessment Single Score illustrating the levels of contribution per damage category of each consumable in one glance.

A relevant comparison to this space launch base-case would be the emissions generated from commercial aircraft. EPA reported in 2016 for GHG emissions that commercial aircraft generated a total of 120.1 million metric tons (MMT CO_2 equivalent) CO_2 emissions. In comparison, one launch with LOx/RP-1 produces about 976 MT (FAA, 2015). For one space vehicle launch to generate the same amount of CO_2 emissions, there would have to be more than 120,000 launches per year.

This base-case of the CST activities in the United States characterizes the environmental implications per Launch for an operational tempo of one launch every two weeks. The LCA methodology and NEPA environmental assessments are complementary analysis which may aid in contributing to a better understanding of environmental burdens and impacts throughout the life cycle for the launch of a space vehicle.

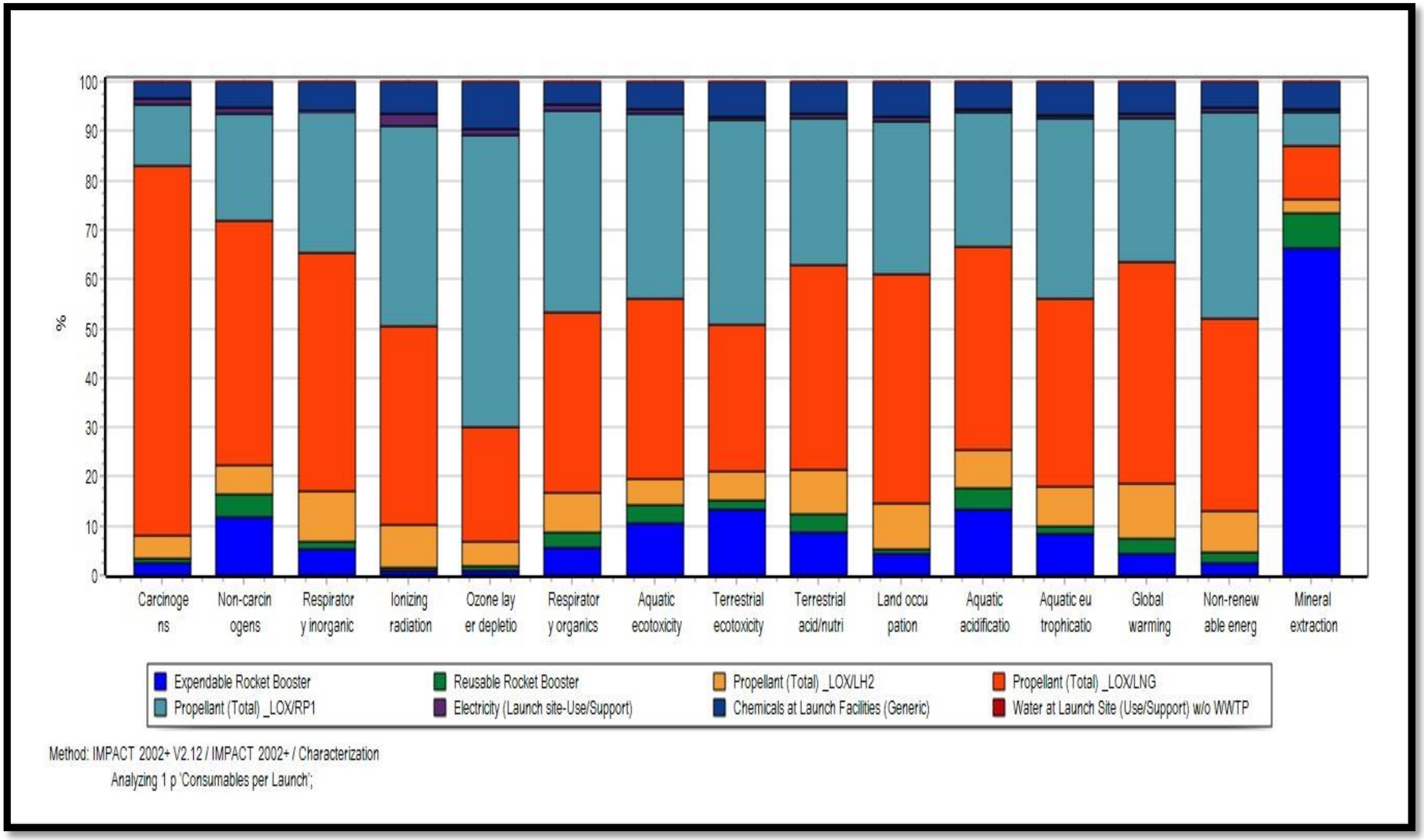


Figure 4-71 All Consumables per Launch Characterization Results

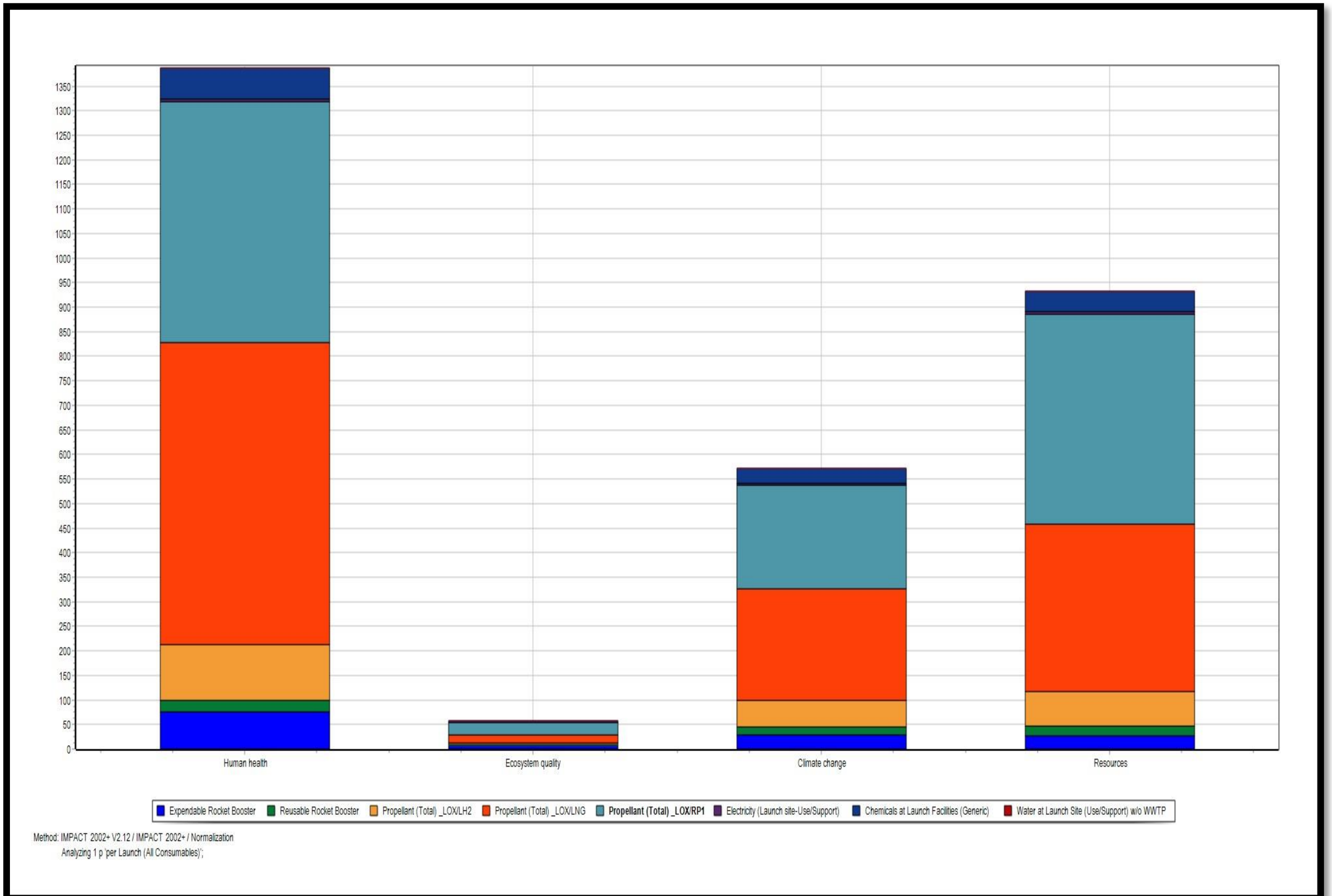


Figure 4–72 All Consumables Per Launch Damage Assessment Normalization

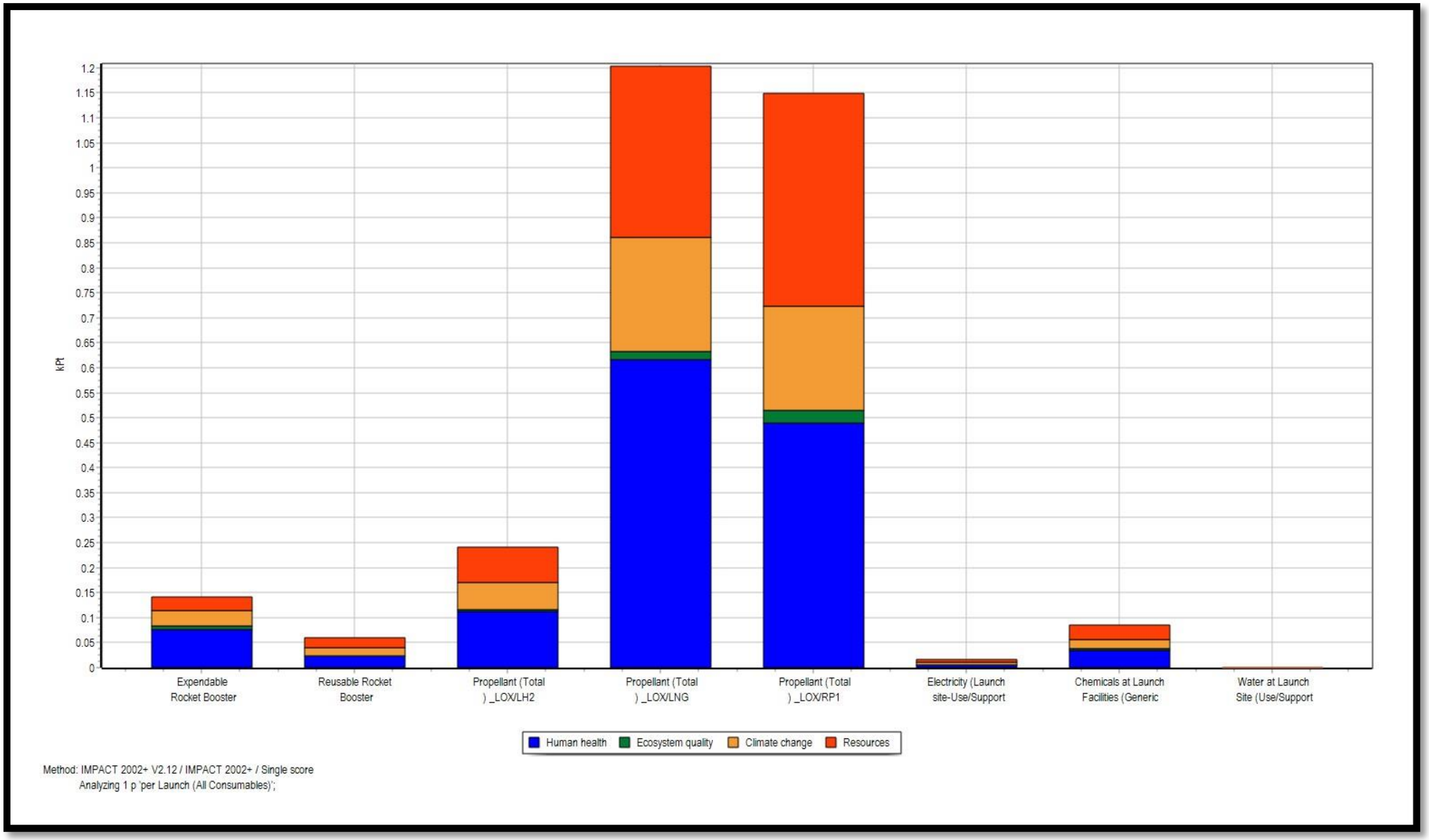


Figure 4-73 All Consumables Per Launch Damage Assessment Single Score

4.2 Results for Objective 2: Range of Environmental Impact Through Sensitivity Analysis and Scenario Analysis

4.2.1 Sensitivity Analysis of Five Sensitivity Parameters

4.2.1.1 Sensitivity Parameter - Reusable Rocket Booster Use Life

The environmental impact of a reusable rocket at 15 use life is slightly higher than the 20 use life with 20 use life as slightly higher than 25 use life of the 1^{st} Stage per launch. Comparing the per Launch with all consumables using the reusable rocket and exchanging the reusable rocket booster use life indicated this parameter has minimal impact on the overall results except in the mineral extraction characterization category, as shown in Figure 4-74. The 25 use life reduces mineral extraction by 2.2% whereas the 15 use life increases mineral extraction use by 3.6% compared to the 20 use life in the base-case. Figure 4-75 shows the damage assessment; as expected, the increased use life decreases the damage impact. So, this sensitivity parameter is ranked as 5 in the ranking of 1-5.

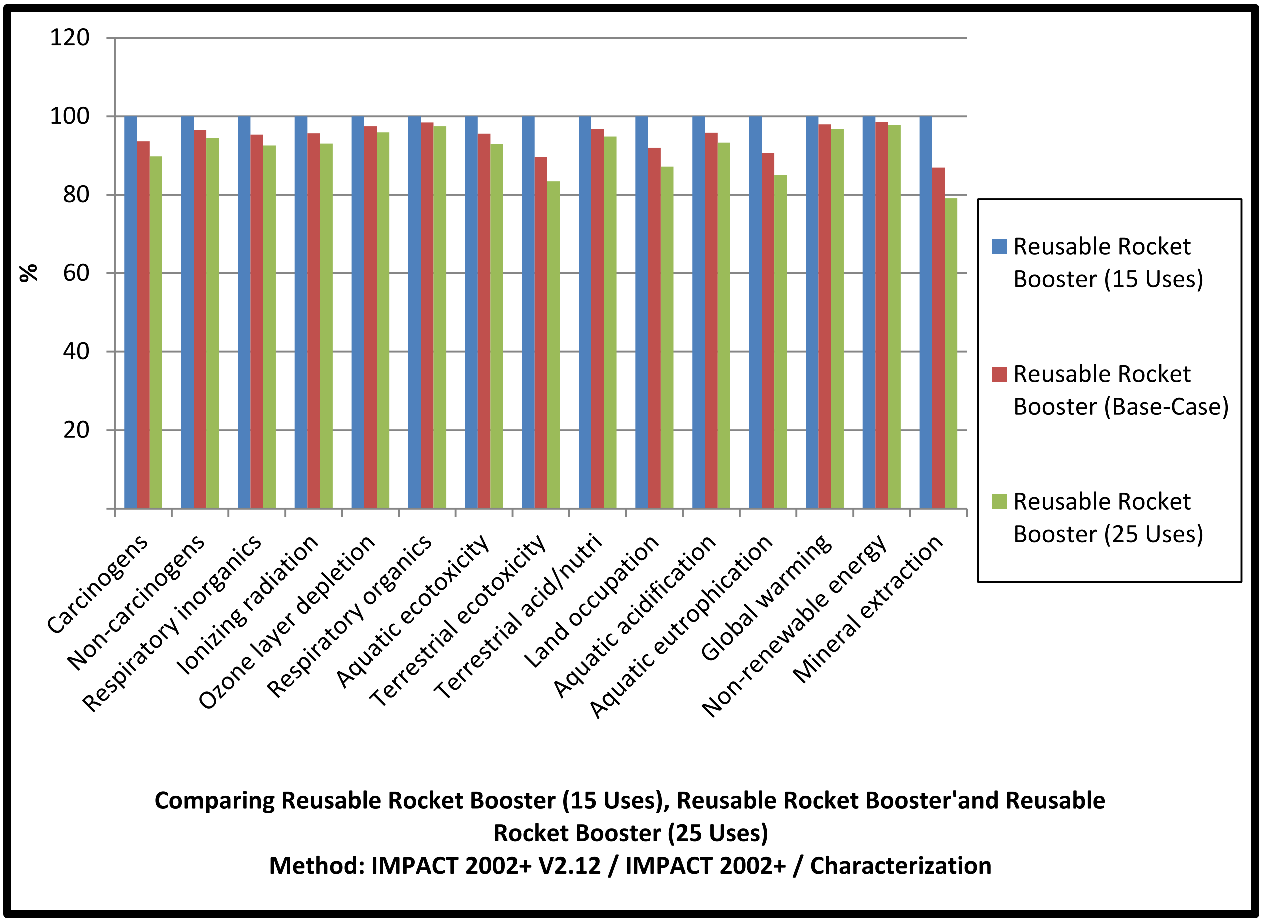


Figure 4-74 Reusable Rocket Booster Use Life Comparison Characterization Results

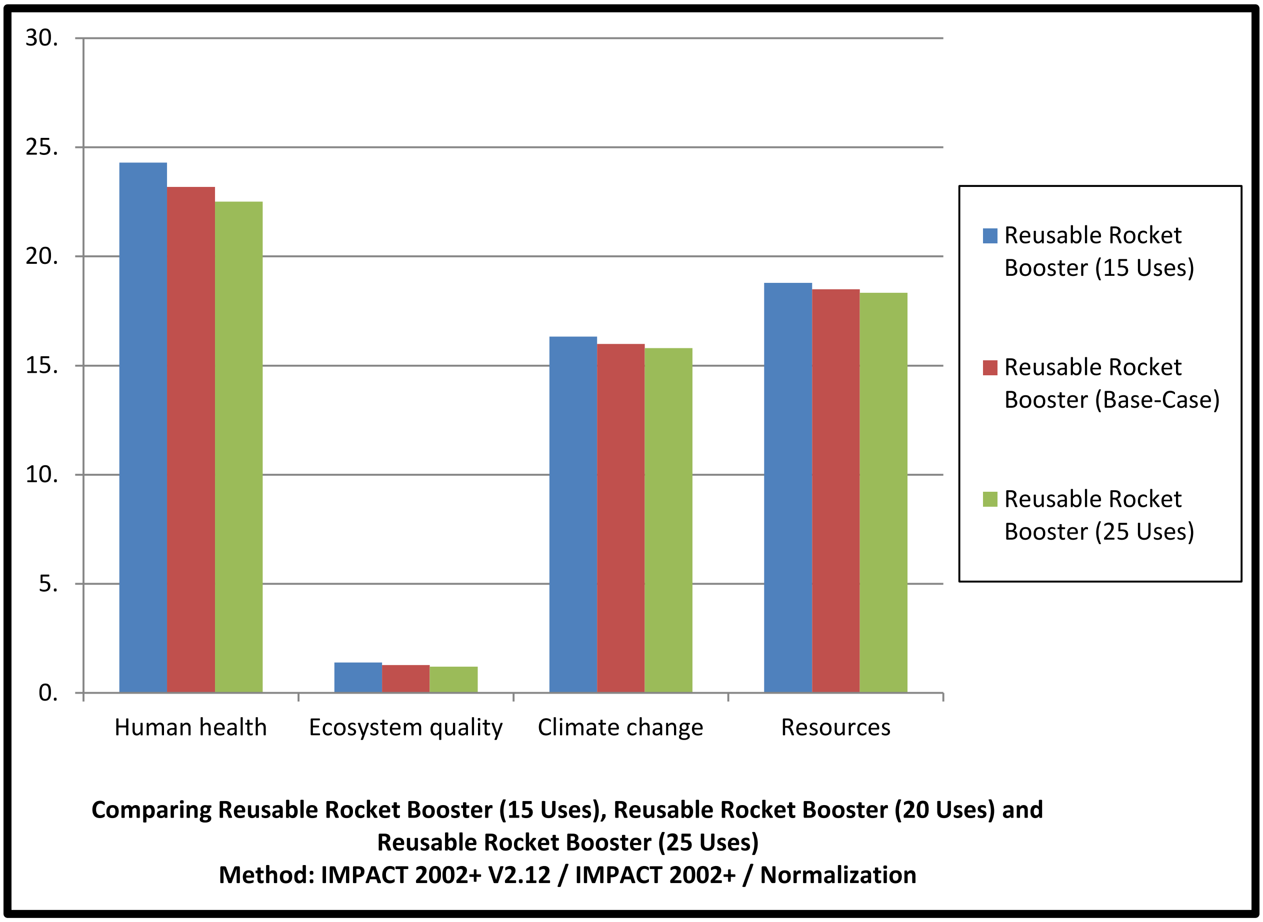


Figure 4-75 Reusable Rocket Booster Use Life Comparison Damage Assessment Results

4.2.1.2 Sensitivity Parameter – Material Composition of Engine Components

From the engine components, combustion chamber, turbopump, nozzle and miscellaneous housing and fittings were assessed for influence on the LCA model. Each component was increased by 5% while the other components were decreased proportionately to accommodate for this increase in mass and hold the mass of the engine constant. Material composition for engine parts were estimated based on textbooks and other images for liquid propulsion engines since exact design information were not available. Percentage weights were estimated based on these textbooks and images. Because of this uncertainty in the composition percentage, this parameter was chosen for sensitivity analysis.

The comparison with the base-case engine with these four component changes are shown in Figure 4-76. With only the 5% increase to the combustion chamber mass using the material in the study, it has a higher impact on the Human Health (10% increase) and Ecosystem Quality (8% increase) damage areas. The nozzle increase would impact Resources very slightly more than the base-case. Overall, the combustion chamber increase in mass would impact the Human Health damage area most if the mass amounts were changed. So, this sensitivity parameter with emphasis on the combustion chamber would be ranked 3 in the ranking of 1-5.

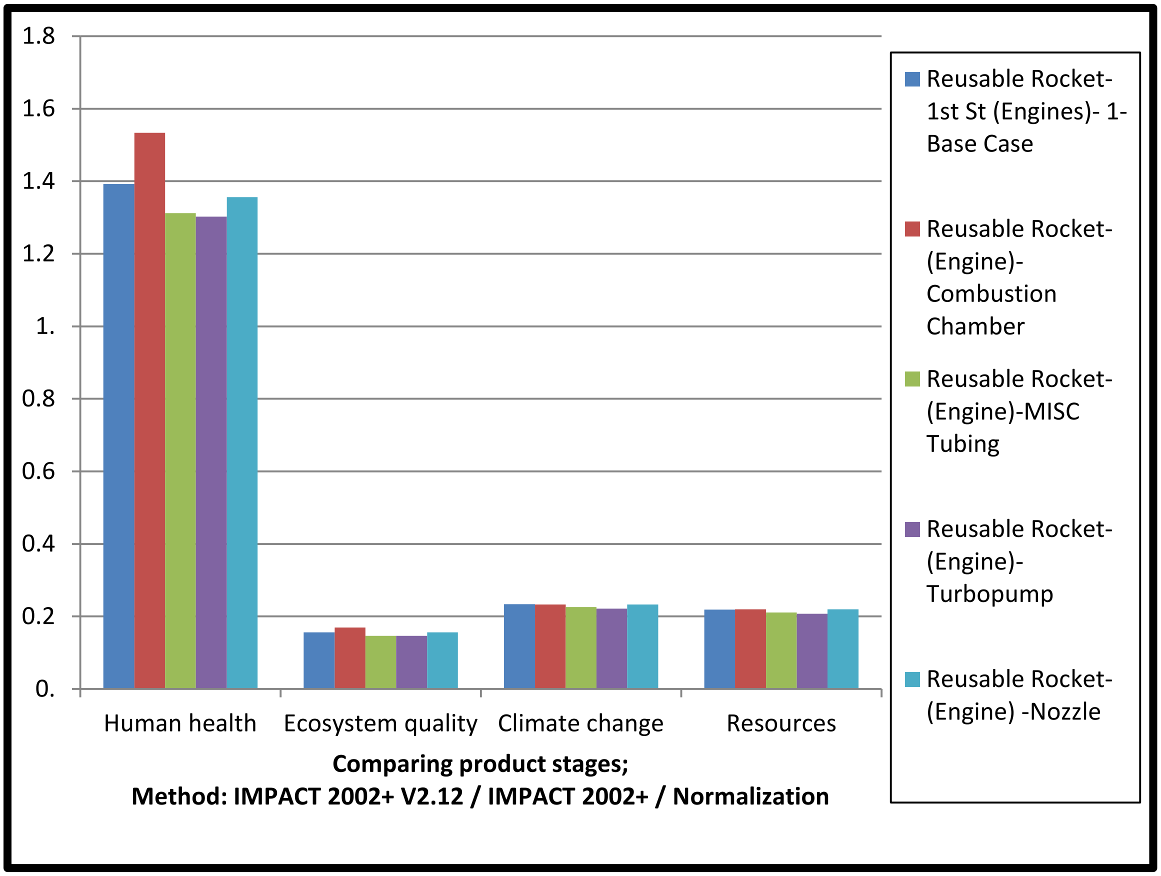


Figure 4-76 Sensitivity – Material Composition of Engine Components

4.2.1.3 Sensitivity Parameter – Electricity from Diesel Hours

The sensitivity parameter of diesel generator hours used during a launch was identified as having most influence in the electricity overall per Launch. The number of diesel hours was varied from 120 hours and 400 hours versus the base-case of 224 hours. The 120 hours was selected as decrease of approximately 50% usage and applying a green technology energy source. The 400 diesel hours were chosen if more reliance or need for the generators were increased to provide power than the base-case. This scenario might use additional generators for the same amount of time. As expected, the more use of diesel generator hours then the more impact to all four damage areas. The characterization categories, shown in Figure 4-77, showed as expected with the increased hours of the diesel generators then there will be increased impact to these categories and most seen in the terrestrial acidification/nutrification. The carcinogens impact was the least affected by the increased hours of use.

Figure 4-78 revealed the damage area most affected was the Resources (44% increase) then Climate Change (58%). The 120 hours, as expected was less than the base-case in all areas. However, the decrease in the Resources (26%) and Climate Change (33%) was substantially lower than the base-case. This sensitivity parameter would influence the ELCA model. So, the ranking for this sensitivity parameter is 2 in a 1-5 scale.

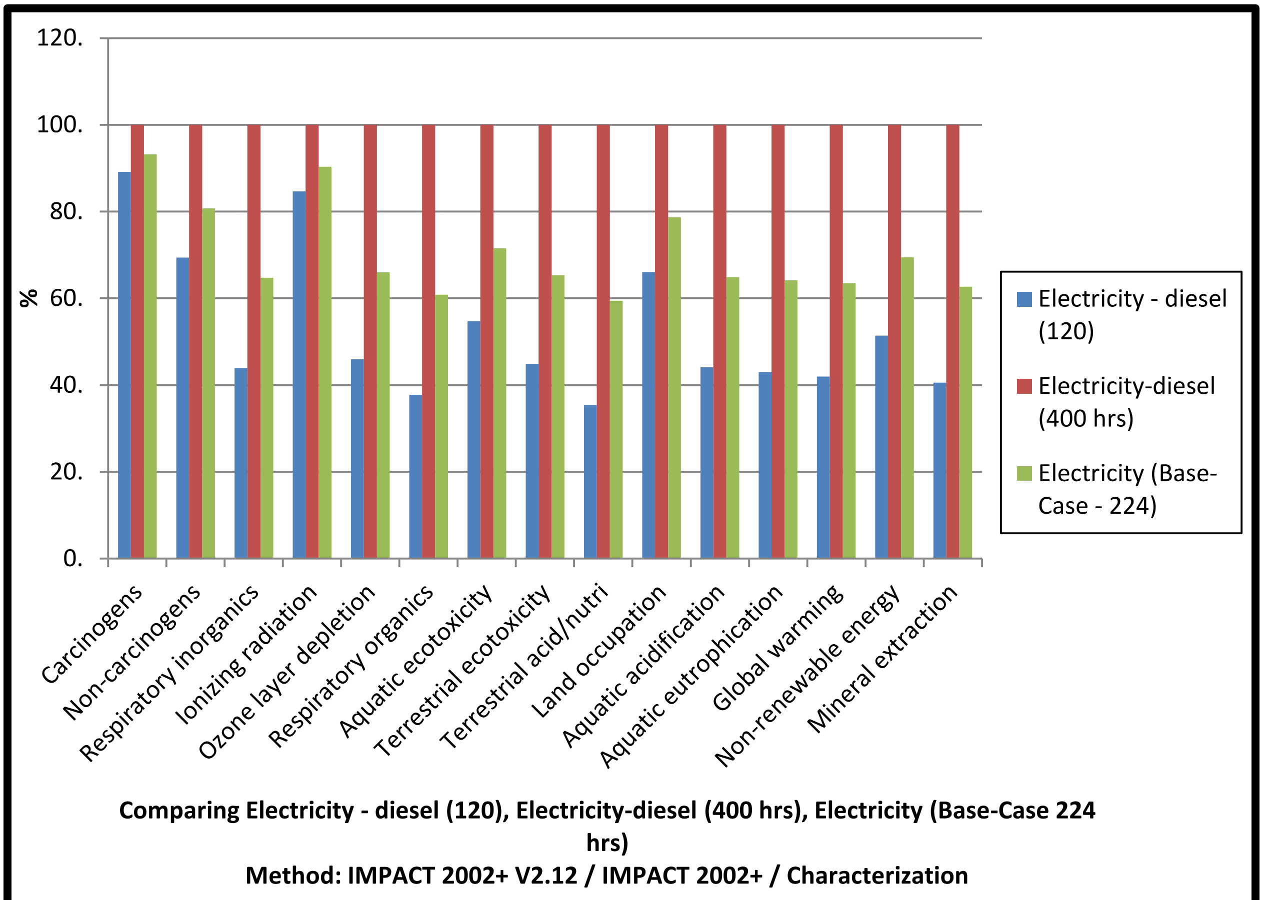


Figure 4-77 Electricity Diesel Hours Sensitivity Comparison Characterization Results

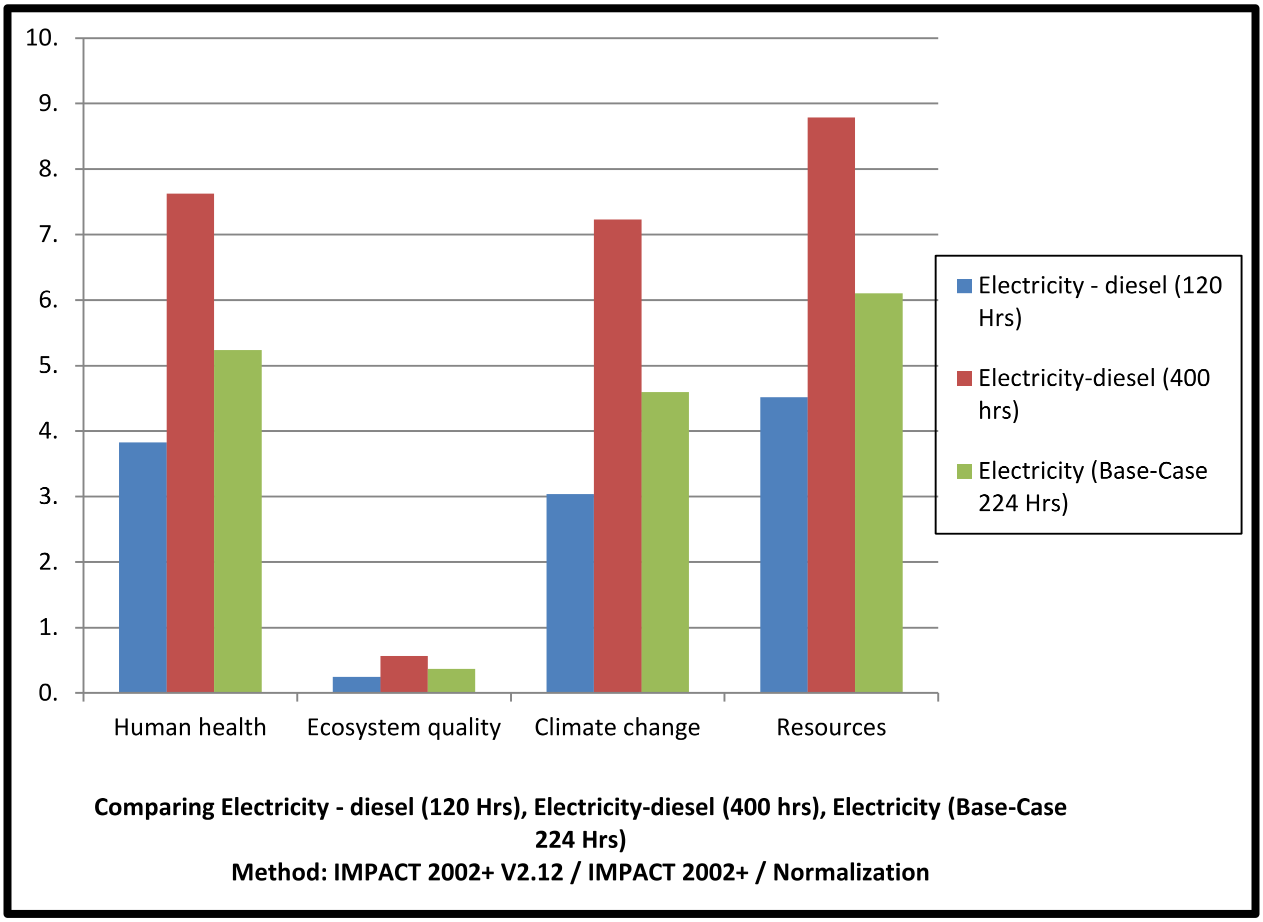


Figure 4-78 Electricity Diesel Hours Sensitivity Comparison Damage Assessment Normalization Results

4.2.1.4 Sensitivity Parameter – Test Firings Propellant Quantities Used Per Launch

Test firings have been found to be either one or two prior to a launch currently. However the exact propellant amount was not given with the exception of stating that enough propellant was used to run the test for approximately 200 seconds. The base-case assumes one test firing uses the same amount of propellant as the 1st Stage during a launch. SimaPro product stages were built for the 50% and 75% of the base-case amount of each of the three propellants for one test firing. Figure 4-79 shows the greatest impacts within each category occurred from the base-case test firings. As expected, shown in Figure 4-80, the impact were proportional to the amount of propellant used in the test firings. Thus, these quantities generated less impact to the damage areas than the base-case. If the propellant amount used for the test firings is less than the base-case or greater than the base-case, then this sensitivity parameter would have greater influence on the ELCA model. The sensitivity to this parameter indicated that streamlined engine test procedures might be a good candidate for eco-design. The ranking for this sensitivity parameter is 1 on a 1-5 scale.

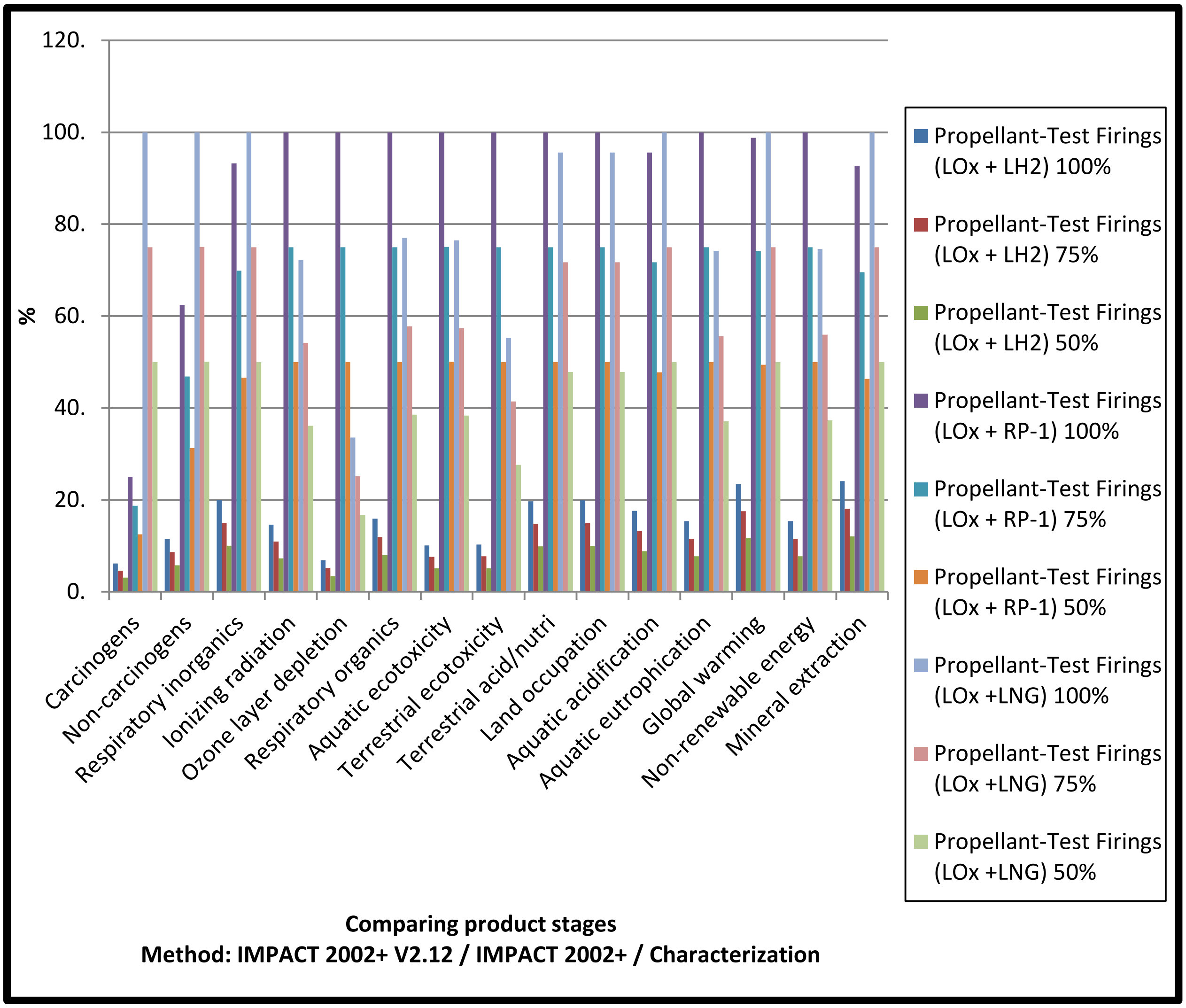


Figure 4-79 Test Firings Quantity Sensitivity Comparison Characterization Results

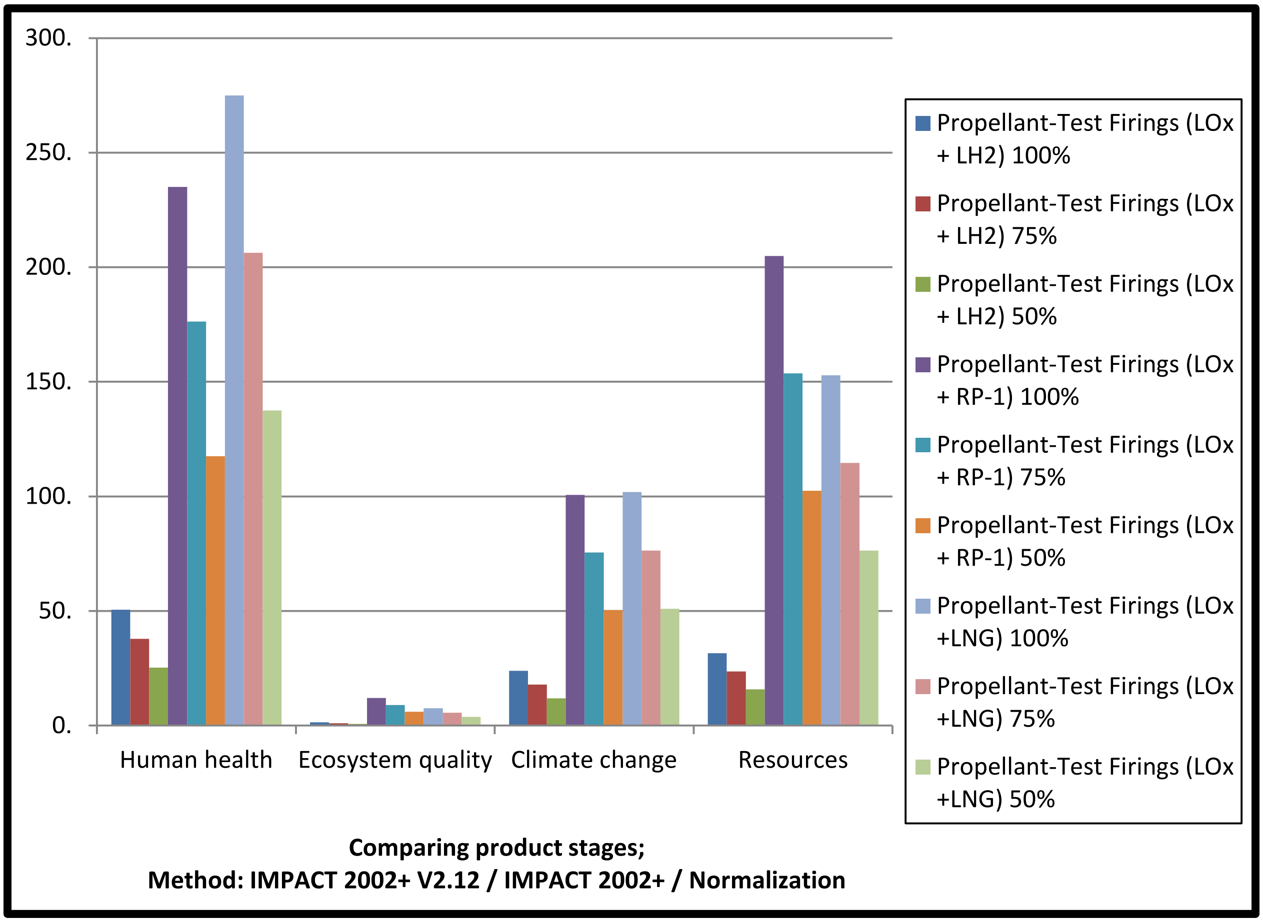


Figure 4-80 Test Firings Quantity Change Sensitivity Comparison Damage Assessment Normalization Results

4.2.1.5 Sensitivity Parameter – Chemical Quantities Used Per Launch

The chemicals were evaluated OAT at half of their base-case amounts to determine the sensitivity of this consumable labeled Chemicals in the ELCA. These chemicals were chosen as a sensitivity parameter because several chemicals showed higher impacts to the characterization and damage categories. Varying these chemicals' quantities was seen as a potential to inform future eco-design and environmental planning.

Figure 4-81 shows the hydrazine impacts land occupation, mineral extraction, carcinogen and non-carcinogen the most. Diesel impacts ozone layer depletion, respiratory organics and the aquatic and terrestrial toxicity the most. Figure 4-82 shows that hydrazine causes the greatest reduction in all damage areas. In Resources, diesel reduced the impact when reduced by half of its base-case amount. So, the analysis on the sensitivity of the chemicals evaluated OAT revealed that hydrazine and diesel impacted all four areas the most. Based on these results and the base-case, diesel was evaluated for a green technology alternative shown in Section 4.3. However, they did not have as great an influence on the ELCA model. So, the ranking of this sensitivity parameter is 4 on a 1-5 scale.

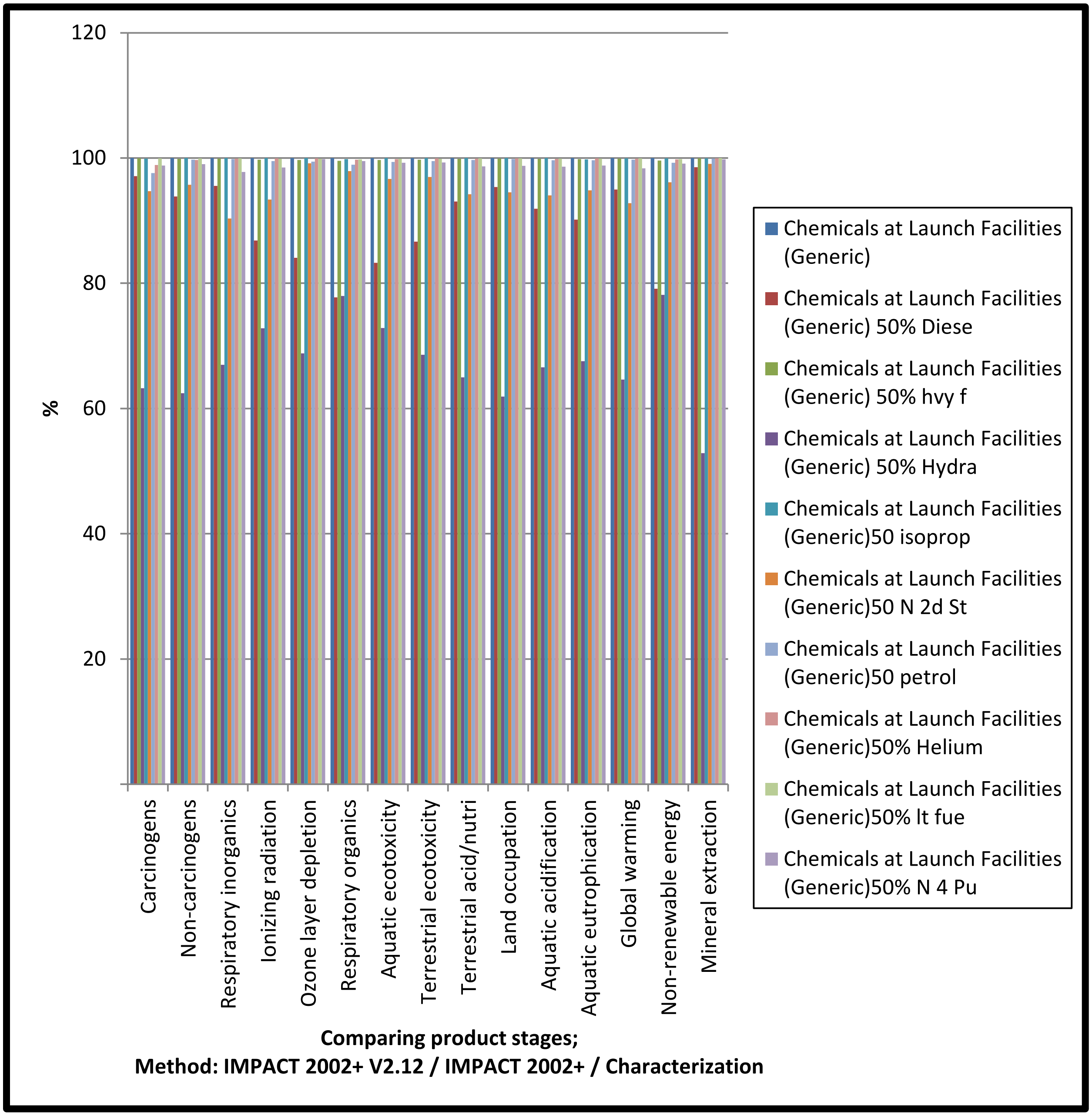


Figure 4-81 Chemical Quantities Change Sensitivity Comparison Characterization Results

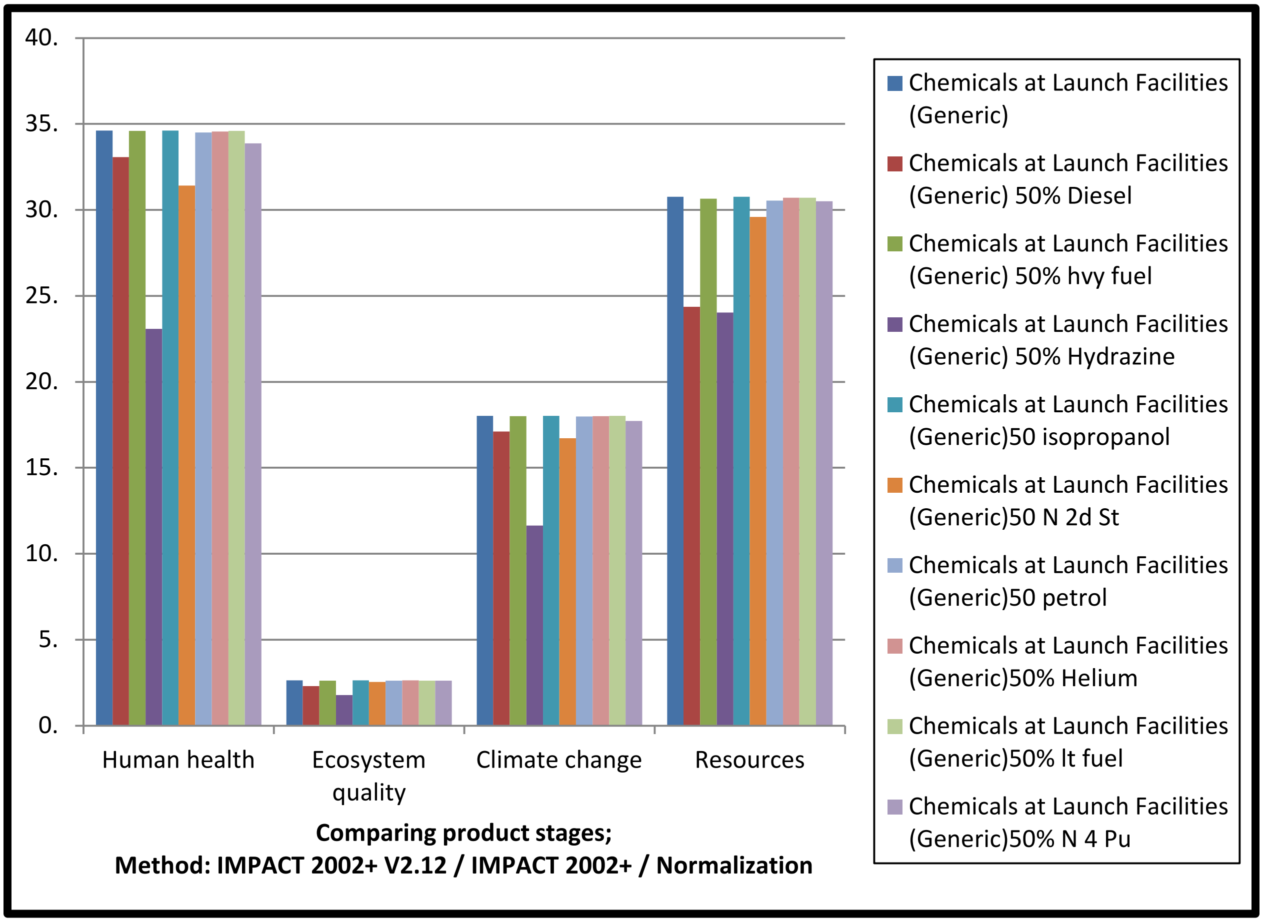


Figure 4-82 Chemical Quantities Change Sensitivity Comparison Damage Assessment Normalization Results

The overall ranking is shown in Table 4-30. These rankings from 1-5 identify the sensitivity parameter having the most influence on the ELCA model for CST activities in the United States using the SimaPro software. With more accurate data and additional information about each of these consumables, these outputs can have less variability within the ELCA model.

Table 4-30 Sensitivity Parameter Ranking

Sensitivity Parameter	Ranking (1-5) 1=Highest
Test Firings Propellant Quantities	1
Diesel Hours at the Launch Facility	2
Material Composition of Engine Components	3
Chemicals at Launch Facility	4
Reusable Rocket Booster Life Use	5

4.2.2 Frequency of Launches Over the Next 10 Years

For the examination of frequency of launches, the base-case was compared with two other launch campaigns. The base-case of one launch per two weeks (base-case), 2.5 launches per two-weeks and 4 launches per two-weeks were used to characterize what this increased frequency might show in the damage assessment. For the Human Health area, 2.5 launches increased the damage impact by 150% and 4 launches increased the damage impact by 300% as compared with the base-case. The other damage categories increased the same for each launch campaign frequency. These results are to be expected since in the LCA methodology and the use of SimaPro, the environmental impacts increase linearly with the number of launches. .

4.2.3 Cumulative Effects from Frequent Launches

The frequency of the CST launch cumulative effects cannot be fully characterized by this LCA study since other influencing factors such as atmospheric conditions, location of launch, etc., are necessary to determine these cumulative effects. The LCA methodology does not take into account the persistence of effects. However, it is reasonable to assume that increased launch frequency would then increase the need for raw materials acquisition and other manufacturing processing with increased waste streams from Use and Maintenance Phases to End-of-Life impacts. The areas possibly most affected from increased launches might be the propellant production, the expendable launch booster with components, the reusable launch 2nd Stage and Fairing unless they are also reused after each launch, and the chemicals used to enable each launch. The characterization and damage areas will also be affected as discussed in the previous section. With refined data, an analysis of cumulative launches could inform NEPA planners in understanding what frequency of launches that would generate emissions exceeding state and local thresholds.

The additional waste will increase the need for wastewater treatment facility capacity due to the increased personnel and deluge wastewater. Trying to reuse more of the deluge water as launches increase would help reduce the increased wastewater treatment. The solid and hazardous waste disposal will increase as well. The CST launch campaigns will increase the demand for water and electricity as the launch campaign shortens from 14 days to 7-8 days. However, this demand will depend on the tempo of the launch campaign and if shift work is used to maintain the mission tempo. For the electricity, diesel was the greatest contributor to the damage areas so trying to find a better power resource might reduce the environmental burden in future launches especially if more diesel generators are needed to maintain the increased launch tempo. Data on the amount of waste generated per Launch would aid a planner or systems engineer in understanding the environmental implications at the Use and Maintenance Phases per Launch.

4.2.4 Scenario Analysis – Frequency of Launches and Number of 1st Stage Engines

Scenario analysis was used to understand the implications of the number of engines used in the core boosters for launch and the frequency of launches with these engines. The mix of engines per core booster was chosen based on possible engines per booster. The number of engines considered for the three core[43] boosters was 3, 9, and 27. To retain the same performance, the configuration with fewer engines would need higher performing engines. Higher performing engines can be assumed to have a lower mass than the 27-engine configuration with smaller engines. For this scenario, the actual scaling factors between smaller and larger engine masses were not known. The effect was modeled in SimaPro using smaller number of equivalent engines to show the environmental impact trends. The frequency of launch was the base-case of one launch per two weeks, 2.5 launches per two weeks and 4 launches per two weeks.

The quick-look or screening LCA of the sensitivity of the change in number of engines per Launch in the reusable and expendable rocket boosters showed the expendable rocket booster with 27 engines generated the most impact to all of the damage areas (base-case). Characterization results, Figure 4-83, show the expendable booster with 27 engines is the worst case scenario for environmental impacts. Even with only three engines in the expendable rocket booster, the results show this scenario has greater impact than the 27 engines used 20 times in the reusable rocket booster (base-case). Figure 4-84 shows the base-case of the expendable rocket with 27 engines impacts Human health the greatest. The Human health is about five times the amount affected than the other four damage areas by the configuration of the number of engines and the booster type.

---

[43] Core consists of casing, engines and other elements comprising a 1st Stage rocket booster. This study with the generic rocket uses three cores and 27 engines for the 1st Stage.

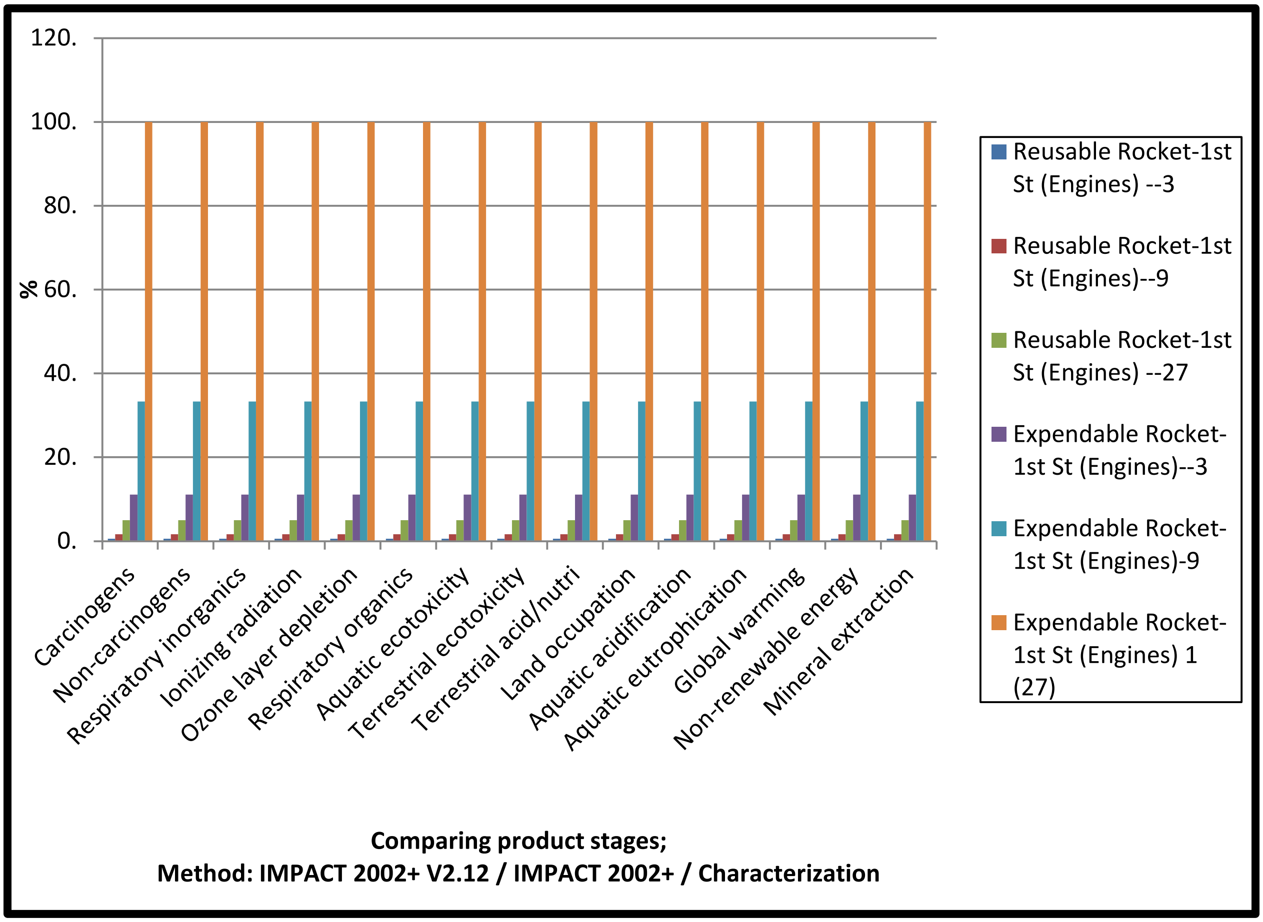


Figure 4-83 Scenario Analysis of Reusable and Expendable Rocket Boosters Comparison Characterization

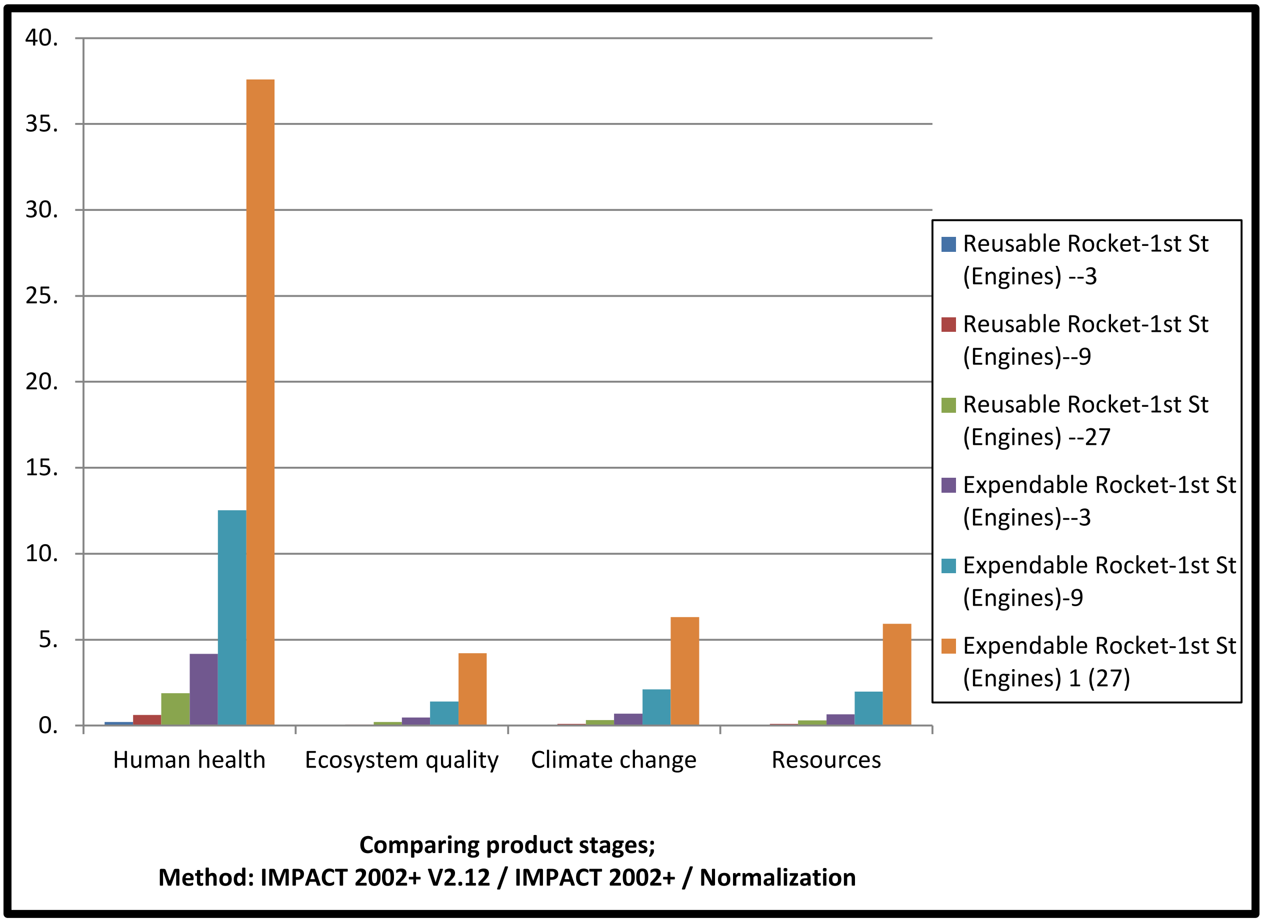


Figure 4-84 Scenario Analysis of Reusable and Expendable Rocket Booster Comparison Damage Assessment Normalization

The worst-case scenario would be launches with 27 engines, expendable rocket booster and 4 launches every two-weeks to include all of the other consumables. All three liquid propellants are included in this analysis as worst-case environmental impacts. Comparing a similar scenario is the use of reusable rocket booster with 27 engines and 4 launches per two weeks. When comparing the LCA results, the reusable rocket was better for all of the damage areas. The reusable rocket scenario yields the most favorable results in the Characterization category having a significant less impact on mineral extraction, and terrestrial and aquatic ecotoxicity. From the damage areas, the advantage of the reusable rocket scenario was most apparent in the Human Health area which was decreased by 4%.

4.2.5 Monte Carlo Analysis of the Data Quality in SimaPro of Per Launch Consumables

A Monte Carlo analysis was generated on the quality of the data used from SimaPro and the database libraries chosen. The uncertainties generated from the Use and Maintenance Phases for the launch campaign were examined in the sensitivity and scenario analysis Sections 4.2.1. Figure 4-85 presents the uncertainty range for the SimaPro data at the 95% confidence interval. The Monte Carlo used 2500 runs to determine the 95% confidence uncertainty. The following characterization categories had the highest uncertainty in the data: ionizing radiation and carcinogens informing the Human Health damage assessment (end-point) area and aquatic eutrophication informing the Ecosystem Quality damage area. Thus in Figure 4-86, Human Health was shown to have higher uncertainty in the data and is most likely influenced by the carcinogens and ionizing radiation uncertainty. The uncertainty in the Ecosystem Quality data is influenced by the aquatic eutrophication uncertainty. Of the SimaPro library databases' data used in this study, 63.7% had a lognormal distribution and 35.3 % undecided (no distribution). Future studies might be to develop U.S. library databases relevant to CST activities for those specific materials and processes that are not available in those current library databases to minimize the uncertainty in the data.

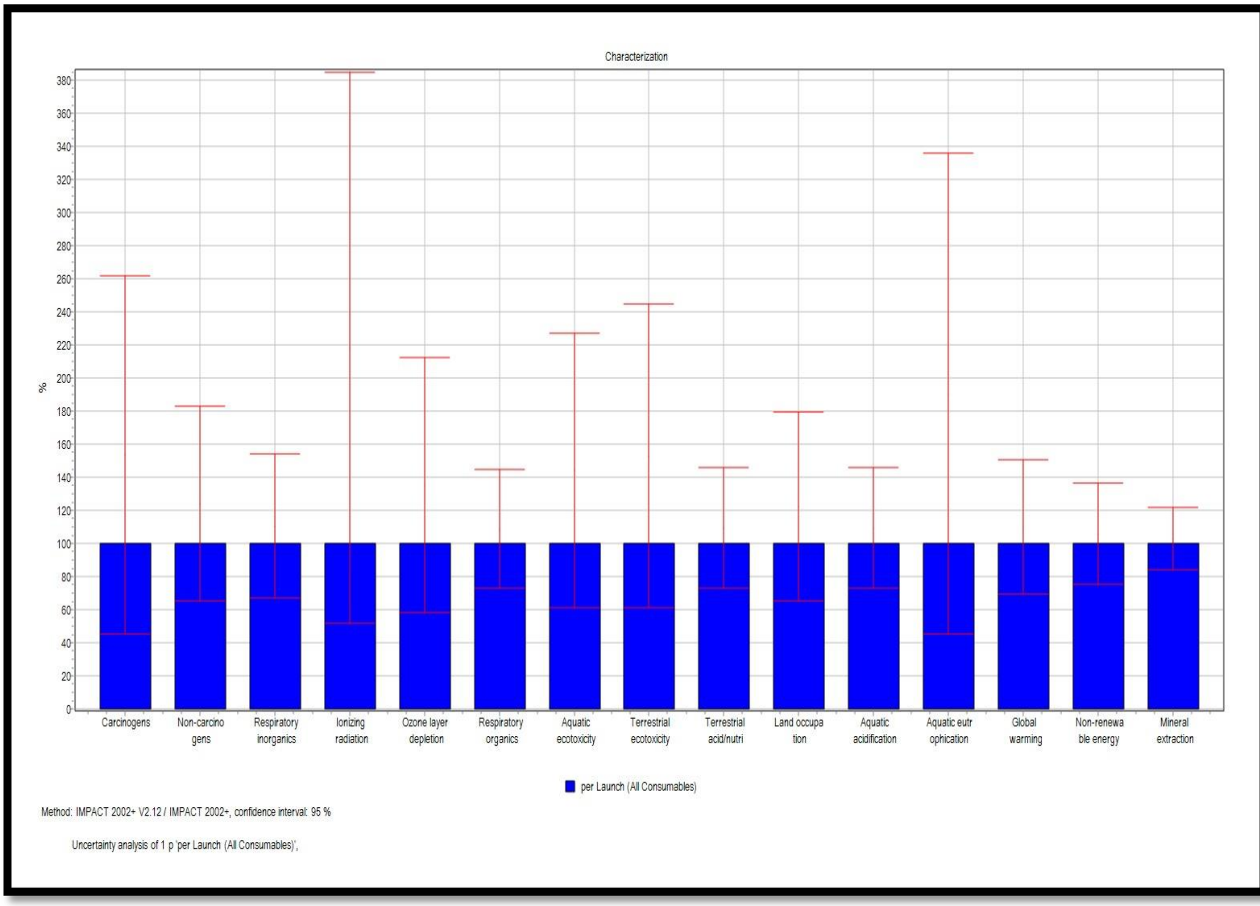


Figure 4- 85 Monte Carlo Analysis on All Consumables Per Launch Characterization Categories (SimaPro Software)

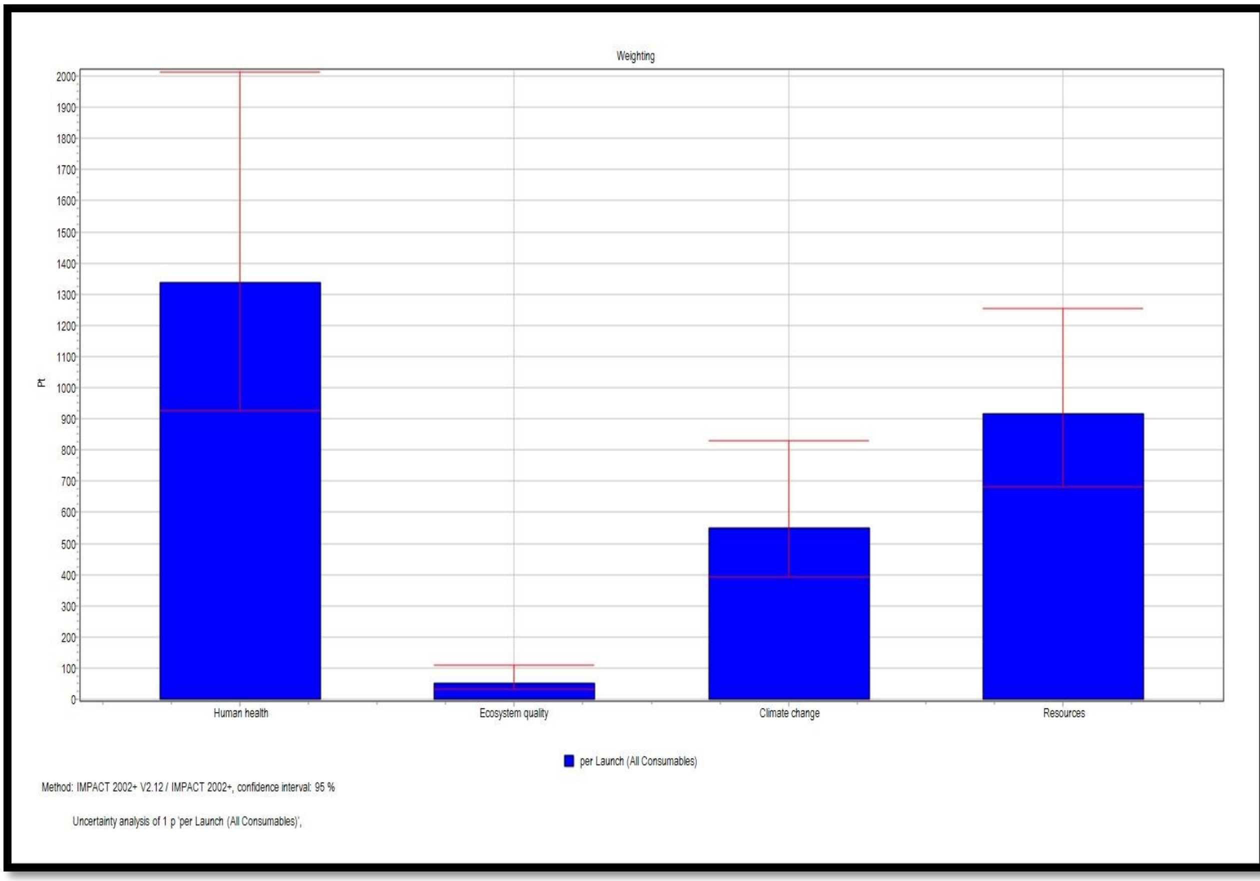


Figure 4-86 Monte Carlo Analysis on All Consumables Per Launch Damage Assessment Weighting (SimaPro Software)

4.2.6 Comparison Between Base-Case and TRACI Impact Method

The results for the base-case six consumables per launch applying the EPA TRACI Method, 2.1 V1.03/US 2008 revealed the following impacts in the characterization categories, Figure 4-87.

The results were carcinogens and ecotoxicity were the most environmentally impacted from the consumables per launch. Within these categories, carcinogens were most influenced by propellant (LOx/LNG); for ecotoxicity, chemicals at the launch facilities were the biggest influencer. Ozone depletion, global warming, smog and fossil fuel depletion was least impacted by the consumables per launch. For the TRACI damage assessment results shown in Figure 4-88, ecotoxicity is heavily influenced by the chemicals and the carcinogens are mostly influenced by LOx/LNG.

Comparing the IMPACT2002+ method , Figures 4-71 and 4-72, with the TRACI method, the results seemed to be similar in that the LOx/LNG contributed the most to all of the characterization and normalization areas. Different categories and damage areas make it more challenging to compare directly. However, overall it would appear that these methods show similar results for major contributors in the CST activities in the United States.

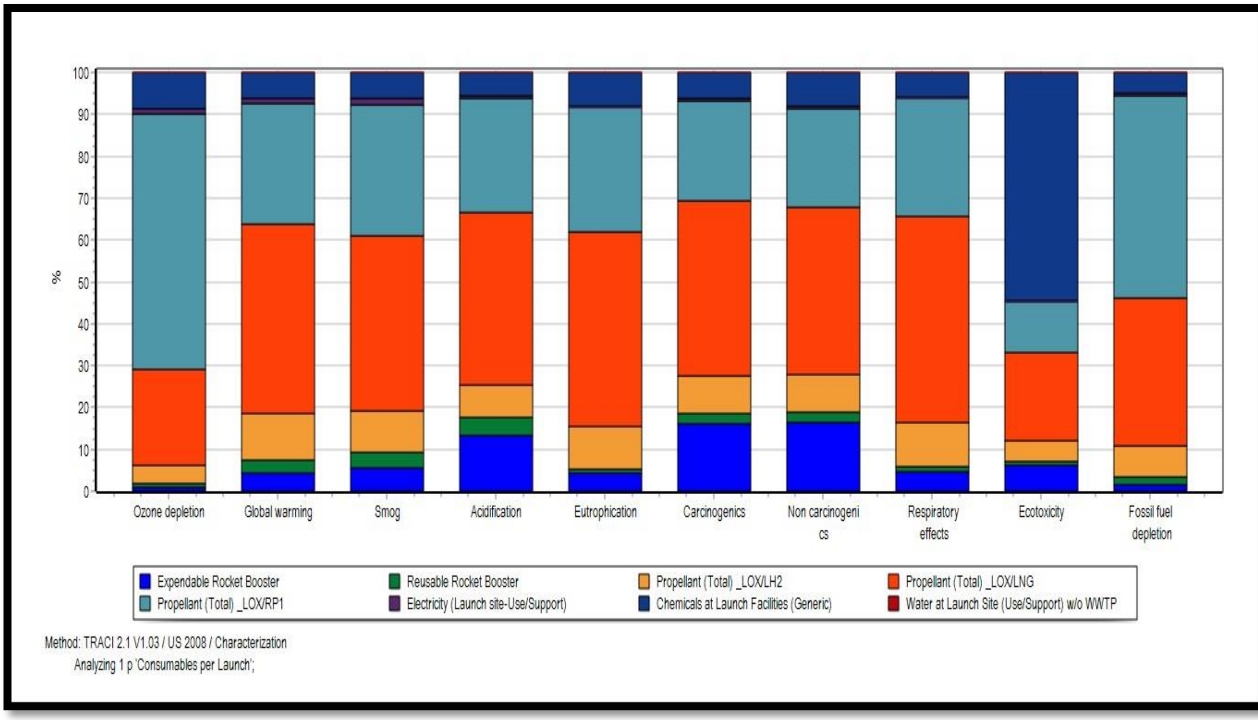


Figure 4-87 TRACI Impact Method Characterization Results for Base-Case All Consumables

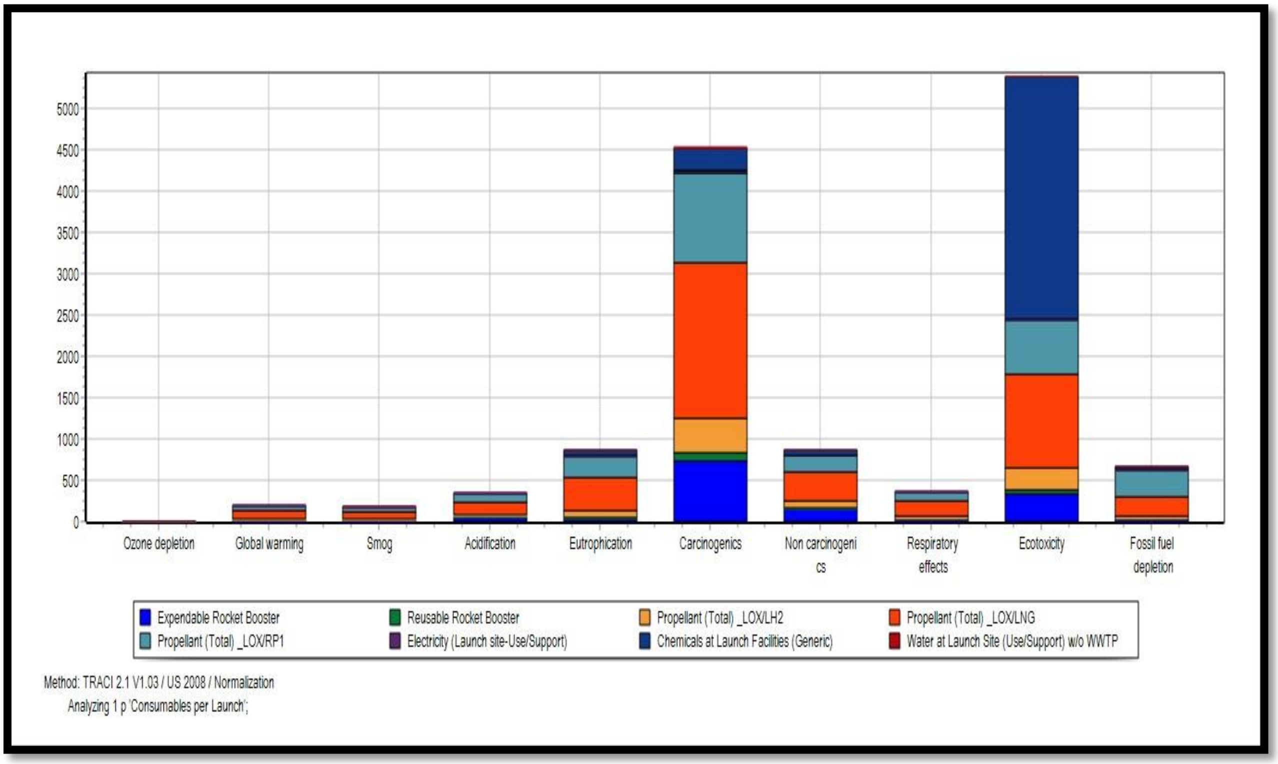


Figure 4-88 TRACI Impact Method Damage Assessment Results for Base-Case All Consumables

4.2.7 Comparison Between Base-Case and ReCiPe Impact Method

The results for the ReCiPe impact method revealed the Resources in the damage assessment was the most environmentally impacted from all consumables used per launch. Of the damage assessment, the three liquid propellants generated the highest environmental burdens per launch. The results are shown in the next figures.

When compared with the base-case all consumables shown in Figure 4-71, the propellant LOX/LNG did impact these characterization categories the most as shown in Figure 4-89. The ReCiPe damage assessment results are shown in Figure 4-90 and 4-91. The damage assessments reveal that LOx/LNG and LOx/ RP-1 heavily influence the three damage areas. The results show these propellants contributed most to the environmental impacts. These results are similar to the base-case damage assessment, Figure 4-72. However, this comparison between impact methods does not directly relate one for one but shows the various emphasis of the method developer or group of developers.

Overall, the method chosen for the LCA will provide somewhat different perspective in the characterization or normalization but will arrive at similar results. These three impact method comparisons reveal that the goal and scope should inform the choice of impact method.

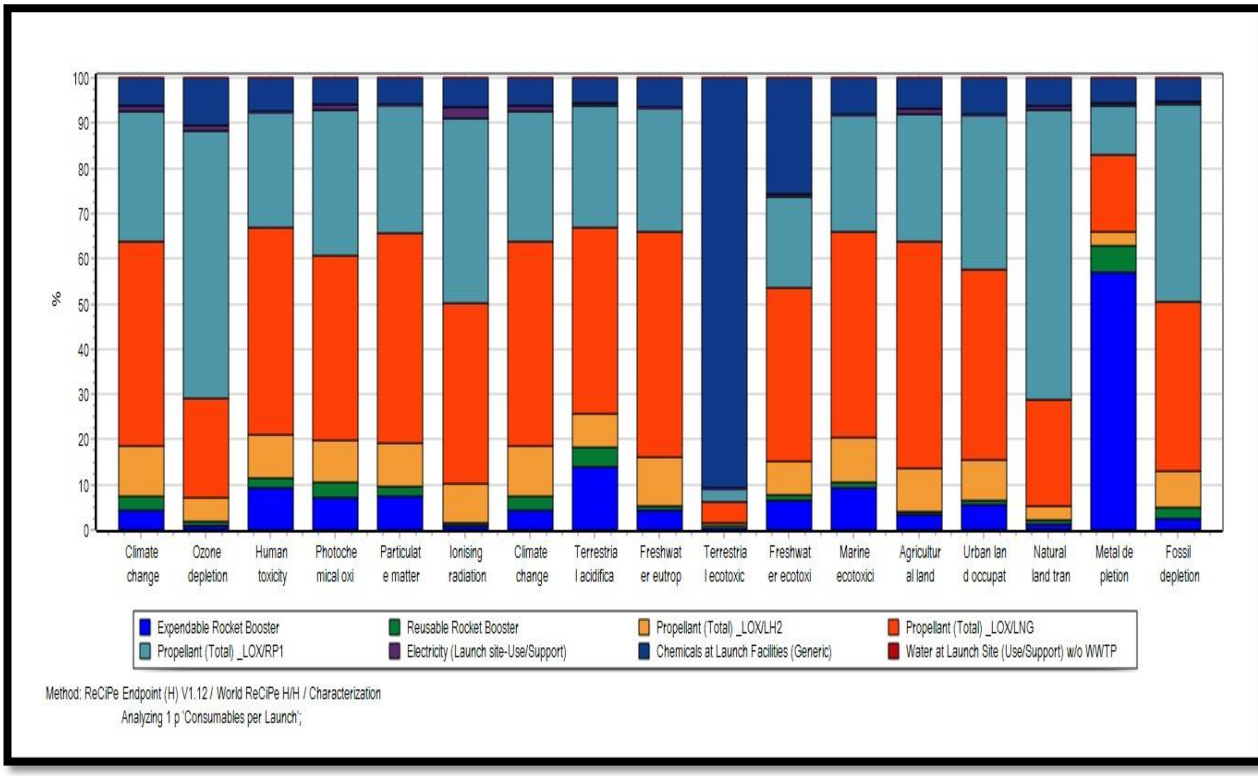


Figure 4-89 ReCiPe World V1.2 Characterization Results for Base-Case All Consumables

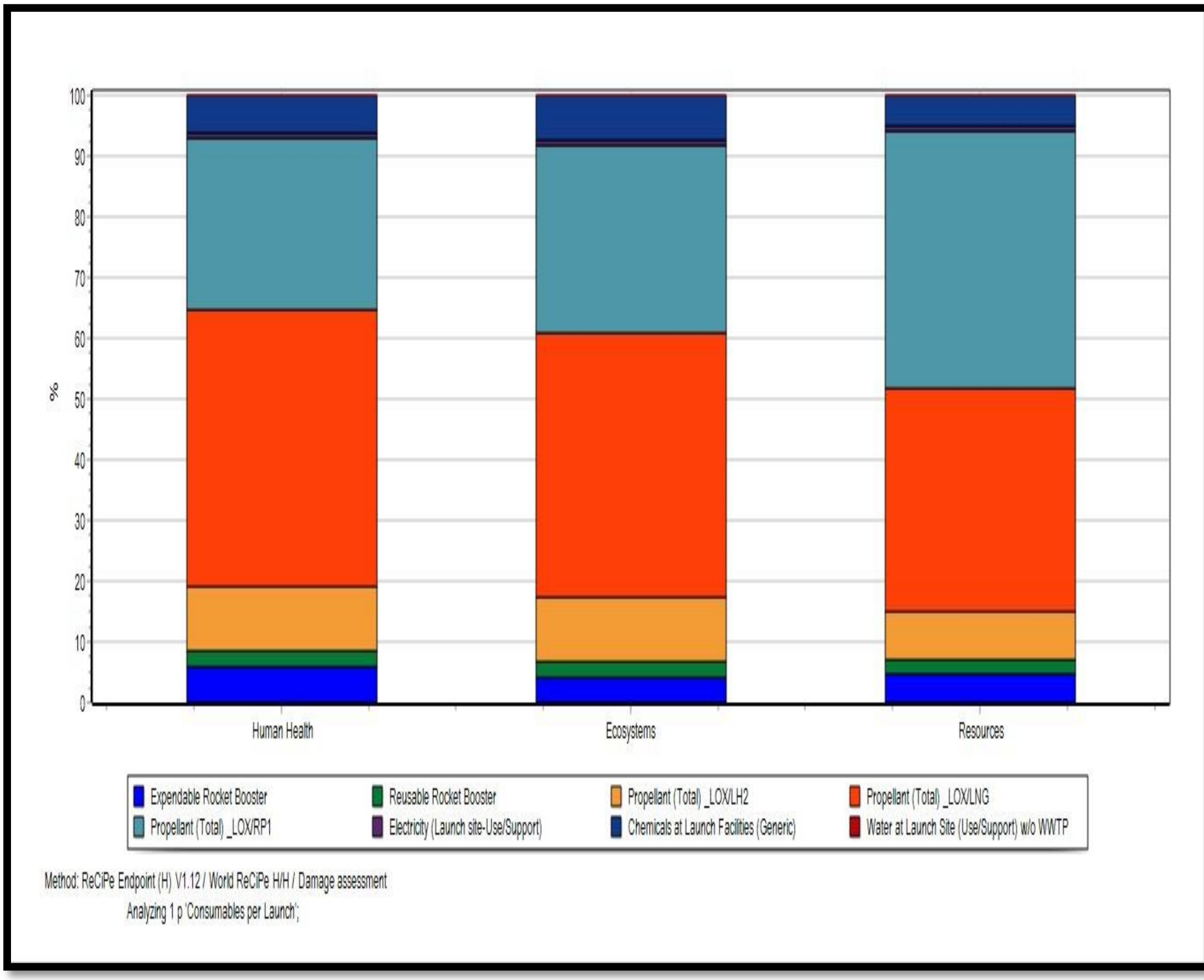


Figure 4-90 ReCiPe World V1.2 Impact Method Damage Assessment Results for Base-Case All Consumables

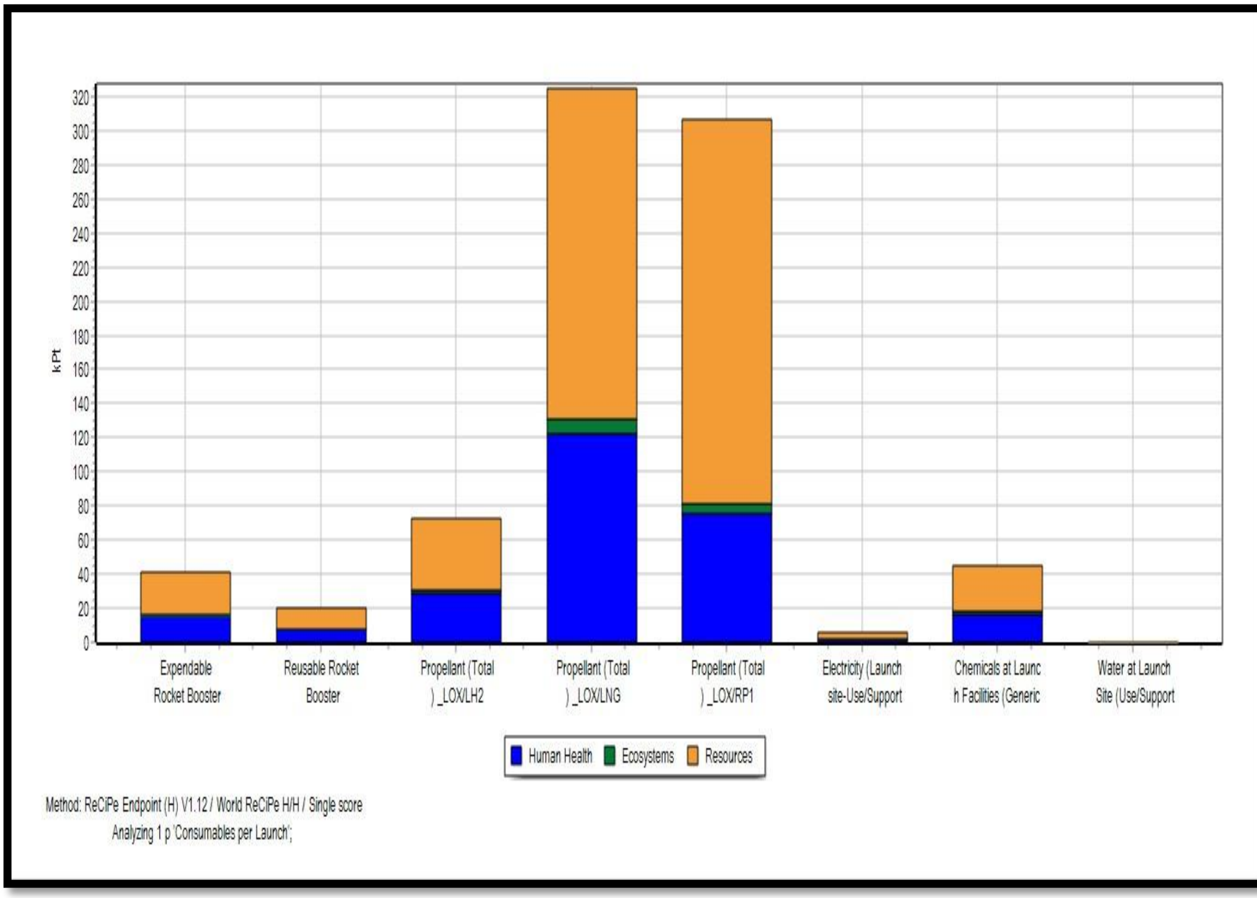


Figure 4-91 ReCiPe World V1.2 Impact Method Single Score Results for Base-Case All Consumables

4.3 Results for Objective 3: Green Technology Recommendations for Launch Campaign

4.3.1 Green Technology Scenarios

4.3.1.1 Green Technology Recommendation: Replace Diesel with More Electricity or Solar Power

Scenario 1: No Diesel. The screening LCA results for the use of only electricity showed Human Health was reduced by 55%; Resources reduced by 53%; Climate Change reduced by 80% and Ecosystem Quality was reduced by 67%. A distinct reduction in Climate Change damage impacts is observed when removing the use of diesel generators even when adding more electricity per day.

Scenario 2: No Diesel with Solar Power Substitution: The screening LCA results indicated that the solar energy added slightly more than Scenario 1 without diesel and only electricity to both the respiratory organics and mineral extraction. Scenario 2 showed slight reductions from Scenario 1 in all damage areas. The reductions from Scenario 1 were: Human Health reduced by 7%, Climate Change reduced by 6%, Resources reduced by 7%, and Ecosystem Quality reduced by 4%. The LCA results revealed this scenario would be the best environmental decision when compared with the base-case and Scenario 1. Figure 4-92 shows the damage areas comparison of these scenarios with the base-case.

Overall, the use of solar power instead of a diesel generator to augment the electricity might be an advantage to reducing the environmental impacts per launch while also adding additional resources to the launch facility and local community with the solar power.

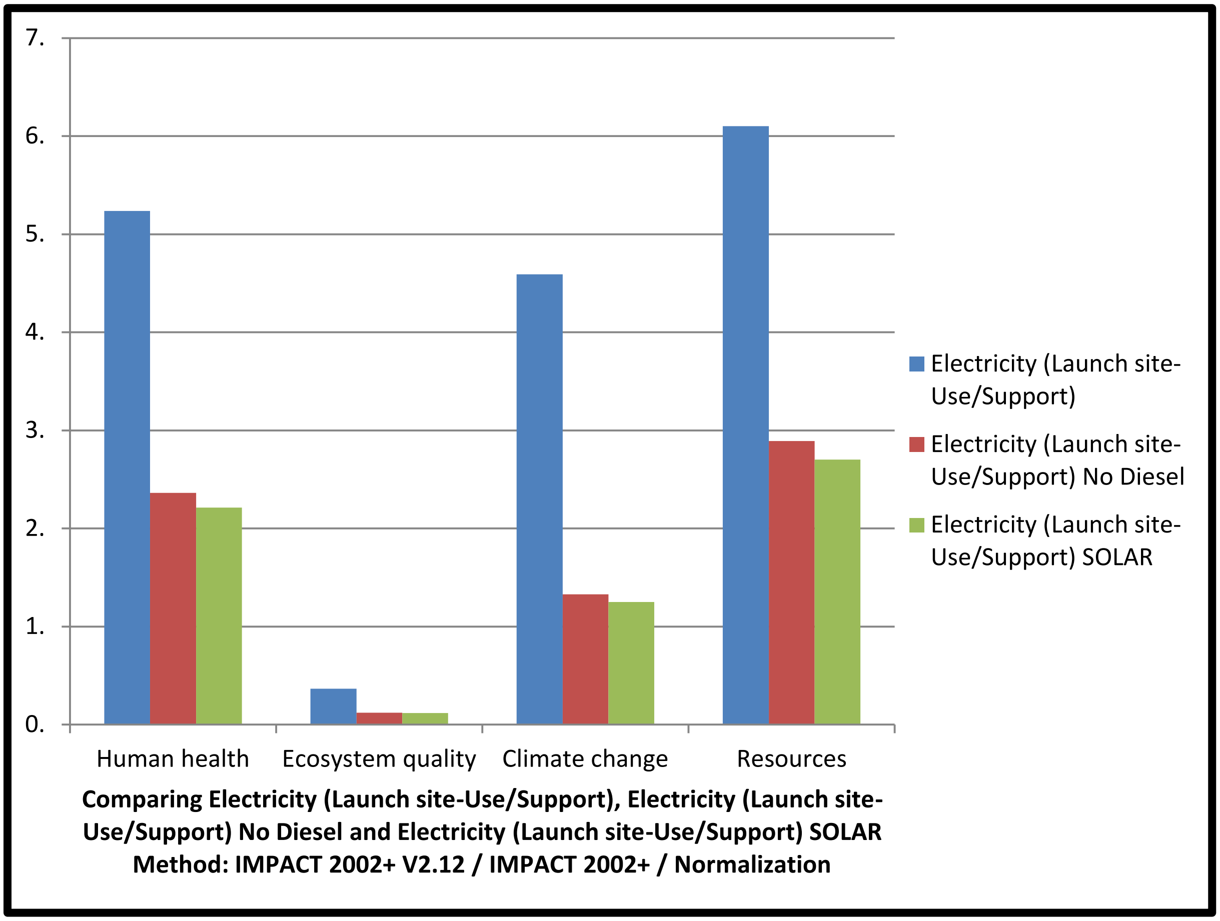


Figure 4-92 Green Technology Change with Diesel Comparison Damage Assessment Normalization

4.3.1.2 Process Change Recommendation: Use Armstrong Process Titanium Powder for Titanium instead of Kroll Process

The titanium grid fins on the generic reusable rocket booster in this ELCA was replaced with Armstrong process for titanium. The Damage Assessment results, Figure 4-93, showed the Armstrong process achieved the following reductions: Human Health by 55%, Climate Change by 43%, Resources by 43%, and Ecosystem Quality by 21%. Another comparison found was the electricity needed for the Armstrong titanium process was 19% of the Kroll process (DOE, 2015). Other specifics about the Armstrong process are not known other than what was found in the literature cited in this study. The Kroll process requires a single piece of titanium, which implies there will be excess titanium after casting, so this may require additional processing to produce a finished part. Future studies might have the full available process data for Armstrong titanium process to compare more robustly with the Kroll and other titanium processes. This process would appear to have less environmental impacts and optimize the limited titanium resources.

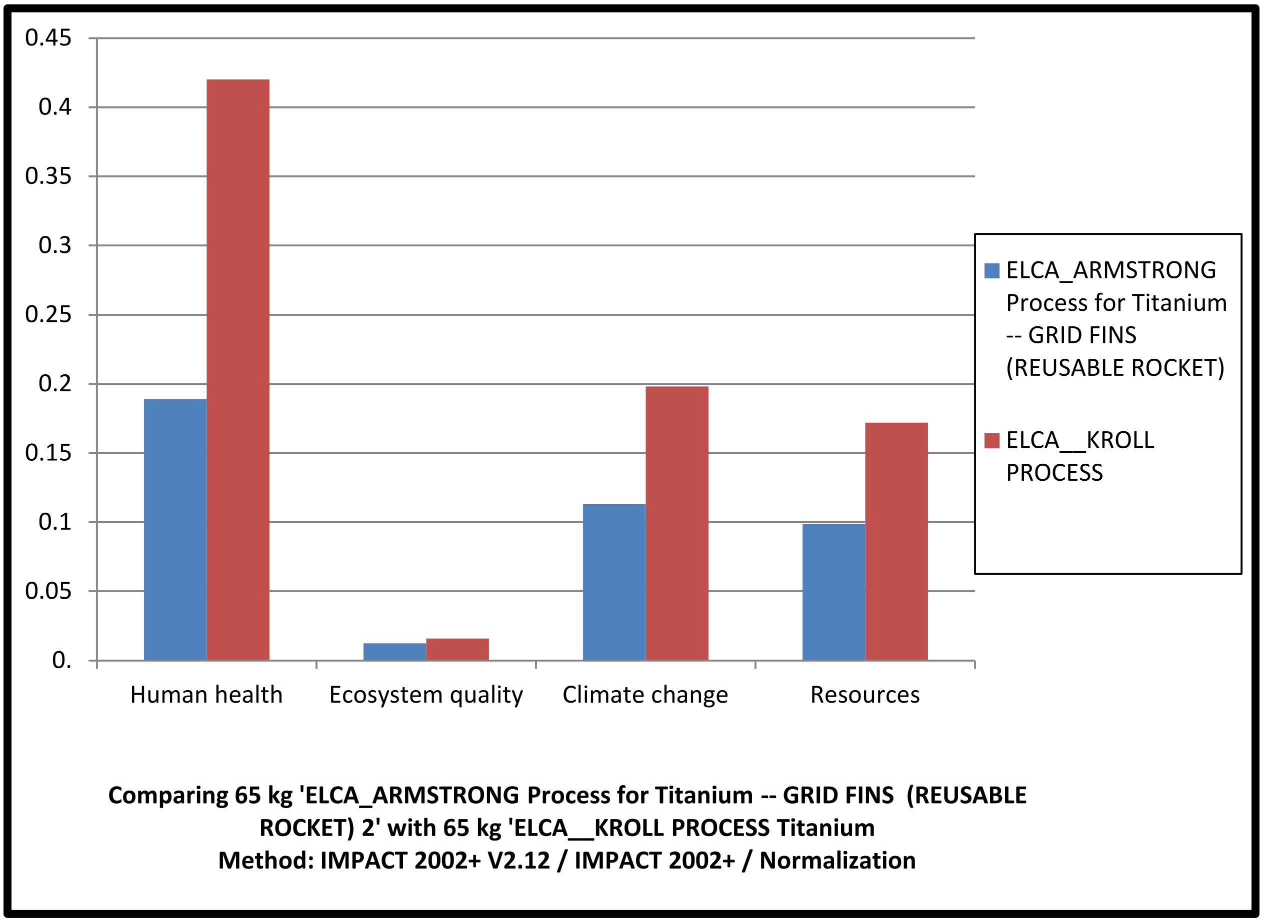


Figure 4-93 Green Technology Armstrong Process Titanium Substitution Damage Assessment Normalization

4.3.1.3 Material Change Recommendation: Additive Manufacturing for Parts

Additive manufacturing or (3-D printing) is being used to varying extents and is viewed as being a key transformative technology. The amount of time from concept to actual product is as little as 60 days whereas the same component might take years to manufacture and test. NASA is investigating this additive manufacturing technology for use on the Space Launch System. Currently, SpaceX is using 3-D printing for engine chamber and a main oxidizer valve (MOV) reported in 2014. Also, Aerojet Rocketdyne has used the Selective Laser Melting (SLM) process to make engines like AR1 (Peels, 2017). These processes are proprietary and companies are even attempting to develop a space vehicle from 3-D. This study was not able to do a screening LCA on this technology use for engine components or other parts due to the limited data available on the process. A future study is recommended comparing the current process and the 3-D process for manufacturing of space vehicles or specific parts or components.

4.3.1.4 Propellant Change from LOx/RP-1 to LOx/CH_4 (Methane)

Using the methodology described in Section 3.3.4, a comparison with RP-1 propellant showed the propellant with methane was only less than RP-1 in the ionizing radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, aquatic eutrophication, non-renewable energy. For the damage areas, methane was less only in the Resources area as shown in Figure 4-94. The top three constituents in methane propellant for Climate Change was carbon dioxide, fossil and methane, fossil and biogenic. The single score for methane versus RP-1 does show overall damage combined that methane is less than RP-1.

Overall, methane as a propellant does not seem to be the better green propellant choice than kerosene (RP-1) propellant. If the bigger environmental concern is from Resources then the methane propellant would be a better choice than RP-1. So, if exploration and development for Mars continues then methane propellant might be the best operational choice but environmental impacts are greater from the use of methane.

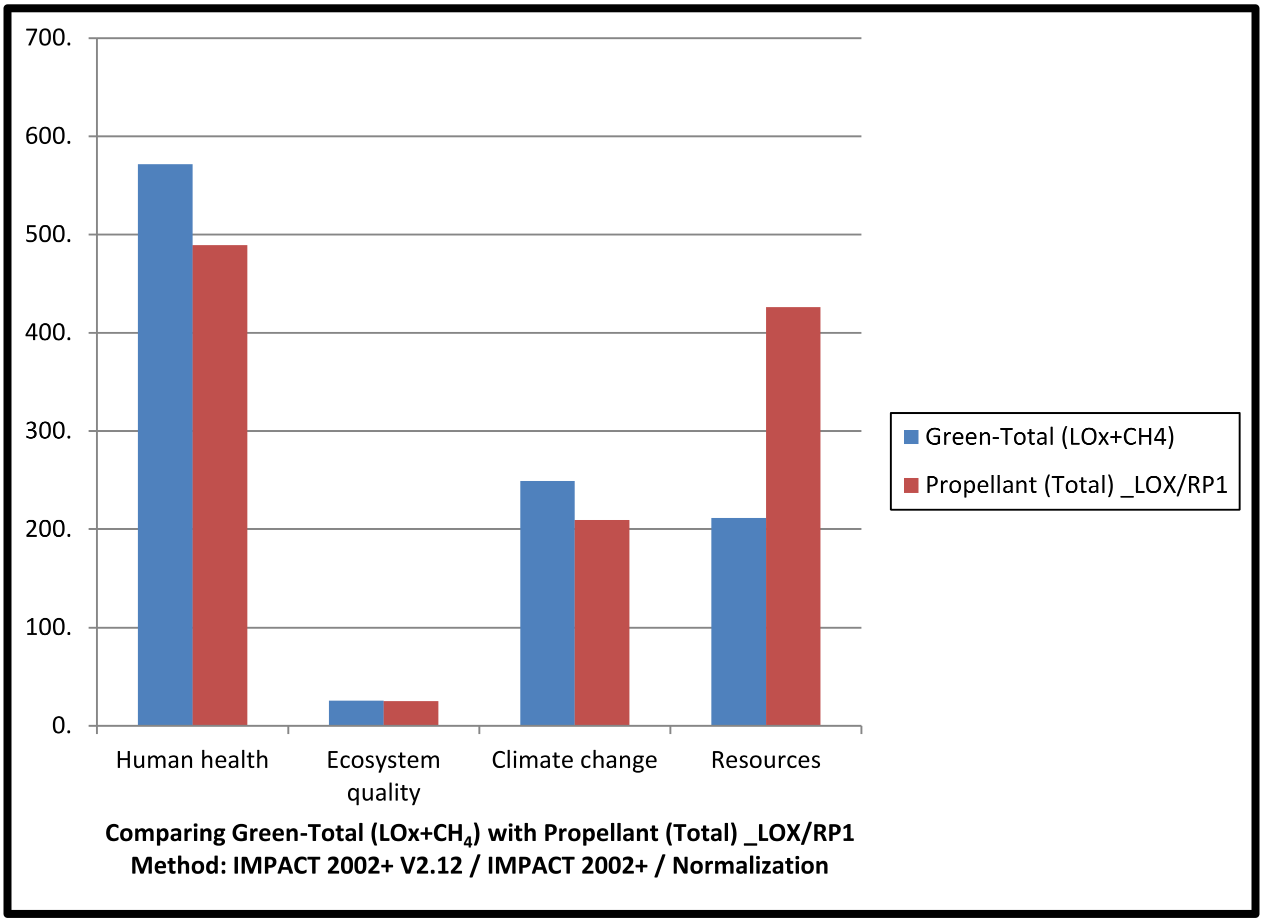


Figure 4-94 Green Technology Fuel Change to Methane from RP-1 Alternative Damage Assessment Normalization

4.3.2 Notional Launch Campaign with Green Technologies

The insertion of the solar power instead of diesel-generated electricity with a reusable rocket booster is an example of a notional launch campaign using green technology. Figure 4-95 presents the Damage Assessment Normalization for the comparison between the reusable rocket booster with propellant LOx/RP- 1 with diesel as part of the electricity generation and the notional launch campaign without diesel. Green notional launch campaign reduced damage areas of Resources by 1.6%, reduced Climate change by 2.1%, reduced Ecosystem quality by 1.6% and reduced Human health by 1.3%. Overall, impact change for all damage areas combined is 1.5%. The STEP-L for the notional launch campaign with green technology additions generated slight reductions in impact to all damage areas.

Even though the reductions appear small, adding a green technology to a full launch campaign can provide a meaningful decrease in environmental impacts.

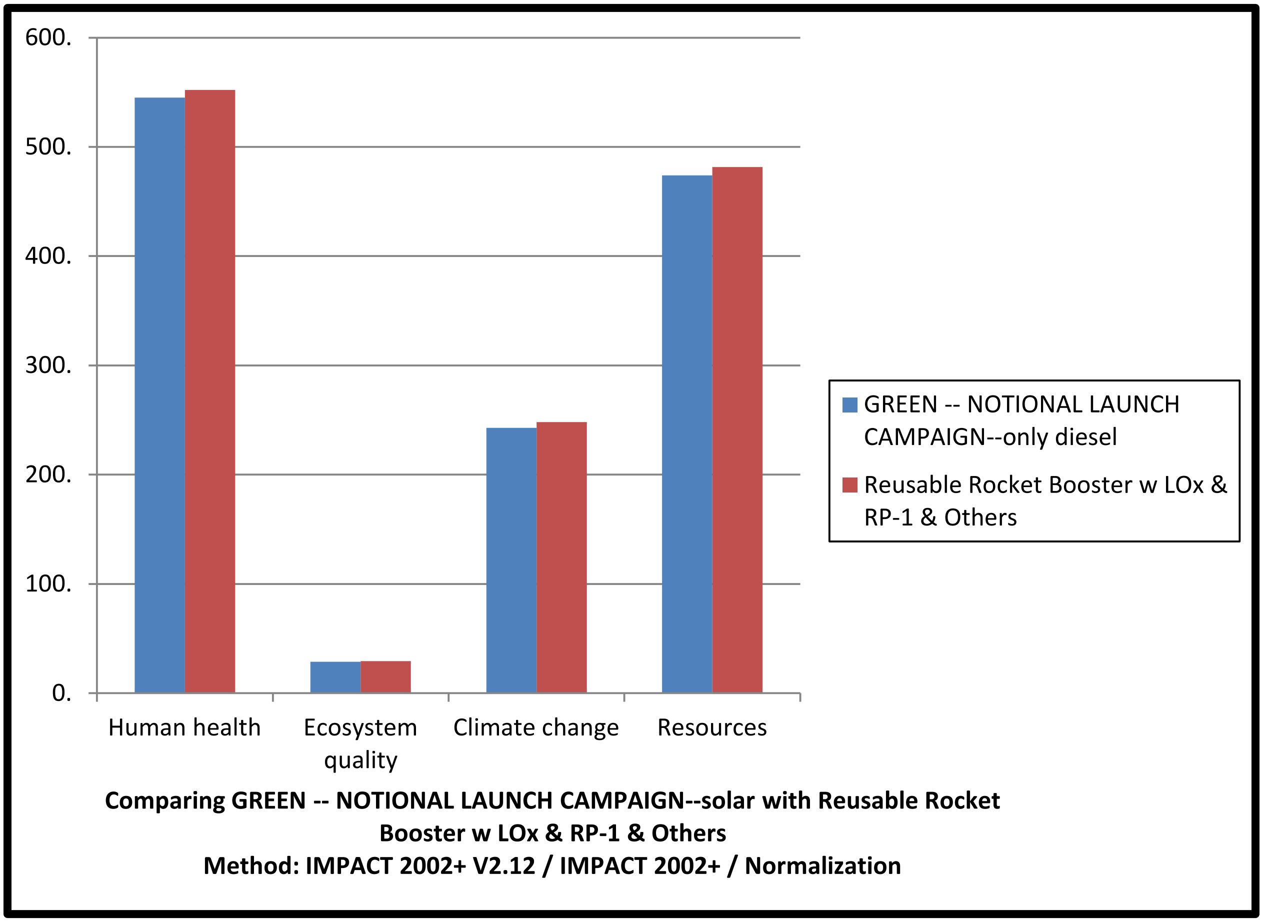


Figure 4-95 Notional Launch Campaign with Green Technologies

4.4 **Results for Objective 4. Operationalizing the LCA and the Development of the Space Transportation Environmental Profiles for Launch (STEP-L) Dashboard**

Operationalizing the LCA and the development of the STEP-L Dashboard is interactive dashboard using sensitivity analysis and varying each of the inputs used SimaPro for CST activities.

The STEP-L is one of the modules that can show the launch environmental impacts. If specific manufacturing and raw materials were known and the end-of-life was known for each type of launch vehicle, then the STEP-L could be added to a STEP for Manufacturing, STEP for Raw Materials Acquisition, and STEP for End-of-Life. These combined STEPS would build the total STEP for specific launch vehicles. The STEP-L Dashboard would provide a general snapshot surrounding the launch operation for environmental implications. Also, modules can be built specifically to the launch campaign with its applicable chemicals, propellant types and amounts, etc., to enable the launch environmental professional and other operators to understand the environmental implications for each launch or combination of launches. As the data becomes more robust by other sampling from the launch such as Environmental, Safety and Health data, and integrated with the LCA results, then the STEP-L operational environmental impacts will become more accurate.

Figure 4-96 is shown as a typical dashboard view for the STEP-L Dashboard and the associated damage area results for the operational scenario. The dashboard allows for selection of either a reusable or expendable rocket, input of number of test firings, propellant used in mass amounts, electricity, water, or chemical quantities in mass can be input. The dashboard will provide a graph with the damage assessment areas and the associated total numerical value in each damage area. This STEP-L Dashboard operationalizes this ECLA and is one phase of the life cycle that can be added to the other phase modules for CST activities as previously mentioned to give a full system view of the environmental impacts, implications and burdens from launching one space vehicle into orbit. Appendix B provides more details on the step-by-step procedures of the STEP-L Dashboard development.

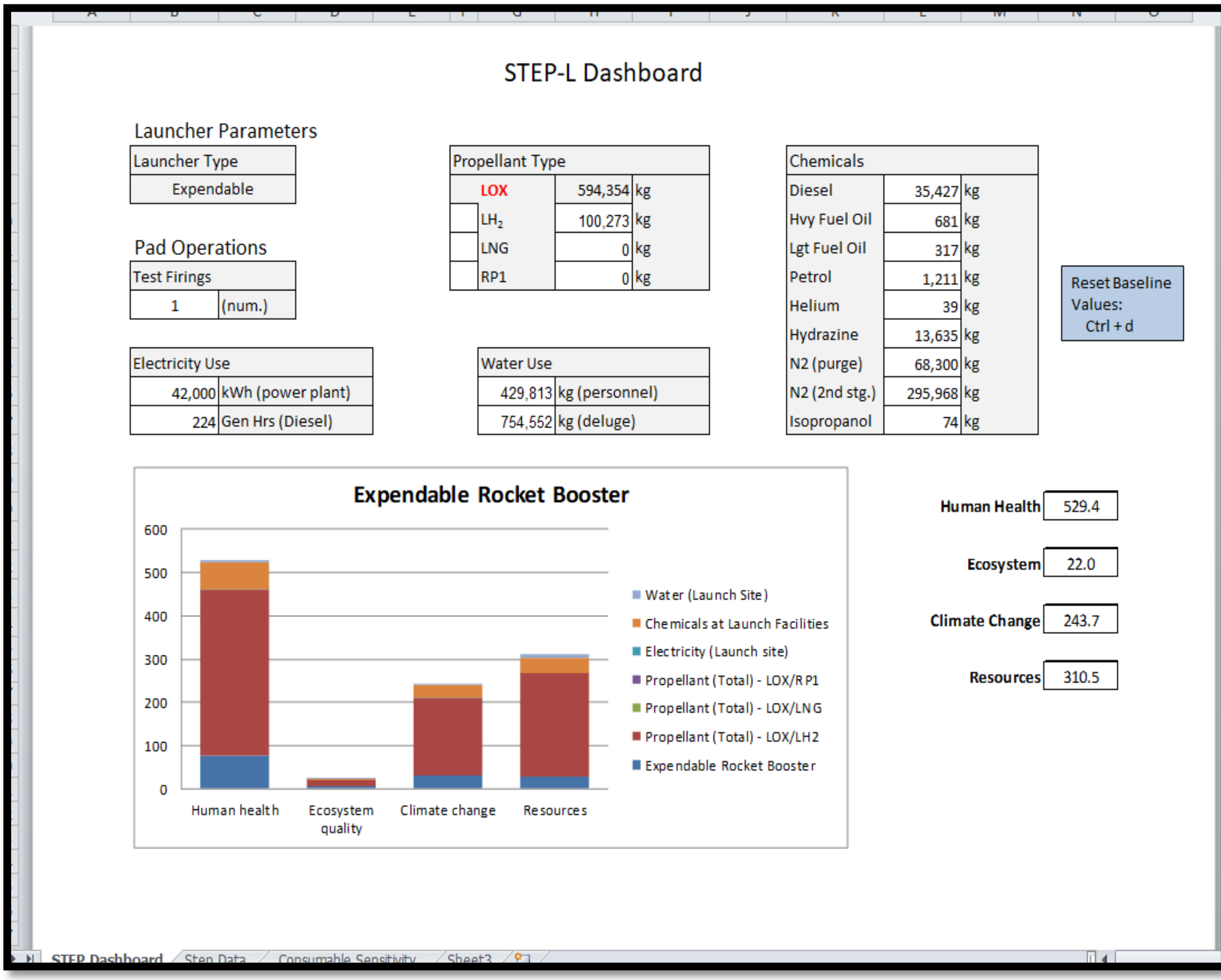


Figure 4-96 Space Transportation Environmental Profile for Launch (STEP-L)

4.5 Answers to the Research Questions

The main question addressed in this ELCA is:

As U.S. commercial space transportation activities expand, how are these activities impacting the environment today and within the next five to ten years?

This study provided the characterization and damage assessments for the per Launch activities in current launch tempo of one launch every two weeks and then expanded up to four launches every two weeks. Each consumable was evaluated using the LCA methodology applying the IMPACT 2002+ impact method and then viewed as a whole system of consumables used for launch. Comparison with commercial air transportation emissions generated per year revealed over 120,000 launches per year would reach the same amount of emissions. STEP-Ls were generated for each of the reusable rocket boosters and the liquid propellant to show the environmental domain of these launches.

Other relevant questions include:

- **What are the environmental impacts from launch operations using space rocket propulsion liquid propellants (liquid oxygen (LOx)/Liquid Hydrogen (LH_2), LOx/RP-1, LOx/LNG)?**

The base-case provided the insight into what the environmental impacts were from various configurations of these rocket boosters and propellant types. Human Health and Resources were the most impacted by the launch operations. Climate change was mostly impacted by the propellants and the electricity used to create these propellants and chemical used for the launch.

Among the propellants evaluated, liquid hydrogen has the least impact. The propellant, LOx/LH_2 has the least impact because the quantities of both LOx and LH_2 modeled using Delta IV Heavy rocket booster data are less than the amount for the other two propellants modeled. For the Delta IV Heavy used as the model for this propellant, less amount of propellant is needed to achieve the performance and thrust designed for this launcher. On a per-kg basis calculated from the sensitivity analysis, the LOx/LH_2 propellant has more influence across all four damage areas. However, on an equivalent launch performance basis, LOx/LH_2 propellant has less impact than RP-1 in all four damage areas because less LOx/LH_2 is required to achieve the same performance. For the reusable booster, it reduces impacts by over 70% compared to liquefied natural gas and kerosene for all categories except mineral extraction (40% reduction). For the expendable booster, liquid hydrogen reduces impacts by over 60% for all categories except mineral extraction (8.4% reduction).

See Figures 4-37 through Figure 4-44 for the base-case environmental impact results.

- **What damage impact categories (Human Health, Climate Change, Ecosystem Quality, and Resources) are generated from each type of launch operation?**

    - These launch operations include: three propellant types for the 1st stage and the 2nd stage Low Earth Orbit (LEO) and Geostationary Transfer Orbit (GTO) payloads; and expendable and reusable rocket boosters.

Each specific launch consumable of propellant and rocket booster impacted Human Health and Resources the most while Climate change and Ecosystem quality were less impacted. Figure 4-6 through Figure 4-17 for the reusable rocket booster and its elements characterization and normalization damage assessment. For the expendable rocket booster, Figure 4-18 through Figure 4-29 provides the impact analysis for this booster. However, the propellants did have more impact to the Climate change and the engine from the rocket booster influences the damage areas as well. The material used in the engine is important as it will be a key factor to what environmental impacts are generated from the rocket launcher life cycle.

- **Which consumable (s) used in launching one space vehicle contributes the greatest environmental impacts and how would this consumable (s) impact the environment?** The greatest environmental impacts seems to be generated from the propellants and the engine used in the 1st and 2nd Stage of the rocket boosters. The expendable rocket booster was found to have a higher impact in those areas as well. See Figures 4-18 to 4-29 for the characterization and damage assessment results.

How would an increased launch rate of space vehicles impact the environment over the next 10 years? Increased launch rate for space vehicles would impact the environment mostly from the expendable rocket booster with the three propellants evaluated in this study. The reusable rocket booster will also have some environmental impact to the upstream life cycle phases with the Human Health and Resources. This study provided some visibility into the frequency of launches, the use of the propellants and other consumables possibly used for one launch and then increase the launches to 2.5 launches and 4 launches every two-weeks. As expected with more launches, the rate of environmental impacts to the characterization categories and damage areas calculated using the IMPACT2002+ impact method to analyze the specific mid-points and end-points did increase by 150% to 300%. Figures 4-85 through 4-86 show the increased launches damage area results.

- **What green technologies might aid to minimize environmental impacts during the launch operation?** Four green technologies were examined with two being evaluated using SimaPro. The four include diesel removed from the electricity consumable and replacing it with solar power; the replacement of kerosene (RP-1) with methane (CH_4) fuel in the propellant; the use of additive manufacturing (3-D printing) to reduce wastes and time from conception to use on space vehicles; and use of a titanium process that is reduced energy and minimizes the waste stream in manufacturing. Only the replacement of diesel with solar power was modeled in SimaPro with a notional green launch campaign generated to show the possible improved environmental burden and impacts per Launch as shown in Figures 4-90 through Figure 4-93.

- **What would a general space transportation environmental profile to Launch (STEP-L) be for a reusable launch vehicle with the three types of propellant and the expendable launch vehicle with the three types of propellants?** The various STEP-Ls were generated and shown in the previous sections and provide a snapshot of the launch campaign for each of the consumables as a holistic system for launch. These modules can be designed for each launcher system and used to inform the various stakeholders about the environmental impacts per Launch while also showing potential environmental implications. For example, the systems engineer or environmental professional can use the STEP-L to be informed of the waste streams and the environmental burdens per launch to make decisions about eco-design or enhance environmental sampling strategies at the launch facility. Figures 4- 59 through Figure 4-70 show the radar graphs representing these STEP-L operational scenarios.

CHAPTER 5

CONCLUSIONS, FINDINGS, AND RECOMMENDATIONS FOR FUTURE STUDIES

"Once we set our limits, we go beyond them." Albert Einstein

5.1 Conclusions and Findings

CST launch activities in the United States are increasing to meet various goals from delivering supplies to the ISS to launching satellites and other communications to preparing for Mars. This life cycle assessment study of the CST activities begins to characterize the per Launch impacts in the environmental domain with focus on the Use and Maintenance life cycle phases. This domain understanding can allow for more robust eco-design and environmental implications for the launch of one space vehicle.

Six consumables were evaluated as part of the per Launch functional unit. These consumables are: reusable and expendable rocket boosters; water at launch; electricity at launch; chemicals used at launch; and liquid propellant (LOx/LH_2; LOx/LNG; LOx/RP-1). Each consumable was assessed one-at-a-time (OAT) for its environmental impacts per Launch and then all the consumables analyzed as a whole system per Launch. For the impact assessment phase, IMPACT2002+ Method was used to provide those characterization (mid-point) categories and damage (end-point) areas of importance for characterizing the environmental impacts. From each of these LCA analyses, a STEP-L was created to show the characterization and damage assessment areas impacted.

Specific conclusions and findings are as follows:

<u>Inventory</u>

- The overall inventory analysis for each of the consumables per Launch contained greenhouse gases (GHG)s and criteria air pollutants (CAP)s in the top 10-15 constituents with the heaviest masses. GHGs (Carbon dioxide, methane, nitrous oxides) and traditional air pollutants (carbon monoxide, $PM_{2.5}$) were seen in all six of these consumable inventories as some of the top 10-15 contributors.

- Calcium, iron and silicon were the greatest contributors to the soil emissions. For the water emissions, strontium and lithium were the greatest substance contributors. These emissions may be due to the manufacturing processes and even possibly the materials processing.

<u>Impact Assessment – Base-Case</u>

- The impact assessment for the consumables provided more insight into the contributing influences from the consumables and which damage area was most affected as follows:.
    - The reusable rocket booster as a system impacted Human Health and Resources the most.
        - For the 1st Stage reusable rocket booster, the engines contributed the most to mineral extraction and to the four damage areas. Propellant used for the re-entry was the highest contributor to all the other 13 characterization categories (besides mineral extraction).
    - For the expendable rocket booster, engines were the major contributor to all 15 characterization categories, and Human Health was the most impacted from this consumable.
    - Among the chemicals, hydrazine, diesel, and liquid nitrogen contributed the most to the characterization and influenced the damage assessment in the Human Health and Resources damage areas.
        - Diesel was a key influencer along with hydrazine and liquid nitrogen, in the Climate Change damage area.
- The reusable rocket booster and expendable rocket booster were compared using the three liquid propellants. For both rocket boosters, RP-1 fuel affected the Resources damage area the most and LNG fuel affected the Human Health damage area the most.
- <u>**Conclusions:**</u> Overall, the reusable rocket booster has lower impacts in each of these damage areas, as expected.

- A comparison of the three propellants revealed the Human Health damage area was most impacted by all three propellants. The highest contributor to the damage areas was the LOx/LNG propellant and the least environmental impact was from the LOx/LH_2.
- **Conclusion:** The propellant, LOx/LH_2 has the least impact because the quantities of both LOx and LH_2 modeled using Delta IV Heavy rocket booster data is less than the amount for the other two propellants modeled. On a per-kg basis calculated from the sensitivity analysis, the LOx/LH_2 propellant has more influence across all four damage areas. However, on an equivalent launch performance basis, LOx/LH_2 propellant has less impact than RP-1 in all four damage areas because less LOx/LH_2 is required to achieve the same performance.
- Overall, the transportation contribution as identified in this study did not have significant impact on the damage areas relative to the six consumables examined. Both coasts were identified for transportation and the West coast diesel for 100 miles was slightly higher impact than the Southeast diesel. The Damage Assessment, Normalization revealed that transportation impacted Human Health the most and Climate Change slightly higher than Resources.
- **Conclusions:** This base-case of the CST activities in the United States characterizes the environmental implications per Launch for an operational tempo of one launch every two weeks. The LCA methodology and NEPA environmental assessments are complementary analysis which may aid in contributing to a better understanding of environmental burdens and impacts throughout the life cycle for the launch of a space vehicle.
- The Delphi Method was used to understand what stakeholders would identify as the environmental impact level of concern in the four damage areas from the consumables of rocket boosters and propellants as part of the CST activities. The participants identified that the reusable rocket booster would impact the Climate change damage area the most. For expendable rocket booster, they identified that the Resources damage area was impacted the most. For the propellant LOx/$LH_{2,}$ both Human health and Resources were deemed the most impacted. For propellant LOx/LNG, Resources were seen as the most impacted.

Finally, for propellant LOx/RP-1 both Resources and Ecosystem quality were selected as the most impacted. These results were then compared with the SimaPro results. The Delphi method and SimaPro results showed agreement in their top two of the damage results: reusable rocket booster impacted Human health the most; expendable rocket booster impacted the Climate change the most; LOx/LH_2 agreement in both Human health and Resources; and LOx/LNG and LOx/RP-1 impacted Resources the most.

- **Conclusions:** So, the use of a Delphi Method allows the key stakeholders an opportunity to decide on what is the most important impact or damage areas (end-points) in their decision making. By using experts to inform the LCA results, another perspective emerged showing how various end-points are seen as most impacted from CST activities in the United States.
- Six individual STEP-Ls were generated for a reusable rocket with each propellant and with all the other consumables and an expendable rocket with each propellant and with all of the other consumables representing operational scenarios. The results showed propellant was the highest contributor and the 1st Stage for the expendable rocket booster. Chemicals were also seen as a major contributor to the system perspective of per Launch.
- **Conclusions:** The STEP-Ls using radar graphs enabled pattern recognition more quickly about the consumable contributions to environmental impacts for the operational scenarios.

Sensitivity Analysis

- Sensitivity analysis was performed on the following parameters: reusable rocket booster use lives, engine material composition mass change, electricity using diesel alternatives, amount of propellant used in test firings, and chemical mass changes. Of the five sensitivity parameters evaluated, the highest influencer was the amount of propellant used in a test firing as part of the launch campaign.
- The quick-look or screening LCA of the scenario analysis of the change in number of engines per Launch in the reusable and expendable rocket boosters showed the expendable rocket booster with 27 engines generated the greatest impact to all of the characterization categories and damage areas (base-case).

- **Conclusions:** Even with only three engines in the expendable rocket booster, the results show this scenario has greater impact than the 27 engines used 20 times in the reusable rocket booster.
- A Monte Carlo analysis was conducted on the per Launch consumables as a whole system to determine the uncertainty in the data within the SimaPro library databases used for this study. These results aided in understanding the calculated results for both the data quality analysis and sensitivity analysis. Higher uncertainty is seen in the Human Health and possibly due to the higher uncertainty found in the ionizing radiation and carcinogens. The SimaPro library databases were shown with 63.7% lognormal distribution and 35.3% undecided or no distribution.
- **Conclusions:** Specific library databases need to be generated for CST activities in the United States to minimize the relative uncertainty when performing a LCA.

Green Technology Evaluation

- Green technology recommendations included replacing diesel with solar for the electricity; replacing current titanium manufacturing process (Kroll) with the Armstrong® process, replacing conventional manufacturing for parts with 3-D additive manufacturing, and replacing kerosene (RP-1) with methane as a fuel.
- A notional green technology STEP-L was developed with solar replacement for diesel-generated electricity. Green notional launch campaign reduced damage areas of Resources by 1.6%, reduced Climate change by 2.1%, reduced Ecosystem quality by 1.6% and reduced Human health by 1.3%. Overall, impact change for all damage areas combined is 1.5%. The STEP-L for the notional launch campaign with green technology additions generated slight reductions in impact to all damage areas.
- **Conclusions:** The integration of these green technology recommendations might be practical and effective for both the environment and operations. For example, even though the amount of reduced environmental impacts was small, the operational change to use the solar substitute for diesel-generated electricity might provide environmental benefits over a

relative short period of time. Applying this study's framework to integrate a green technology to a full launch campaign can provide a meaningful decrease in environmental impacts.

5.2 Future Research Recommendations

Future research in the environmental implications or impacts of per Launch is recommended to provide a full spectrum comprehension of a launch of one space vehicle. These recommendations are below.

- A comparison study with reusable and expendable rocket boosters to determine what additional differences would contribute to the environmental burden or implications. This study was not able to obtain exact data for the manufacturing and production of these rocket boosters and assumed a couple of differences. So, better data on the differences and complete design materials and manufacturing process would determine the environmental impacts from each rocket booster.
- The engine from both the rocket boosters was identified as the highest contributor in these consumables. The exact material type, composition, and mass would aid in refining this result. A study to compare current traditional materials and manufacturing processes versus the 3-D additive manufacturing for parts and components of a rocket launcher to determine the environmental impact changes, if any.
- Apply the DoD Scoring Factors found in the DENIX government website to determine to compare this sustainability tool and the SimaPro library databases. The DoD Scoring Factors are a predominant method used to understand sustainability for weapon systems. This method might have related processes used in space operations. The use of the Scoring Factors may also reveal additional environmental considerations for eco-design and operations in CST activities.
- Evaluate the current environmental conditions around each launch site to build a baseline. . Collect samples at the launch site to validate one life cycle phase, Use phase. Then, collect specific launcher data to build those launcher baselines and continued launches. Build specific launcher conditions. Apply the baseline from all launchers' environmental profiles to

build a database of the environmental domain around the launch facilities to determine if any environmental impacts on the local environment might occur from cumulative launches. This study was not able to gain this baseline data to add to the LCA inputs. The NEPA environmental assessment does provide a good understanding of these impacts however, this study would be able to show more precisely what conditions are changing as seen years after the Space Shuttle launches with the fish kills and other vegetation losses.

- Develop a comprehensive inventory of solid and hazardous waste limited to the per Launch activities, if these inventories do not already exist, and perform a study of the overall End-of-Life aspects of this waste in context of per Launch. This study of the end-of-life might provide information to inform systems engineers or other environmental professionals on the waste streams being generated and environmental burden seen per Launch. Also, relevant costs from disposal inventory and end-of-life processes could be used for future planning.
- This study was limited to transportation of consumables to the launch facility for evaluating the East and West Coast environmental impacts from the launches. The understanding of each of these launch sites might provide insight into what aspects are needed for future launch sites. Also, this future research might identify those spaceport or military-leased launch complex parameters which are most suited for more frequent launches.
- This study was not able to research the various payload types. However performing a LCA on these payload types and their material composition to include adding to this current base-case any additional requirements at the launch facility (Use Phase), would add additional knowledge to the launch campaign and environmental domain. A STEP-L for payloads might be generated and added to the systems view of launching one space vehicle with a payload.
- Adapt this ELCA framework to non-commercial or government space vehicles. Modify the input conditions in SimaPro or apply other datasets related to the life cycle phases for space vehicles. The ELCA framework for the notional green technologies can also be adapted to aid in evaluating operational decisions to minimize the environmental burdens or impacts at the launch or use phase.

- Identify and request the system engineers to validate this ELCA's systems engineering model of the rocket boosters. Identify where additional model validation is needed applying their expertise to refine the rocket boosters' configuration.

5.3 STEP-L Dashboard for Operators, Environmental and Occupational Health Professionals, and Decision-Makers

This ELCA for CST activities in the United States can provide additional information into the environmental impacts and implications of a space vehicle launch.

- Tool for Operators: One key tool is the Space Transportation Environmental Profile for Launch (STEP-L). The STEP-L Dashboard provides a snapshot of the environmental impacts of a specific rocket booster, chemicals and liquid propellant examined in this study. Changes can be made in the current base-case model in the propellant amounts, chemical amounts, and number of test firings with either a reusable or expendable rocket booster.
- .STEP-L results and the sensitivity analysis were used to construct an interactive dashboard. Operators can used this STEP-L dashboard for quick-looks at the environmental impacts per launch and see potential ways to develop other opportunities for material substitution or end-of-life choices.
- System View of Environmental Domain for Systems Engineers and Environmental Professionals or Other Decision Makers: This study provided several STEP-Ls to show how to generate future STEP-Ls relevant to a specific launcher. In addition, the other life cycle areas of manufacturing could have STEP-M, and end-of-life could be STEP-EL. All these STEP-Ls combined would provide a holistic systems view STEP of the environmental impacts in each life cycle phase.
- Eco-Design or Environmental Sampling Options for Future Launchers: A STEP-L Dashboard was generated from this study to show operators relevant launch conditions in terms of the environmental domain prior to launch and even after the launch to see how to improve or

modify future launches or potential eco-design recommendations. This new knowledge can aid for eco-design changes or focused environmental sampling at the launch facility to better characterize and evaluate environmental damage or impacts.

APPENDIX

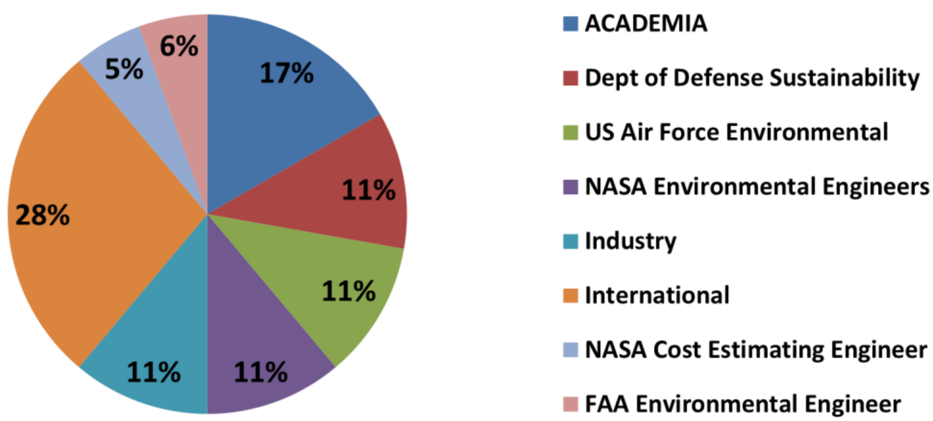
APPENDIX A

DELPHI METHOD

METHODOLOGY AND SURVEYS

Methodology

1. Research other research using Delphi method for LCAs and other problem solving such as water and infrastructure priorities
2. Identify potential participants based on the conversations and connections during the research
3. Send out invitations to identify who might be available to participate for approximately three to five days and would be a timed survey of 24-30 hours
   - Contacted 35 people, 22 responded to participate
   - Overall group involved consisted of the following as shown in Pie chart:



4. Request a brief biography for each participant prior to the exercise (at least 2 weeks)
5. Used online Delphi tool, Qualtrics© [44][45] to administer and capture the results
   - Developed the questions for the survey and input into the online tool at least 2 weeks prior
   - Developed series of three surveys related to the LCA methodology and the CST activities
   - Identified participants using the online tool
6. Strategy for developing questions
   - Three surveys where the participants can view the previous survey

[44] Zangernehmader, Z., Moselhi, O., Prioritizing deterioration factors of water pipelines using Delphi method, Measurement 90 (2016) 491-499.
[45] Used the University of Texas at Arlington license for Qualtrics

- Types of questions used are Ranking, Open Ended and Scaled
- Questions about expertise and experience was also the very first questions to understand the overall complexion of the results
- After the 1^{st} indicators through multiple choice, then narrow or confidence level and 2^{nd} (high/med/low)
- Minimize the number of questions but make relevant to the IMPACT2002+ method for future input into the weighting portion of SimaPro
- Open-ended questions used to refine numerical answers and solicit feedback for future studies with Delphi method and CST activities

7. Test run questions with a non-participant at least 2 weeks prior
8. Send out detailed instructions at least one week prior to exercise week
    - Send out link to participants on the day prior
    - Send out Thank you email after the week exercise
9. Send out preliminary final results to participants each day after the exercise to allow for change in inputs on the previous survey
10. Review results and apply the weighting values for the propellants and the rocket boosters only

DELPHI Method for Weighting Environmental Impacts

Start of Block: Environmental Life Cycle Assessment - Commercial Space Transportation Activities

Q1 The first questions will ask your level of expertise with Environmental and other related topic areas. Please identify your level as: Low to None; Medium - Working knowledge with some application of the topic; and High - Expert level knowledge with application of the knowledge

---

Q2 Environmental Impacts [Aquatic/Policy/Renewable or Non-Renewable/Ozone/Waste/Hazardous Materials/Chemicals/Dispersion]

- ▢ Low to None (1)
- ▢ Medium [Working Knowledge with some application] (2)
- ▢ High [Expert Knowledge with applications] (3)

Q3 ISO 14040 [Life Cycle Assessment Experience--Use of Methodology/Review Results]

- ◯ Low to None (1)
- ◯ Medium (2)
- ◯ High (3)

Q4 Aerospace Operations [Manufacturing/Aircraft maintenance/infrastructure to support flying operations/logistics/research & development/Policy & Laws]

- ◯ Low to None (1)
- ◯ Medium (2)
- ◯ High (3)

Q5 Rocket Systems & Operations [manufacturing/rocket maintenance/infrastructure for launching vehicle/logistics/research & development/Policy & Laws]

- ◯ Low to None (1)
- ◯ Medium (2)
- ◯ High (3)

Q6 Chemicals/Fuels [Hazardous wastes/Handling/Storage/Manufacturing]

- ◯ Low to None (1)
- ◯ Medium (2)
- ◯ High (3)

Q7 Health & Safety [Toxicity/Carcinogens/Personal Protective Equipment/Monitoring & Surveillance]

- ◯ Low to None (1)
- ◯ Medium (2)
- ◯ High (3)

Q8 Radiation [Ionizing]

- ◯ Low to None (1)
- ◯ Medium (2)
- ◯ High (3)

Q9 The following set of questions ask to evaluate the 3 liquid propellants and their potential environmental impacts. These 3 propellants are: Liquid Oxygen/Liquid Hydrogen; Liquid Oxygen/Liquefied Natural Gas; Liquid Oxygen/RP-1 (Kerosene-Based). Think about each propellant and its environmental impacts.

Q10 Of the 3 Propellants [Liquid Oxygen/Liquid Hydrogen; Liquid Oxygen/Liquefied Natural Gas; Liquid Oxygen/RP-1 (Kerosene-based], which one would you expect to pose the greatest or least environmental impacts to include human health toxicity during the Launch Phase? [2 weeks prior/launch/1 week after].

	Environmental Impacts	
	Greatest (1)	Least (2)
Liquid Oxygen/Liquid Hydrogen (1)	◯	◯
Liquid Oxygen/Liquefied Natural Gas (2)	◯	◯
Liquid Oxygen/RP-1 (3)	◯	◯

Q25 Provide your rationale for your decisions above for GREATEST IMPACTS.

____

____

____

Q11 What is the Level of Concern of the Environmental Impact posed by the Liquid Oxygen/Liquid Hydrogen?
Use the slider bar to provide your answer for each of the impact categories from 0 to 100.

	0 10 20 30 40 50 60 70 80 90 100
Carcinogen (1)	
Non-Carcinogen (2)	
Respiratory Inorganics (3)	
Ionizing Radiation (4)	
Ozone Layer Depletion (5)	
Respiratory Organics (6)	
Aquatic Toxicity (7)	
Terrestrial Ecotoxicity (8)	
Terristrial Acid/Nutrification (9)	
Land Occupation (10)	
Aquatic Acidification (11)	
Global Warming (12)	
Non-Renewable Energy (13)	
Mineral Extraction (14)	

Q12 What is the Level of Concern of the Environmental Impact posed by the Liquid Oxygen/Liquefied Natural Gas?

	0 10 20 30 40 50 60 70 80 90 100
Carcinogen (1)	
Non-Carcinogen (2)	
Respiratory Inorganics (3)	
Ionizing Radiation (4)	
Ozone Layer Depletion (5)	
Respiratory Organics (6)	
Aquatic Toxicity (7)	
Terrestrial Ecotoxicity (8)	
Terrestrial Acid/Nutrification (9)	
Land Occupation (10)	
Aquatic Acidification (11)	
Global Warming (12)	
Non-Renewable Energy (13)	
Mineral Extraction (14)	

Q13 What is the Level of Concern of the Environmental Impact posed by the Liquid Oxygen/RP-1 (Kerosene-Based)?

0 10 20 30 40 50 60 70 80 90 100

Carcinogen (1)	
Non-Carcinogen (2)	
Respiratory Inorganics (3)	
Ionizing Radiation (4)	
Respiratory Organics (5)	
Aquatic Toxicity (6)	
Terrestrial Ecotoxicity (7)	
Terrestrial Acid/Nutrification (8)	
Land Occupation (9)	
Aquatic Toxicity (10)	
Aquatic Acidification (11)	
Global Warming (12)	
Non-Renewable Energy (13)	
Mineral Extraction (14)	

Q14 Describe your rationale for those Environmental Impacts you rated >70 for Liquid Oxygen/Liquid Hydrogen propellant?

Q15 Describe your rationale for those Environmental Impacts you rated >70 for Liquid Oxygen/Liquefied Natural Gas (Methane-Based) propellant?

____

____

____

____

____

Q16 Describe your rationale for those Environmental Impacts you rated >70 for Liquid Oxygen/RP-1 (Kerosene-Based) propellant?

____

____

____

____

____

Q17 The following Section will ask you to consider the REUSABLE and EXPENDABLE rockets. ISO 14040 defines life cycle phases as Raw Materials Acquisition; Manufacturing; USE & Support; and End of Life. These questions will ask you to consider these systems from this perspective.

Q18 Based on your experience/background, which rocket (EXPENDABLE or REUSABLE) would contribute the greatest or least environmental impacts at the ISO 14040 -- Life Cycle Phases [Raw Materials Acquisition/Manufacturing/Use & Support/End of Life]?

	ISO 14040 Life Cycle Phases-Environmental Impacts	
	Greatest (1)	Least (2)

REUSABLE Rocket (1)	○	○
EXPENDABLE Rocket (2)	○	○

Q24 Describe your rationale for selection for GREATEST environmental impacts at the ISO 14040 Life Cycle Phases.

____

____

____

____

____

Q19 Rank the Environmental Impacts during the Life Cycle Phases from 1 (Lowest) to 5 (Highest) for the REUSABLE ROCKET
You can select more than one number so may have two #2s, etc.
______ Raw Materials to make the reusable rocket (1)
______ Manufacturing to include transportation (Barge/Tanker/Semi-Truck) to the Launch Site (2)
______ Launch to include test firings at the launch site (3)
______ Support at Launch site with energy (electricity), chemicals, water, and personnel (4)
______ End of Life - Disposal/Landfill/Recycle/Reuse (5)
______ Reusable rocket is reused up to 20 times - Transportation back to Refurbishment facility (6)

Q20 For the Rank of #5, describe your rationale for your decision. Describe rationale for your highest ranking even If you do not have a #5.

____

____

____

____

____

Q21 Rank the Environmental Impacts during the Life Cycle Phases from 1 (Lowest) to 5 (Highest) for the EXPENDABLE ROCKET
You can select more than one number so may have two #2s, etc.
______ Raw Materials to make the expendable rocket (1)
______ Manufacturing to include transportation (Barge/Tanker/Semi-Truck) to the Launch Site (2)
______ Launch to include test firing at the launch site (3)
______ Support at Launch site with energy (electricity), chemicals, water, and personnel (4)
______ End of Life – Disposal/Landfill/Recycle/Reuse (5)

Q22 For the Rank of #5, describe your rationale for your decision. Describe rationale for your highest ranking even If you do not have a #5.

____

____

____

____

____

Q23 Any other environmental impacts not identified or mentioned in the survey that should have been? Any other comments or thoughts?

____

____

____

____

____

End of Block: Environmental Life Cycle Assessment - Commercial Space Transportation Activities

DELPHI Method for Weighting Environmental Impacts-Survey #2

Start of Block: Survey #1 Responses

Q18 Survey #1 Results–Liquid Propellants – Which one poses the greatest environmental impacts? (Please see attached results)

Q1 Survey #1 Results – Reusable and Expendable Rockets ISO 14040 Life Cycle Phases and Greatest Environmental Impacts (See attached powerpoint)

Q3 Based on the other participants responses, do you want to modify or update your inputs for either the propellants and/or the rockets? If so, please identify which ones and why.

____

____

____

____

____

End of Block: Survey #1 Responses

Start of Block: LCA METHODOLOGY ENDPOINTS -- LIQUID PROPELLANTS (3)

Q4 From Endpoints [HUMAN HEALTH; ECOSYSTEM QUALITY; CLIMATE CHANGE; RESOURCES (Renewable/Non-Renewable)], Please provide your Level of Concern of Environmental Impact from the 3 Propellants [Liquid Oxygen/Liquid Hydrogen; Liquid Oxygen/Liquefied Natural Gas; Liquid Oxygen/RP-1].

Q5 Liquid Oxygen/Liquid Hydrogen

	0 10 20 30 40 50 60 70 80 90 100
Human Health (1)	
Ecosystem Quality (2)	
Climate Change (3)	
Resources (Renewable/Non-Renewable) (4)	
No Opinion (5)	

Q6 Please explain why you rated the Environmental Impact with > 70 or if you chose No Opinion, please explain.

Q7 Liquid Oxygen/Liquefied Natural Gas

	0 10 20 30 40 50 60 70 80 90 100
Human Health (1)	
Ecosystem Quality (2)	
Climate Change (3)	
Resources (Renewable/Non-Renewable) (4)	
No Opinion (5)	

Q8 Please explain why you rated the Environmental Impact with > 70 or if you chose No Opinion, please explain.

Q9 Liquid Oxygen/RP-1

	0 10 20 30 40 50 60 70 80 90 100
Human Health (1)	
Ecosystem Quality (2)	
Climate Change (3)	
Resources (Renewable/Non-Renewable) (4)	
No Opinion (5)	

Q10 Please explain why you rated the Environmental Impact with > 70 or if you chose No Opinion, please explain.

End of Block: LCA METHODOLOGY ENDPOINTS -- LIQUID PROPELLANTS (3)

Start of Block: LCA METHODOLGY ENDPOINTS - REUSABLE and EXPENDABLE ROCKETS

Q11 REUSABLE ROCKET (20 Uses)

	0 10 20 30 40 50 60 70 80 90 100
Human Health (1)	
Ecosystem Quality (2)	
Climate Change (3)	
Resources (Renewable/Non-Renewable) (4)	
No Opinion (5)	

Q12 Please explain why you rated the Environmental Impact with > 70 or if you chose No Opinion, please explain.

Q13 EXPENDABLE ROCKET

0 10 20 30 40 50 60 70 80 90 100

Human Health (1)	
Ecosystem Quality (2)	
Climate Change (3)	
Resources (Renewable/Non-Renewable) (4)	
No Opinion (5)	

Q14 Please explain why you rated the Environmental Impact with > 70 or if you chose No Opinion, please explain.

End of Block: LCA METHODOLGY ENDPOINTS - REUSABLE and EXPENDABLE ROCKETS

Start of Block: COST

Q16 From a Life Cycle Cost (LCC) perspective, identify which Life Cycle Phases [Research & Development; Testing; Manufacturing; Operations; Support; and Disposal] for each propellant and rocket would (in your expert opinion) be most or least expensive? [Select one most and one least for each propellant and rocket system]

	Liquid Oxygen/Liquid Hydrogen		Liquid Oxygen/Liquefied Natural Gas		Liquid Oxygen/RP-1		REUSABLE ROCKET		EXPENDABLE ROCKET	
	Most (1)	Least (2)	Most (1)	Least (2)	Most (1)	Least (2)	Most (1)	Least (2)	Most (1)	Least (2)

Research & Development (1)	○	○	○	○	○	○	○	○	○	○
Testing (2)	○	○	○	○	○	○	○	○	○	○
Manufacturing (3)	○	○	○	○	○	○	○	○	○	○
Operations (4)	○	○	○	○	○	○	○	○	○	○
Support (5)	○	○	○	○	○	○	○	○	○	○
Disposal (6)	○	○	○	○	○	○	○	○	○	○

Q17 Any other environmental impacts to include cost that should be consider for the propellants and rockets?

____

____

____

____

____

End of Block: COST

DELPHI Method for Weighting Environmental Impacts-Survey#3

Start of Block: Results from Survey #2

Q1 Survey #2 Participant Responses

Q2 Do you want to change or modify your responses from Survey #2

- ◯ Yes (1)
- ◯ Maybe (2)
- ◯ No (4)

Q3 If you do want to change/modify response, please provide your change below and describe why. If maybe, what would you like to think about changing?

____

____

____

____

____

End of Block: Results from Survey #2

Start of Block: PROPELLANTS (3) RANK THE ENVIRONMENTAL IMPACT AREAS

Q4 For each of the liquid propellants, please RANK the Environmental Impacts from 1 (Greatest) to 14 (Least). LIQUID OXYGEN/LIQUID HYDROGEN

______ Carcinogen (1)
______ Non-Carcinogen (2)
______ Respiratory Inorganics (3)
______ Respiratory Organics (4)
______ Ionizing Radiation (5)
______ Aquatic Toxicity (6)
______ Terrestrial Ecotoxicity (7)
______ Terrestrial Acid/Nutrification (8)
______ Land Occupation (9)
______ Aquatic Acidification (10)
______ Global Warming (11)
______ Non-Renewable Energy (12)
______ Mineral Extraction (13)
______ Ozone Layer Depletion (14)

Q11 For each of the liquid propellants, please RANK the Environmental Impacts from 1 (Greatest) to 14 (Least). LIQUID OXYGEN/LIQUEFIED NATURAL GAS

______ Carcinogen (1)
______ Non-Carcinogen (2)
______ Respiratory Inorganics (3)
______ Respiratory Organics (4)
______ Ionizing Radiation (5)
______ Aquatic Toxicity (6)
______ Terrestrial Ecotoxicity (7)
______ Terrestrial Acid/Nutrification (8)
______ Land Occupation (9)
______ Aquatic Acidification (10)
______ Global Warming (11)
______ Non-Renewable Energy (12)
______ Mineral Extraction (13)
______ Ozone Layer Depletion (14)

Q12 For each of the liquid propellants, please RANK the Environmental Impacts from 1 (Greatest) to 14 (Least).   LIQUID OXYGEN/RP-1

______ Carcinogen (1)
______ Non-Carcinogen (2)
______ Respiratory Inorganics (3)
______ Respiratory Organics (4)
______ Ionizing Radiation (5)
______ Aquatic Toxicity (6)
______ Terrestrial Ecotoxicity (7)
______ Terrestrial Acid/Nutrification (8)
______ Land Occupation (9)
______ Aquatic Acidification (10)
______ Global Warming (11)
______ Non-Renewable Energy (12)
______ Mineral Extraction (13)
______ Ozone Layer Depletion (14)

Q5 After which RANKING for Liquid Oxygen/Liquid Hydrogen did the Environmental Impacts become insignificant? Why?

____
____
____
____
____

Q13 After which RANKING for Liquid Oxygen/Liquefied Natural Gas did the Environmental Impacts become insignificant? Why?

____
____
____
____
____

Q14 After which RANKING for Liquid Oxygen/RP-1 did the Environmental Impacts become insignificant? Why?

____

____

____

____

____

End of Block: PROPELLANTS (3) RANK THE ENVIRONMENTAL IMPACT AREAS

Start of Block: REUSABLE and EXPENDABLE ROCKET MOST & LEAST IMPORTANT Environmental Impact Areas

Q6 For each of the Reusable and Expendable Rockets, please RANK the Environmental Impacts from 1 (Greatest) to 14 (Least). REUSABLE ROCKET

______ Carcinogens (1)
______ Non-Carcinogen (2)
______ Respiratory Inorganics (3)
______ Respiratory Organics (4)
______ Ionizing Radiation (5)
______ Ozone Layer Depletion (6)
______ Aquatic Toxicity (7)
______ Terrestrial Ecotoxicity (8)
______ Terrestrial Acid/Nutrification (9)
______ Land Occupation (10)
______ Aquatic Acdification (11)
______ Global Warming (12)
______ Non-Renewable Energy (13)
______ Mineral Extraction (14)

Q15 For each of the Reusable and Expendable Rockets, please RANK the Environmental Impacts from 1 (Greatest) to 14 (Least). EXPENDABLE ROCKET

______ Carcinogens (1)
______ Non-Carcinogen (2)
______ Respiratory Inorganics (3)
______ Respiratory Organics (4)
______ Ionizing Radiation (5)
______ Ozone Layer Depletion (6)
______ Aquatic Toxicity (7)
______ Terrestrial Ecotoxicity (8)
______ Terrestrial Acid/Nutrification (9)
______ Land Occupation (10)
______ Aquatic Acdification (11)
______ Global Warming (12)
______ Non-Renewable Energy (13)
______ Mineral Extraction (14)

Q7 After which RANKING for REUSABLE ROCKET did the Environmental Impacts become insignificant? Why?

____
____
____
____
____

Q16 After which RANKING for EXPENDABLE ROCKET did the Environmental Impacts become insignificant? Why?

____
____
____
____
____

Q17 Which Rocket poses the greatest environmental impacts?

◯ Reusable Rocket (1)

◯ Expendable Rocket (2)

◯ No opinion (3)

Q18 Provide your rationale for your choice to include No Opinion.

____

____

____

____

____

End of Block: REUSABLE and EXPENDABLE ROCKET MOST & LEAST IMPORTANT Environmental Impact Areas

Start of Block: ENVIRONMENTAL DAMAGE DURING LAUNCH

Q8 Where might the MOST environmental damage occur during the Launching of Rocket Systems – within 240 seconds from liftoff? Rank the Greatest (1) to Least (7)

______ Air (1)
______ Water (2)
______ Human (3)
______ Plants/Animals (4)
______ Infrastructure (5)
______ Noise (6)
______ Land Area (7)

Q9 Please provide rationale for the #1 ranking of environmental damage.

____

Q10 Any comments or recommendations for a future DELPHI Method exercise on Commercial Space Transportation Activities?

End of Block: ENVIRONMENTAL DAMAGE DURING LAUNCH

APPENDIX B

SPACE TRANSPORTATION ENVIRONMENTAL PROFILE FOR LAUNCH (STEP-L) DASHBOARD STEP-BY-STEP DEVELOPMENT PROCEDURES

STEP-L Dashboard

Purpose of STEP-L Dashboard: Develop a quick-look analysis of the per Launch consumables using either a reusable or expendable rocket booster. The environmental damage areas of Human Health, Climate Change, Ecosystem Quality and Resources are derived and available for operators or other decision-makers.

Description of STEP-L Dashboard: The STEP-L inputs are: reusable or expendable rocket booster; liquid propellant type (LOx/LH_2, LOx/LNG, and LOx/RP-1); eight chemicals at launch facility; and water and electricity. The Dashboard is functional and all STEP-L inputs can be adjusted. The environmental damage areas will be calculated using SimaPro results from the base-case and the inputs and their mass amounts in kilograms (kg). Both graphical and numerical results will be generated from these inputs and are displayed on an interactive dashboard.

Methodology for STEP-L Dashboard: The STEP-L dashboard was constructed with Microsoft Excel through a three-part process of consumable sensitivity analysis; data calculation; and iterative dashboard development.

Methodology for STEP-L Dashboard: The STEP-L dashboard was constructed with Microsoft Excel through a three-part process of consumable sensitivity analysis; data calculation; and interactive dashboard development.

- Step 1- Conduct a consumable sensitivity analysis: The main assumption was each consumable's contributions to the damage areas were independent and linear with mass change. The data used for the sensitivity analysis were the base-case all consumable SimaPro results and the damage assessment results of the base-case recalculated with consumable mass (for the chemicals and propellants) changed by 50% OAT From these data, a slope with units of kilo points of damage per kg was calculated for each of the damage areas for each chemical and each propellant. A similar process was used to calculate the damage impact slope for the electricity and water consumables.

- Step 2 - Data Calculation: A separate data worksheet was used to calculate the damage impact for each consumable, construct two tables to contain the dashboard data and generate the overall damage impact charts.
    - Using the slope from step 1 and quantity of the consumable, pulled from user data inputs (described in step 3), a section of the worksheet calculated the kilo points of damage in the four damage areas for each consumable.
    - For the propellants, the input quantity was for 1st stage only, so the 1st Stage propellant is multiplied by 1.24 to account for the additional 2nd Stage propellant and multiplied by the number of test firings to determine the total propellant mass. (One test firing is assumed to use a full load of 1st stage propellant.)
    - The LOx for each of the propellants is calculated by multiplying the total propellant by the mixture ratio for each propellant type. The damage impacts were then added to calculate the total damage in each of the four areas for each consumable.
    - The total damage impact for each consumable was then transferred to two tables, one for reusable boosters and one for expendable boosters. These tables were then used to generate the two stacked column damage impact charts.
    - Finally, a section of the worksheet kept the original base-case consumable mass values (kWh and diesel hours for the electricity consumable) in order to reset the dashboard values as described in Step 3.
- Step 3 – Interactive dashboard development: The Dashboard was built to allow user data input and display the damage assessment results. The input section of the dashboard has a cell for the quantity of each consumable and the number of test firings.
    - The test firing input can either be a whole number or a decimal fraction of a test firing. The LOx quantity displayed is a calculated value from step 2.

- The booster type selection was constructed as a drop down list with the option for reusable or expendable. Clicking on the cell displays the data from the drop down list. The bottom section of the Dashboard contains the display area for the Damage impact chart and the total numerical values for each of the damage areas based on the user inputs for the scenario.
- Either the reusable or expendable chart is selected for display using an MS Excel technique which calls the chart created in step 2 using a formula and the type of booster chosen by the user.
- A feature was also included which uses an MS Excel macro to reset the Dashboard inputs to the base-case values.
- The default values are selected by using "Ctrl + d" which activates the macro and calls the data from the base-case table constructed in step 2.

- The dashboard directions:

  Enter Launch campaign parameters (rocket launcher and pad operations inputs). White cells are fillable (Lox is calculated).

  - Choose either a reusable or expendable rocket booster using drop-down list.
  - Choose the fuel type and input mass amount used in 1st Stage; LOx will be calculated.
  - Input mass amounts of each of the chemicals listed, input can also be "0".
  - Input number of test firings used for launch campaign, input can be whole numbers or decimal fractions.
  - Ctrl+d will reset dashboard to base-case values.
    -

References

American Center for Life Cycle Assessment (ACLCA), www. aclca.org; "Life Cycle Assessment ISO Standards Overview" webinar, 2018, accessed 1/2018.

Adams, Ramona, 2016, "Air Force to Award Contract to ULA for Delta 4 Rockets," http://www.govconwire.com/2016/08/space-news-air-force-to-award-contract-to-ula-for-delta-4-rockets/?utm_source=ExecutiveBiz+Daily+RSS+Feed&utm_campaign=1aebbbb6aRSS_EMAIL_CAMPAIGN&utm_medium=email&utm_term=0_378117c9e8-1aebbb3b6a-81418273; accessed 8/16.

Arcadia, K., Mangabhai, D., and Akhtar, K., Chapter 9, Production of titanium by the Armstrong Process®, Titanium Powder Metallurgy. http://dx.doi.org/10.1016/B978-0-12-800054-0.00009-5, Elsevier Inc., 2015.

Armstrong, J. Scott, 2003, "Delphi-forcasters.com," http://armstrong.wharton.upenn.edu/delphi2/, accessed 9/16.

Bare, J. Clean, *TRACI 2.0: the tool for the reduction and assessment of chemical and other environmental impacts 2.0*, Techn Environ Policy (2011) 13: 687. https://doi-org.ezproxy.uta.edu/10.1007/s10098-010-0338-9.

Baumann, H., Tillman, Anne-Marie, The Hitch Hiker's Guide to LCA: An Orientation in life cycle assessment methodology and application, Studentlitteratur, 2004.

Bell, Lee, 2016, "Virgin Galactic SpaceShipTwo Gets FAA Approval," http://www.wired.co.uk/article/virgin-galactics-spaceshiptwo-gets-faa-approval, Original brief found in Aviation eBrief (AOPA); accessed 8/16.

Bennett, R.R., Hinshaw, J.C., Barnes, M.W, *The Effects of Chemical Propulsion on the Environment,* Aeta Astronautica Vol. 26, No. 7, pp. 531-541, 1992.

Blue Origin and 45th Space Wing, Patrick Air Force Base, Florida, Final Environmental Assessment Blue Origin Orbital Launch Site at Cape Canaveral Air Force Station, Florida, November 2016, http://www.patrick.af.mil/Portals/14/documents/Enviromental%20Documents/Final%20Environmental%20Assessment%20Blue%20Origin%20Orbtal%20Launch%20Site%20CCAFS.pdf?ver=2017-03-27-090038-627, accessed 11/17.

Bowden, J., Cantu, T., Scheidt, D., Lowers, R., Nocito, B,, Young, V., and Guillette, Jr., L., Examination of *Metals from Aerospace-Related Activity in Surface Water Samples from Sites Surrounding the Kennedy Space Center (KSC), Florida*, American Chemical Society publications, dx.dol.org/10.1021/es4047796, Environ. Sci. Technol. 2014, 48, 4672-4680.

Bowman, C.R., J.R. Bjorklund, and J.E. Rafferty, User's manual for the revised REEDM (Rocket Exhaust Effluent Diffusion Model) computer program for launches at Kennedy Space Center. Volume 1. TR-84-157-02. Prepared by H.E. Cramer Co., Salt Lake City, Utah for Eastern Space and Missile Center, Patrick Air Force Base, Florida, 1984.

Brady, B.B., Martin, L.R, and Lang, V.I., *Effects of Launch Vehicle Emissions in the Stratosphere, Journal of Spacecraft and Rockets*, Vol. 34, No.6, November-December 1997.

Brown, H., Hamel, B., Hedman, B., Energy Analysis of 108 Industrial Processes, Prentice-Hall, Inc., 1996.

Burkhardt, H., Sippel, M., Herbertz, A., and Klevanski, J., *Comparative Study of Kerosene and Methane Propellant Engines for Reusable Rocket Booster Stages*, 4th International Conference on Launcher Technology "Space Launcher Liquid Propulsion," 2002.

Carlton R., Hall P. A., Schmalzer ,D. R., Breininger, B. W., Duncan, J.H., Drese, D. A., Scheidt, R. H., Lowers E. A., Reyier, K. G., Holloway-Adkins, D. M., Oddy Naresa, R., Cancro, J. A., Provancha, T. E., Foster, Stolen, E. D., Ecological Impacts of the Space Shuttle Program at John F. Kennedy Space Center, Florida, Contract NASA/TM-2014–216639, 2014.

Chytka, T.M., Brown, R.W., Shih, A.T., Reeves, J.D., and Dempsey, A. J, *An Integrated Approach to Life Cycle Analysis*, American Institute of Aeronautics and Astronautics, AIAA Paper 2006-7027, 2006.

Cirucci, John, Personal Communications with independent contractor, Principal, Spatial Analytics; Lehigh Valley PA, 2016.

Commercial Space Launch Act, 51 U.S.C. Ch. 509 and other amendments, 2015, http://uscode.house.gov/view.xhtml?path=/prelim@title51/subtitle5/chapter509&edition=prelim

Commercial Space Transportation Competitiveness Act, 2015, http://www.faa.gov/about/office_org/headquarters_offices/ast/media/US-Commercial-Space-Launch-Competitiveness-Act-2015.pdf (PDF).

Curran, Mary, 2011, EPA's Computational Toxicology Communities of Practice Series: Using Life Cycle Assessment for Risk Management https://www.epa.gov/sites/production/files/2014-08/documents/using_lca_for_rm_comptox_cop_series_curran_042811.pdf (PDF), accessed 8/16.

Curran, Mary Ann, Editor, Life Cycle Assessment Handbook: A Guide for Environmentally Sustainable Products, Scriver Publishing, Beverly, MA, 2012.

David, Leonard. 2016. "Spacecraft Powered by 'Green' Propellant to Launch in 2017."http://www.space.com/32567-nasa-green-propellant-mission-gpim.html, accessed 8/16.

Darrieu, S., Nelson, R.F., *Earth observation from space-The issue of environmental sustainability*, Space Policy 29 (2013), p. 246.

Delta IV Heavy image, Delta IV Launch Services Users Guide, June 2013. https://web.archive.org/web/20131014123330/http://www.ulalaunch.com/site/docs/product_cards/guides/Delta%20IV%20Users%20Guide%20June%202013.pdf., accessed 3/16.

Department of Defense (DoD), 2014, Department of Defense Guidance, "Integrating Sustainability into DoD Acquisitions, Version 2.0-Draft," www.denix.osd.mil/.../Draft-DoD-Sustainability-Analysis-Guidance.pdf (PDF), accessed 2/16.

DoD, 2016, DoD Sustainability Analysis Guidance, Environmental, Safety and Occupational Health (ESOH) website, http://www.denix.osd.mil/esohacq/home/, accessed 8/16.

Department of Energy (DOE), 2016, Draft Report Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Titanium, https://energy.gov/sites/prod/files/2016/04/f30/Titanium%20Report%20031816.pdf, accessed 2/18.

Eccleston, C., Integrating a Life-Cycle Assessment with NEPA: Does it Make Sense?, prepared for Department of Energy, HNF-3105-FP, https://onlinelibrary.wiley.com/doi/abs/10.1002/tqem.3310080306, 2007, https://doi.org/10.1002/tqem.3310080306, accessed 8/16.

Environmental Protection Agency, 2017, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015; Chapters 1-6; accessed 02/2018.

European Space Agency, Webex video telecon with Julian Austin and Jakob Huesing on 28 March 2016 and other conversations through email, Personal communications.

European Space Agency, 2013, “Clean Space Eco-Design Pamphlet,” http://www.esa.int/Our_Activities/Space_Engineering_Technology/Clean_Space/Eco-design/(print); accessed 06/15.

European Space Agency, Science and Technology, 2012, “Cycle of Life Diagram,” http://www.esa.int/Our_Activities/Space_Engineering_Technology/Cycle_of_life; accessed 6/15.

European Space Agency (ESA), 2016, Jakob Heusing and Julian Austin, Personal Communication, March 2016.

Executive Biz, 2016, NASA Awards 2nd ISS Crew Mission Task Order to SpaceX, http://blog.executivebiz.com/2016/08/nasa-awards-2nd-iss-crew-mission-task-order-to-spacex-gwynne-shotwell-julie-robinson-comment/?utm_source=GovConWire+6AM&utm_campaign=b21e8edf0f-GovConWire_6am_Daily_News10_1_2014&utm_medium=email&utm_term=0_92fa6d4f58-b21e8edf0f-81418261; accessed 8/16.

Executive Government, 2016, “NASA Space Launch Systems 1st Exploration Mission Remains on Track for Fall 2018”, http://www.executivegov.com/2016/07/nasa-space-launch-systems-1st-exploration-mission-remains-on-track-for-fall-2018/?utm_source=ExecutiveBiz+Daily+RSS+Feed&utm_campaign=114337b82b-RSS_EMAIL_CAMPAIGN&utm_medium=email&utm_term=0_378117c9e8-114337b82b-81418273; accessed 8/16.

Executive Biz, 2016, “ULA Launches NROs National Defense Payload Aboard Atlas V Rocket,” http://blog.executivebiz.com/2016/07/ula-launches-nros-national-defense-payload-aboard-atlas-v-rocket/?utm_source=ExecutiveBiz+Daily+RSS+Feed&utm_campaign=c363258091-RSS_EMAIL_CAMPAIGN&utm_medium=email&utm_term=0_378117c9e8-c363258091-81418273; accessed 8/16.

Federal Aviation Administration (FAA), 2011, “Office of Commercial Space Environmental Policy,” http://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/media/AST%20ENVIRONMENTAL%20POLICY.pdf (PDF), accessed 8/16.

Federal Aviation Administration (FAA), 2015, Headquarters Offices-Office of Commercial Space, http://www.faa.gov/about/office_org/headquarters_offices/ast/about/ accessed 6/15.

Federal Aviation Administration, 2014, “U.S. Space Transportation Industry,” http://www.faa.gov/about/office_org/headquarters_offices/ast/industry/media/private_company_org.gif, accessed 8/16.

Federal Aviation Administration, 2016, “Annual Federal Aviation Administration Commercial Space Compendium: 2016”; http://www.faa.gov/about/office_org/headquarters_offices/ast/media/2016_Compendium.pdf (PDF), p. 1-3, 9, accessed 8/16.

FAA, 2016, “Office of Commercial Space Transportation Environmental Programs, NEPA documents,” Adoption of the Environmental Assessment and Finding of No Significant Impact for Boost-back and Landing of the Falcon 9 Full Thrust First Stage at SLC-4 West at Vandenberg Air Force Base, California and Offshore Landing Contingency Option, http://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/ accessed 8/16.

FAA, 2016, “Office of Commercial Space Transportation Environmental Programs, NEPA Documents,” https://www.faa.gov/about/office_org/headquarters_offices/ast/environmental/nepa_docs/review/launch/spacex_texas_launch_site_environmental_impact_statement/media/FEIS_SpaceX_Texas_Launch_Site_Vol_I.pdf., 4-79-80, accessed 1/17.

FAA, 2018, “Annual Federal Aviation Administration Commercial Space Compendium: 2018”; https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2018_AST_Compendium.pdf (PDF), accessed 2/18.

Foust, Jeff, 2016, “SpaceX Performs First Test of Raptor Engine,” http://spacenews.com/spacex-performs-first-test-of-raptor-engine/, accessed 3/18.

Freedom of Information Act (FOIA) response, Valliere, S. and Duce, A., 45th Space Wing, Cape Canaveral AFS, FL, “Electricity and Water Consumption for Launch Facilities at CCAFS,” Sep 2016.

Friedenthal, S., Moore, A., Steiner, R., A Practical Guide to SysML (The Systems Modeling Language), 3rd Ed., Morgan Kaufman (Elsevier), Waltham Ma, 2015; p. 115.

General Launch Campaign Activities figure, images found in yahoo search for launch campaign, SpaceX official website, Flicker.com, NASA.gov, accessed 1/18.

Griffin, M.D., French, J.R., Space Vehicle Design, 2nd Ed., American Institute of Aeronautics and Astronautics, Inc. Reston, Va, 2004.

Gruss, Michael, 2015, “SpaceX Leasing Second Pad at Vandenberg,” http://spacenews.com/spacex-leasing-second-pad-at-vandenberg/, accessed 8/16.

Hall, C.R., Schmalzer, P.A., Breininger, D.R., Brean, W.D., Drese, J.H, Scheidt, D.A., Lowers, R.H., Reyier, E.A., Holloway-Adkins, K.G, Oddy, D.M., Cancro, N.R, Provancha, J.A, Foster, T.E., Stolen, E.D InoMedic Health Applications, Inc. Kennedy Space Center, Florida, Ecological Impacts of the Space Shuttle Program at John F. Kennedy Space Center, Florida, NASA/TM-2014–216639, 2014, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20140012489.pdf (PDF), accessed 9/16.

Hamby, D.M., *A Review of Techniques for Parameter Sensitivity Analysis of Environmental Models*, Env Monitoring and Assessment 32:135-154, 1994.

Haynes, Jeff, Aeroject Rocketdyne, Program Manager, personal communications on 3-D printing work with Air Force Research Laboratory, May 2017.

Huesing, J. and Austin, J., European Space Agency Clean Space Design, Systems Engineers, personal communications, correspondence and discussions, 2015-2017.

Huzel, D., and Huang, D., Modern Engineering for Design of Liquid-Propellant Rocket Engines, American Institute of Aeronautics and Astronautics, Inc., Rocketdyne Division of Rockwell International, ISBN 1-56347-013-6,1992.

Jolliet, O., Margni, M., Charles, R. et al., *IMPACT 2002+: A New Life Cycle Impact Assessment Methodology*, Int J LCA (2003) 8: 324. https://doi-org.ezproxy.uta.edu/10.1007/BF02978505, accessed 1/18.

International Council on Systems Engineering (INCOSE), Systems Engineering Handbook: A Guide for System Life Cycle Processes and Activities, p. 25, 26, 2011.

International Organization for Standardardization (ISO), Environmental management – Life cycle assessment - Principles and framework (ISO 14040:2006) print.

International Organization for Standardardization (ISO), Environmental management – Life cycle assessment – Requirements and Guidelines (ISO 14044:2006) print.

Jackman, C.H., Considine, D. B., Fleming, E.L., *Space Shuttle's Impact on Stratosphere an Update*, Journal of Geophysical Research 101(D7) 12523-12529, 1996.

Johnson, C. C. (2012). *Environmental life cycle criteria for making decisions about green versus toxic propellant selections* (Order No. 3503549). Available from ProQuest Dissertations & Theses Global. (1009896335). Retrieved from https://login.ezproxy.uta.edu/login?url=http://search.proquest.com.ezproxy.uta.edu/docview/1009896335?accountid=7117; accessed 8/16.

Jones, A.E., Bekki, S. and Pyle, J.A., *One the atmospheric impact of launching the Ariane 5 rocket*, Journal of Geophysical Research, Vol. 100, No. D8, p. 16651-16660, 1995.

Klopffer, W., Grahl, B., Life Cycle Assessment: a guide to best practice, Wiley Publishing, 2014.

Lloyd, Shannon PhD, Personal Communication with contractor- Department of Defense, LCA practitioner, 2016.

Meier, A. J., Shah, M.G., Hintze, P.E., Ph.D., Muscatello, A.C., Ph.D., and Petersen, E., *Mars Atmospheric Conversion to Methane and Water: An Engineering Model of the Sabatier Reactor with Characterization of Ru/Al2O3 for Long Duration Use on Mars,* 47th International Conference on Environmental Systems, ICES-2017-161, Charleston, South Carolina, July 2017; accessed through NTRS on 3/18.

Mooring, Jr., Frank, 2016, "Blue Origin New Shephard Flies and Returns Third Time," http://aviationweek.com/space/blue-origin-new-shepard-flies-and-returns-third-time?NL=AW-05&Issue=AW-05_20160404_AW-05_771&sfvc4enews=42&cl=article_3&utm_rid=CPEN1000001793358&utm_campaign=5503&utm_medium=email&elq2=33f683be137547d4b17719fc839b0fd9; Original found in Aviation Week, accessed 8/16.

Murray, N., Bekki, S., Toumi, R., and Soares, T., *On the Uncertainties in Assessing the Atmospheric Effects of launchers,* Progress in Propulsion Physics 4, p. 671-688, 2013.

Musgrave, G., Larsen, A. M., Sgobba, Tommaso (editors) with numerous contributors, Safety Design for Space Systems, The International Association for the Advancement of Space Safety, Butterworth-Heinemann, Elsevier Ltd, 2009.

Musk, Elon, 2017, "Tweet about titanium used for grid fins," https://twitter.com/elonmusk/status/878821062326198272, accessed 3/18.

National Aeronautics and Space Administration (NASA), 2004, Archived news reports, "President Busch Announces New Vision for Space Exploration Program," http://www.history.nasa.gov/Bush%20SEP.htm; accessed 8/16.

NASA, 2004, Archived NASA reports, "President Bush Offers New Vision for NASA," http://www.nasa.gov/missions/solarsystem/bush_vision.html, accessed 8/16.

NASA, 2014, "NASA Collaborations for Commercial Space Capabilities," http://www.nasa.gov/content/collaborations-for-commercial-space-capabilities-ccsc ; accessed 8/16.

NASA, 2014, "NASA Collaborations for Commercial Space Capabilities-Space Act Agreement –SAA-QA-14-18881, ATK, " https://www.nasa.gov/sites/default/files/atoms/files/saa-qa-14-18881-atk-baseline-12-18-14-redacted_0.pdf; accessed 8/16.

National Aeronautics and Space Administration (NASA), 2016, "Materials and Processes Technical Information System," http://maptis.nasa.gov/; accessed 8/16.

NASA Headquarters, Sam I. Higuchi, Personal communication, discussions, and emails 07/16 and 08/16.

NASA Headquarters, 2012, "Space Debris Webpage," Policies and Standards, http://www.hq.nasa.gov/office/hqlibrary/pathfinders/debris.htm, accessed 9/16.

NASA, 2013, "Green Propellant Infusion Mission Project Fact Sheet," http://www.nasa.gov/sites/default/files/files/Green-Propellant-Infusion-Mission-Project_-Fact-Sheet.pdf; accessed 8/16.

NASA, 2012, "Space Debris," http://www.hq.nasa.gov/office/hqlibrary/pathfinders/debris.htm, accessed 8/16.

NASA, 2016, "Cost Analysis Division Website," https://www.nasa.gov/offices/ooe/CAD/#.V73In5grKUl, accessed 8/16.

NASA, Space Launch System Info, https://www.nasa.gov/exploration/systems/sls/index/html, accessed 3/18.

NASA , Final Environmental Assessment for Multi-use of Launch Pads 39A and 39B, John F. Kennedy Space Center, Florida, http://www.patrick.af.mil/Portals/14/documents/NASA%20FInal%20Use%20Multi%20Use%20EA.pdf?ver=2017-05-22-143217-433, accessed 11/2017.

NASA, Cory Huston graphics of Launch Complexes 39A and 39B used in generic tasks, http://www-pao.ksc.nasa.gov/kscpao/images//large/06pd0390.jpg, Public Domain, https://commons.wikimedia.org/w/index.php?curid=2839076, accessed 2/18.

NASA, 2015, "NASA Cost Estimating Handbook Version 4.0," https://www.nasa.gov/offices/ooe/CAD/nasa-cost-estimating-handbook-ceh/#.V7242o-cGUk, accessed 8/16.

National Aeronautical Space Administration (NASA), 2007, "NASA Systems Engineering Handbook," http://www.acq.osd.mil/se/docs/NASA-SP-2007-6105-Rev-1-Final-31Dec2007.pdf (PDF), accessed 9/16.

NASA Goddard, Kelly Busquets, P.E., Goddard Sustainability manager, Personal communication and correspondence, 2016-2018.

NASA, Kennedy Space Center (KSC), 2016 , "KSC Next Gen Site – The Life Cycle Cost Model Data, References," http://science.ksc.nasa.gov/shuttle/nexgen/Misc_No_Link_to_Mains/Indexed/LCC_Model/, updated frequently by Edgar Zapata, accessed 9/16.

NASA, Kennedy Space Center (KSC), Edgar Zapata, Personal Communication, several emails, August 2015-June 2016. Provided key website with life cycle cost information.

NASA, 2016, "National Technical Reports Server" Database, http://ntrs.nasa.gov/, accessed 9/16.

NASA, 2007, NASA Systems Engineering Handbook – NASA/SP-2007-6105, Rev1, http://www.nasa.gov/sites/default/files/atoms/files/nasa_systems_engineering_handbook.pdf (PDF); accessed 8/15.

NASA Langley Research Center, Jordan J. Klovstad, Space Mission Analysis Branch, Systems Analysis and Concepts Directorate, Personal Communication, 2016.

NASA Wallops Flight Facility, Shari A. Miller, Environmental Planning Lead, Personal communication and correspondence, 2015-2018.

NASA, Launch Complexes 39-A and 39-B, Discussion of the launch complex infrastructure, http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/sts-lc39.html, accessed 10/2016.

National Aeronautics and Space Administration (NASA), 2015, "NASA Technology Roadmaps," www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_1_launch_propulsion_systems_final.pdf, accessed 7/16.

National Institute of Standards and Technology (NIST), 2016, NIST Data and Resources, https://www.nist.gov/data, accessed 9/16.

National Renewable Energy Laboratory (NREL), U.S. Life Cycle Inventory Database." (2012). National Renewable Energy Laboratory, 2012. Accessed November 19, 2012: https://www.lcacommons.gov/nrel/search, accessed 9/16.

National Security Presidential Directive, 2004, U.S. Space Transportation Policy, http://fas.org/irp/offdocs/nspd/nspd-40.pdf (PDF), accessed 8/16.

Nix, M. B. (2005). *Development and application of a model for the analysis of trades between space launch system operations and acquisition costs* (Order No. 3164871). Available from ProQuest Dissertations & Theses Global. (305396129). Retrieved from https://login.ezproxy.uta.edu/login?url=http://search.proquest.com.ezproxy.uta.edu/docview/305396129?accountid=7117, accessed 8/16.

Pasztor, Andy, 2016, FAA Grants Virgin Galactic Approval to Resume Testing Rocket Plane, http://www.wsj.com/articles/faa-grants-virgin-galactic-approval-to-resume-testing-rocket-plane-1470088113; Original brief found in Aviation eBrief (AOPA); accessed 8/16.

Peels, Joris, "Aerojet Rocketdyne 3-D Printing," https://3dprint.com/171453/aerojet-rocketdyne-3d-printing, accessed 2/18.

Pelton, J.N., Jakhu, R.S., (editors) with numerous contributors, Space Safety Regulations and Standards, Butterworth-Heinemann, Elsevier Ltd, 2010.

Public Law, 2004, Public Law 108-428, https://www.congress.gov/108/plaws/publ428/PLAW-108publ428.pdf (PDF), accessed 8/16.

Qian, Ma and Froes, Frances (editors) with numerous contributors, Titanium Powder Metallurgy, Butterworth Heinemann, ISBN: 0-12-800054-6, 978-0-12-800054-0, Araci, K., Mangabhai, D., Akhtar, K., Chapter 9 "Production of Titanium by the Armstrong Process®, 2015.

RAND, 2015, "Delphi Method," http://www.rand.org/topics/delphi-method.html, accessed 9/16.

Rose, Mary A, 2009, "Impacts of Technology on the Environment," EnviroTech, http://envirotech.iweb.bsu.edu/instruction/LCA_Rose_April.pdf (PDF), accessed 6/16.

Ross, M., Toohey, D., Peinemann, M., Ross, P., *Limits on the space launch market related to stratospheric ozone depletion*, Astropolitics 7:1, 50-82, 2009.

Roust, Jeff, http://spacenews.com/relativity-space-aims-to-3d-print-entire-launch-vehicles/, accessed 1/18.

Russell, R., 2011, "University Corporation of Atmospheric Research, Troposphere Overview," http://scied.ucar.edu/shortcontent/troposphere-overview, accessed 9/16.

Sackheim, R.L, Masse, R.K., *Green Propulsion Advancement: Challenging the Maturity of Monopropellant Hydrazine*, Journal of Propulsion and Power, Vol 30, No. 2, p. 265-276, 2014.

James, M., and Saltan, A, *Modeling community noise impacts from launch vehicle propulsion noise,* The Journal of the Acoustical Society of America 142, 2490 (2017)

Smith, S.D., Tevepaugh, J.A, and Penny, M.M., Space Shuttle SRM Plume Expansion Sensitivity Analysis, http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19760014193.pdf (PDF), Contract NASA NAS9-14517,1975, accessed 6/16.

Soares, T., Innocenti, L, and Cucci, A., *LCA for Environmental Impact Assessment of Space Systems – ESA's assessment of European Launchers*, 2012 International Workshop on Environment and Alternative Energy, 4-7 December 2012, received from ESA Eco Design on November 2016.

Spacepolicyonline.com, 2016, "Commercial Space Activities," http://www.spacepolicyonline.com/commercial, accessed 9/16.

Space Exploration Technologies (SpaceX) Corporation, Hawthorne, Ca and 45th Space Wing, Patrick Air Force Base, February 2017, Supplemental Environmental Assessment to the December 2014 EA for Space Exploration Technologies Vertical Landing of the Falcon Vehicle and Construction at Launch Complex 13 at Cape Canaveral Air Force Station Florida, http://www.patrick.af.mil/Portals/14/documents/3-27-2017%20Final%20SpaceX%20LZ-1%20SEA-2.pdf?ver=2017-03-27-150629-603, accessed 11/2017.

SpaceX, 2015, "Falcon 9 User's Guide, Revision 2.0," http://www.spacex.com/sites/spacex/files/falcon_9_users_guide_rev_2.0.pdf (PDF), accessed 8/16.

SpaceX, 2014, "SpaceX Media- Falcon 9 Orbcomm Launch Hangar 0," http://www.spacex.com/media-gallery/detail/116286/3496, accessed 9/16.

SpaceX, SpaceX Launches 3D printed part into space creates printed engine chamber, SpaceX website, http://www.spacex.com/news/2014/07/31/spacex-launches-3d-printed-part-space-creates-printed-engine-chamber-crewed, accessed 3/18.

Sutton, G.P., Biblarz, O., Rocket Propulsion Element, 8th Ed., Wiley & Sons, Inc., USA, 2010.

United Launch Alliance, 2013, "Delta IV User's Guide," http://www.ulalaunch.com/uploads/docs/Launch_Vehicles/Delta_IV_Users_Guide_June_2013.pdf (PDF), accessed 9/15.

United States Air Force Life Cycle Management Center (AFLCMC), Discussions with Michael J. Stock and Mark Smallwood, 2015-2016, Personal communications, http://www.wpafb.af.mil/Portals/60/documents/lcmc/LCMC-Revolution-in-Acquisition.pdf?ver=2016-07-01-110338-350, accessed 8/16.

U.S. Air Force Civil Engineering Center, Kathleen Gerber, AFCEC/CZOW EDWARDS IST, Restoration Program Manager, Vandenberg AFB, Personal Communication, 2016.

U.S. Air Force Civil Engineering Center, John Langett, Installation Restoration Program, Patrick Installation Support Team, Personal Communication, 2016.

U.S. Air Force Civil Engineering Squadron, Cape Canaveral Air Force Station, Michael Blaylock, Chief, Environmental Conservation, Personal Communication, 2015.

U.S. Air Force, Vandenberg Air Force Base, NEPA Document, California, Final Supplemental Environmental Assessment Boost-Back and Landing of the Falcon 9 Full Thrust First Stage at Iridium Landing Area Vandenberg Air Force Base, California and Offshore Landing Contingency Option 20 September 2016, http://www.vandenberg.af.mil/Portals/18/documents/Environmental/SpaceX_Boostback_Iridium%20Final%20SEA_FONSI.pdf?ver=2017-12-20-174730-187, accessed 11/2017.

U.S. Code, Title 51, 2011, "Chapter 509-Commercial Space Launch Activities," http://uscode.house.gov/view.xhtml?path=/prelim@title51/subtitle5/chapter509&edition=prelim, accessed 8/16.

U.S. Congress, 2004, H.R.-3752 Commercial Space Launch Act Amendments of 2004, https://www.congress.gov/bill/108th-congress/house-bill/3752, accessed 8/16.

U.S. Environmental Protection Agency (EPA), Life Cycle Assessment: Inventory Guidelines and Principles, EPA/600/R-92/245, Office of Research and Development, Cincinnati, Ohio, USA, 1993.

U.S. Environmental Protection Agency, Tool for Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI): User's Guide and Documentation, EPA/R-02/052, National Risk Management Research Laboratory, Cincinnati, Ohio, 2003.

U.S. Environmental Protection Agency, 2012, "Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts," https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci, accessed 9/16.

U.S. EPA (United States Environmental Protection Agency). 2006. Air quality criteria for ozone and related photochemical oxidants. EPA/600/R-05/004aF-cF. Research Triangle Park, NC. http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=149923; accessed 1/18.

U.S. Government Accountability Office (GAO), *COMMERCIAL SPACE Industry Developments and FAA Challenges;* Statement of Gerald L. Dillingham, Ph.D., Director, Physical Infrastructure Issues; Statement to House of Representatives, 2016.

U.S. Law, 2015, U.S. Commercial Space Launch Competitiveness Act, http://www.faa.gov/about/office_org/headquarters_offices/ast/media/US-Commercial-Space-Launch-Competitiveness-Act-2015.pdf (PDF), accessed 8/16.

U.S. Space transportation Policy, 2013, "National Space Transportation Policy," https://www.whitehouse.gov/sites/default/files/microsites/ostp/national_space_transportation_policy_11212013.pdf (PDF), accessed 8/16.

University of Texas at Arlington (UTA), Dr. Melanie Sattler, P.E., Personal Communication and presentation materials on LCA framework, 2015.

Virgin Galactic, 2015, "Human Space Flight," http://www.virgingalactic.com/human- spaceflight/, accessed 8/16.

White House, 2013, "National Space Transportation Policy," https://www.whitehouse.gov/sites/default/files/microsites/ostp/national_space_transportation_policy_11212013.pdf (PDF).

White House Press, 2004, George W. Bush, Archives, http://georgewbush-whitehouse.archives.gov/news/releases/2004/01/20040114-3.html; accessed 8/16.

Wikipedia was used for various information sources, liquid hydrogen, liquid oxygen, RP-1, methane, liquefied natural gas, delta IV heavy, Falcon Heavy, New Glenn, Raptor engine, diesel, etc., https://en.wikipedia.org/wiki/[name listed above], accessed 3/18.

Wilson, Andrew, Maury, Thibaut, International PhD students (Scotland, France) collaborating on CST LCA research lessons learned, Personal Communications, on-going SKYPE and email, 2016.

Zapata, Edgar, NASA-KSC, 2016, "NASA State of Play – US Space Systems 2016 Presentation," http://science.ksc.nasa.gov/shuttle/nexgen/Misc_No_Link_to_Mains/Indexed/LCC_Model/State_of_Play-US_Space_Systems-2016_07-29.pdf (PDF), accessed 8/16.

Zapata, E., NASA-KSC, Life Cycle Cost Analysis and Assessment, Engineer, personal communications, emails and discussions, 6/2015- 3/2018.

Biographical Information

Shelia Scott Neumann has earned a doctorate in environmental engineering, masters of science in mechanical engineering, and a bachelor of science in chemical engineering. Dr. Neumann has served in the United States Air Force as a Bioenvironmental Engineer for 20 years and served in federal government service with US Army Corps of Engineers as an environmental engineer and Federal Bureau of Investigation and Department of Homeland Security as a Senior Intelligence Analyst.

Ms. Neumann's key projects were Iraqi Freedom intelligence support to CENTCOM on chemical warfare assessments and medical intelligence at Defense Intelligence Agency; invented new health and environmental test and evaluation discipline for developmental aircraft such F-22, B-2 and F-35 for 412th Test Wing; program manager of $83 million in engineering contracts for Superfund cleanup sites in Space Command and Pacific Air Forces at Air Force Center for Environmental Excellence; developed wastewater characterization methodology and operation plan for Occupational and Environmental Health Laboratory; first woman engineer at Dalecarlia Water Treatment Plant for US Army Corps of Engineers; and developed an intelligence Red Cell Analysis methodology and analysis paper.

Ms. Neumann would like to apply her education and experience in developing new ways to solve problems and develop practical solutions either in the environmental engineering or intelligence analysis disciplines. Also, to mentor, teach or instruct the next generation and build teams motivated to increase knowledge and use creativity and innovation for problem-solving to enhance the sphere of influence we live in.