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The Aviation Fuel Life Cycle Assessment Working Group
For
Universal Technology Corporation

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Interim Report

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14. ABSTRACT

The purpose of this report is to provide a framework and guidance for estimating the life cycle greenhouse gas emissions for transportation fuels, specifically aviation fuels. The focus on aviation fuels was driven by the patterns of fuel use by the federal government. Policies such as those outlined in Section 526 of EISA 2007 cause federal agencies to institute enforceable guidelines for procuring low carbon alternative fuels. Federal consumption of fuels is dominated by the Department of Defense and the Air Force consumes more fuel than any of the other military services or federal agencies (Defense Science Board 2008). Thus, aviation applications may become early adopters of low carbon transportation fuels.

The U.S. Air Force convened a working group of individuals from government agencies, universities and companies actively engaged in assessing greenhouse gas emissions from transportation fuels, and requested that this group develop guidance on procedures for estimating greenhouse gas emissions in aviation applications, using currently available data and tools.

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TABLE OF CONTENTS

Section **Page**

LIST OF FIGURES vi

LIST OF TABLES viii

1.0 EXECUTIVE SUMMARY 1

2.0 INTRODUCTION 4

2.1 Background 4

2.2 Life Cycle Assessments 4

2.3 Characterizing Uncertainties in Life Cycle Assessment of Transportation Fuels 6

2.4 Models in Environment Regulatory Decision-Making 7

2.5 Framework and Guidance for Estimating Life Cycle Greenhouse Gas Emissions for Aviation Fuels in the Context of Section 526 of EISA 2007 8

3.0 GUIDING PRINCIPLES AND FUNCTIONAL UNITS 10

3.1 Setting the Stage 10

3.2 Types of LCAs 11

3.2.1 Average vs. Marginal LCA 11

3.2.2 Attributional vs. Consequential LCAs 11

3.2.3 Levels of Resolution 12

3.3 Goals and Scope Definition 12

3.3.1 Programmatic Goals for Alternative Jet Fuels 12

3.3.2 Conventional Petroleum-Based Fuels: A Baseline for Comparison 13

3.3.3 LCA Study Goal and Scope Definition 14

3.4 The Primary Fuel Process Chain 16

3.4.1 Defining Life-Cycle Stages 16

3.4.2 Life-Cycle Boundaries 16

3.4.3 Example Primary Production Chains 17

3.5 Examining the Life Cycle Stages 21

3.5.1 Primary Production Chain Inventory Modeling 21

3.5.2 System Boundary 22

3.5.3 Disaggregation, System Expansion, and Allocation 22

3.5.4 Inventory Data 23

3.6 Scope Definition Parameters 24

3.7 Combustion Emissions (Tank-to-Wake) 24
3.8 Functional Unit and Reference Flows 29
4.0 SYSTEM BOUNDARY DEFINITION AND ANALYSIS 31
4.1 Background 31
4.2 System Boundary Determination Approaches 31
4.3 Quantitative Process-Based Approaches to Boundary Definition Using Cutoff Criteria 31
4.3.1 The ISO 31
4.3.2 Critique of Cutoff Criteria Approaches to Boundary Definition 33
4.4 Input-Output (IO) Based Approaches to Boundary Definition 33
4.5 System Boundary Guidance 34
4.6 Recommended Method Details 35
4.7 Characterization of the Primary Process Chain 36
4.7.1 Identification of the Initial System Boundaries/First Order Processes 37
4.8 Characterization of Second Order/Secondary Processes 39
4.9 Identification of Surrogate Higher Order Process Information 41
4.10 Surrogate Data Example 42
4.11 Modeling GHG Emissions For Indirect Land Use Change 43
4.11.1 Background 43
4.11.2 LUC Illustrative Example 44
4.11.3 Matching Methodological Assumptions For System Boundary Definition 52
4.11.4 Recommended Steps For Modeling GHG Emissions For Indirect Land Use Change 53
4.11.5 References 54
4.12 Unit Process Exclusions 55
5.0 APPROPRIATE MANAGEMENT OF CO-PRODUCTS 56
5.1 Background 56
5.2 Methods for Allocating Inputs and Outputs Among Co-Products 56
5.2.1 Allocation by Mass, Energy, or Economic Value of Co-Products 56
5.2.2 Disaggregation 57
5.2.3 Expansion of System Boundaries 57
5.3 Discussion of Approaches 58
5.3.1 Discussion of Allocation by Measures Such as Mass, Energy or Value 58
5.4 Discussion of Disaggregation 60
5.5 Discussion of Displacement 62

5.5.1 Completeness of the Displacement 62
5.5.2 Identification of Substitute Production Processes 64
5.5.3 Displacement Uniqueness 64
5.5.4 System Boundary Consistency 64
5.5.5 Time Dependence 64
5.5.6 Consistency With Other GHG Protocols 64
5.6 Guidance for Attribution and Allocation 65
6.0 DOCUMENTING DATA QUALITY AND UNCERTAINTY 70
6.1 Background 70
6.2 Data Quality 70
6.3 Data Sources, Types, and Aggregation 71
6.4 Dealing With Confidential Data 72
6.5 Assessing and Documenting LCA Quality 72
6.6 Assessing Data Quality 74
6.7 Model Uncertainty 79
6.8 Scenario Uncertainty 81
6.9 Documenting LCA Study Quality and Known Data Limitations 83
6.10 Data Limitations 83
6.11 Data Quality Assessment 84
6.12 Minimum Guidelines for Reporting Comparative LCA Results 85
7.0 CONCLUSIONS 88
APPENDIX A
List of Attendees 90
APPENDIX B
IPCC Global Warming Potentials 91
BIBLIOGRAPHY 94
LIST OF ACRONYMS 100
GLOSSARY 103

LIST OF FIGURES

Figure **Page**

1. Greenhouse Gas Emissions (expressed as Global Warming Potential in Units of Equivalent CO_2 Emissions) for 13 Different Assessments of the Well to Tank Emissions for Diesel Fuel Production (Skone and Gerdes 2008) 6

2. Three Objectives That Need to be Balanced With Alternative Fuels 10

3. Simplified Schematic of a Life Cycle Primary Production Chain for a Petroleum-Based Aviation Fuels 18

4. Simplified Schematic of Life Cycles Stages for the Primary Production Chain of a Conventional Bio-Oil to Jet Fuel 18

5. Simplified Schematic of Life Cycle Stages for the Primary Production Chain of a CBTL-Based Jet Fuel Production Chain 19

6. Simplified Schematic f Life Cycle Stages for the Primary Production Chain of an Algae-Derived Bio-Oil to Jet Fuel 20

7. Simplified Schematic of Life Cycle Stages for the Primary Production Chain of a Jet Fuel Created From a Blend of Petroleum-Derived Jet Fuel Stock and a Bio-Derived Jet Fuel Stock 21

8. System Boundary Decision Flow 36

9. Simplified Process Schematic Defining First and Second Order Process Flows 40

10. Second Order Process Flows in Algae Production 41

11. Market Interactions and the Scope of the Example Biojet LCA 46

12. Example Indirect LUC GHG Emissions (Per Indirect Ha Converted From Forest to *the new crop mix*) 48

13. Example Project Life Cycle GHG Emissions: Per mmBTU (30.4 Liters) Produced Per Year 50

14. Cumulative Net Jet GHG Emissions With Variation in the Life Cycle Biojet Production GHG Emissions: Per mmBTU (30.4 Liters) Produced Per Year From 2010-2040 51

15. Processes With More Than One Product Require Decisions About How the Inputs and Outputs of the Process are to be Allocated to Each Product 56

16. Disaggregation Into Sub-Processes May Reveal Additional Insight Into Co-Product Allocations 57

17. An Alternate Process That Produces Product 2 That is the Same as, or Can be Used as a Substitute for, the Co-Product 2 58

18. Tracking the Flow of Products Through Specific Unit Operations at the Refinery Allows Some Disaggregation of the Inputs and Outputs Among Products and Eliminates Some of the Need for Allocation (Derived From (Skone and Gerdes 2008)) 61

19. Illustration of the Process for Developing an Allocation Approach for a Product System .. 66

20. Process for Assessing and Documenting Uncertainty in LCA 73

21. Process for Assessing and Documenting Data Uncertainty 74
22. Process for Assessing and Documenting Model Uncertainty 80
23. Process for Assessing and Documenting Scenario Uncertainty 82

LIST OF TABLES

Table **Page**

1. Certification and Use Goals for the Commercial Aviation Sector (as Represented by CAAFI and the US Air Force) 13

2. Definition of Life Cycle Goal for Alternative Aviation Production/Consumption Chains 15

3. Example of an Alternative Aviation Fuel Life Cycle Greenhouse Gas Study Design 24

4. Compositional Properties and Emissions Indices (EI) for CO_2, H_2O, and SO_x 25

5. Uncertainties, Gaps, and Issues for the Use of GWP to Examine Emissions From Aviation That Impact Global Climate Change. (Wuebbles, Yang and Herman 2008) 28

6. Commercial and Military Jet Fuel Standards for the United States, United Kingdom and Canada 29

7. Global Warming Potential of Greenhouse Gases (IPCC, 2007) 30

8. Life Cycle Stage Descriptions 38

9. CTL Process Primary Inputs and Outputs 39

10. Indirect Land Use Assumptions Used in the Example (For Illustrative Purposes Only) 45

11. GHG Emissions Associated With Indirect Land Conversion for the Biojet LCA Example (Per Indirect Ha Converted, See Table 12 for the Data and Equations Used) 47

12. Estimation of GHG Emissions for Indirect Land Conversion (Per Indirect Ha Converted) 48

13. Allocation of Emissions Between Soy Oil and Soybean Meal (Wong 2008) 59

14. Allocation Based on Mass, Energy and Value for a Refinery (Wang, Lee and Molberg 2004) 59

15. Allocation of Energy Use Based on Plant- and Process-Level Analyses of a Petroleum Refinery (Wang, Lee and Molberg 2004) 62

16. Allocation of GHG Emissions Between Soy Oil and Soybean Meal (Wong, 2008, Table 56) 63

17. Example Alternative Aviation Fuel Life Cycle Greenhouse Gas Study Design 70

18. Example Data Quality Matrix (Adapted From (Weidema and Wesnaes 1996)) 76

19. Data Quality Assessment of Study Methodology and Results (Adapted From (ISO 2006b)) 84

20. Example of Completed Data Quality Assessment of Study Methodology and Results 85

1.0 EXECUTIVE SUMMARY

A number of governmental agencies and non-governmental organizations have developed or are developing requirements for defining and regulating the emissions of greenhouse gases (GHG) resulting from the production, transport, and consumption of transportation fuels. This Framework and Guidance Document was developed specifically in response to the Energy Independence and Security Act (EISA) of 2007, enacted into law on December 19, 2007. EISA 7 placed a unique greenhouse gas emission requirement on all Federal agencies; specifically, Section 526 provides that:

> *No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility-related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources.*

In order for Federal agencies procurement of mobility-related fuels to be in compliance with Sec. 526 of EISA, producers of alternative and synthetic fuels must be able to demonstrate the fuel's GHG emissions is less than or equal to fuel produced from conventional petroleum sources. The first step is to establish GHG emissions baselines for conventional fuels produced from conventional petroleum sources. Once these baselines are established, producers of alternative and synthetic fuels can then determine if the fuel is Sec. 526 compliant.

To determine whether alternative and synthetic fuels are Sec. 526 compliant, the producer must assess all GHG emissions; from production field to vehicle fuel tank and from fuel tank to vehicle exhaust. This scope of emission assessment is commonly referred to as a "well-to-wheels", or in the case of aviation, a "well-to-wake" analysis. To ensure a standardized process for determining Sec. 526 compliance, Life Cycle Assessments (LCA) for both a baseline petroleum fuel and alternative fuels must be developed.

This Framework and Guidance Document was developed to define the LCA methodologies and data required for generating the emissions information on specific fuels at specific locations from defined feedstocks. The life cycle emissions analysis provides the quantitative information for the Defense Energy Support Center (DESC), or other agencies responsible for procurement, to assess compliance with Federal statute.

The U.S. Air Force is the largest user of aviation fuel in the Department of Defense and the lead agency for testing and certifying alternative fuels. In 4 Sep 2008, the AF convened a working group of individuals from diverse government agencies, universities, and corporations who are actively engaged in assessing greenhouse gas emissions from transportation fuels. Under the Air Force's leadership, this group developed this guidance on procedures for estimating greenhouse gas emissions in aviation applications. The working group met four times in the Fall of 2008 and the Spring of 2009 to define issues, review practices, and make recommendations. This report documents the findings and recommendations of the group.

Finding: Although there have been extensive analyses of the greenhouse gas emissions associated with petroleum based fuels and alternative fuels, there are still substantial uncertainties associated with these estimates. Even for well established fuel systems with extensive data availability, differences in excess of 10% are common in estimates of life cycle greenhouse gas emissions based on assumptions used in the analyses. Some uncertainties and modeling differences are much larger. In regulatory contexts, model uncertainties such as these are generally characterized by comparing model predictions to measurements. While the greenhouse gas emissions associated with the individual components of a life cycle are directly measurable, such as the emissions from a vehicle hauling fuel from refinery to market, many of the elements in the life cycle emissions of a fuel system are not directly measurable. Therefore, the collective emissions are not directly measurable. This makes evaluating greenhouse gas emissions a model-dependent exercise.

Recommendation: In developing greenhouse gas emission estimates, in addition to specifying the magnitude of the emissions, data and modeling details must be specified. The specifications should include methods used to determine what should be included in the analysis and what could be omitted (system boundaries), how processes producing multiple products (e.g., food and fuel) could be computationally handled, and how inventory data quality and uncertainty should be assessed.

Finding: Complying with EISA will require the comparison of life cycle greenhouse gas emissions associated with proposed synthetic and alternative fuels to an aviation fuel life cycle baseline; however, there is not currently an official aviation fuel baseline for comparison. Providers of both conventional and alternative fuels are using different data and methods to determine life cycle greenhouse gas emissions, leading to confusion by reviewers of the information. A baseline determined by using a standardized set of LCA methodology is required. Such a baseline is critical to the development of system boundaries for the development of comparative assessments of synthetic and alternative fuels under EISA consideration.

Recommendation: To facilitate comparative analyses of emissions required by EISA, a baseline for greenhouse gas emissions from aviation fuels derived from conventional petroleum sources must be developed. This baseline should describe the methodologies and the data used. It should be transparent in its data sources and should present uncertainty estimates. The baseline should also recognize that, as the sources of oil and the characteristics of oil production and refining change, greenhouse gas emissions are likely to change over time even for conventional petroleum fuels.,.

Finding: The evaluation of greenhouse gas emissions from alternative and synthetic fuels is likely to involve processes and modeling needs that are not included in the evaluation of fuels from petroleum based sources. These might include processes such as irrigation, fertilization, separation of materials such as algae oils from water, and conversion of land from one type of use to another, changing the carbon stored in the land.

Recommendation: Guidance for modeling anticipated processes for alternative fuels should be provided. Methodological guidance is needed in as many of these alternative fuel operations as can be anticipated, providing a framework for agencies responsible for procurement to assess compliance under EISA.

Recommendation: Once published use the framework document as a basis for a few case studies to help establish best practices for LCA analysis of jet fuels.

This report provides methodological guidance for the development of greenhouse gas emission estimation from aviation fuels and is based on the collective consensus of a working group with extensive experience in aviation fuels and LCAs. The methodological guidance is directed toward the analysts who will perform and interpret the LCAs of fuel systems. The methodological guidance addresses issues of system boundaries, allocation and data quality and the need for comprehensive analyses, transparency of methodologies and data, and well-characterized uncertainties. The work group anticipates this methodological guidance will evolve over time and the modeling of life cycle greenhouse gas emissions from transportation fuels will have its own life cycle. This report is intended as a first step toward a well documented and evolving approach to applying life cycle greenhouse gas emission models in a regulatory or contractual context.

2.0 INTRODUCTION

2.1 Background

Although there have been extensive analyses of the greenhouse gas emissions associated with petroleum based fuels and alternative fuels, there are still substantial uncertainties associated with some of the estimates of the greenhouse gas impacts of these fuel systems. Nevertheless, a variety of governmental agencies and non-governmental organizations are developing approaches for estimating or regulating the emissions of greenhouse gases associated with the production and use of transportation fuels. Specifically Congress included Section 526 in the EISA of 2007[1] that states:

> *No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility-related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources.*

In addition, a number of states are considering greenhouse gas emission regulations. For example, the California Global Warming Solutions Act of 2006[2] has resulted in draft regulations that establish a limit for life cycle greenhouse gas emissions of transportation fuels.

Both the California low carbon fuel standard and Section 526 of EISA require a life-cycle evaluation of the greenhouse gas emissions of transportation fuels, and this is becoming a common approach to considering greenhouse gas emissions. Employing a life cycle approach in estimating greenhouse gas emissions from the production and use of transportation fuels means assessing all emissions from field to the vehicle tank and from tank to vehicle exhaust. This scope of emissions assessment is frequently referred to as a “well-to-wheels”, or in the case of aviation, a “well-to-wake” analysis.

With the significant interest in both the Department of Defense (DOD) and the civil aviation community to purchase only alternative fuels that are in compliance with emerging greenhouse gas emission requirements, a consistent framework for conducting a LCA of greenhouse gas emissions must be developed to assure that candidate fuels are adequately evaluated for environmental compliance.

2.2 Life Cycle Assessments

There is some variability in LCA terminology, but the most widely accepted terminology has been codified by the International Standards Organization (ISO 14000 series of standards[3]) and international groups convened by the Society for Environmental Toxicology and Chemistry (SETAC) (see, for example, (Consoli, et al. 1993); (Allen, Consoli, et al. 1997)). Therefore, the terminologies employed by these organizations and governmental agencies, such as the California Air Resources Board, the U.S. Environmental Protection Agency, and the European Environment Agency, are employed in this report. Definitions of life cycle terminology are

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[1] HR 6, available at: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf
[2] AB 32, available at: http://www.leginfo.ca.gov/pub/05-06/bill/asm/ab_0001-0050/ab_32_bill_20060927_chaptered.pdf
[3] Available at: http://www.iso.org/iso/iso_14000_essentials

provided in the Glossary, so detailed explanations of commonly used terms will not be provided in the text of the report.

As applied to the estimation of greenhouse gas emissions from transportation fuels, the steps in a LCA are as follows ((Allen and Shonnard 2001), (ISO 2006a), (ISO 2006b)):

***Step 1*: Determine the goal and scope of the assessment.** Goal and scope definition articulates the intended application and scope of the LCA by defining what the system will produce and what processes and impacts will be studied. Multiple choices are made at this stage, which have the potential to significantly impact the results of the assessment. For example and depending on the study goal, an LCA can be scoped to quantify climate change impacts based on the heat released by a fuel (e.g. kg CO_2e/mmBTU or g CO_2e/MJ) or the distance traveled by a vehicle using the fuel (e.g., kg CO_2e/vehicle mile traveled). Further, an LCA can be based on greenhouse gas data representing the operation of a specific fuel refinery, or data representing the average operations of all refineries in a state, region, or nation. Also, the contribution to climate change might be estimated to include not only industrial and combustion related greenhouse gas emissions but also the implications of changes in land use at local, regional, national or global scales.

***Step 2*: Develop an inventory of the greenhouse gas emissions throughout the life cycle system.** In an LCA, inventory analysis prepares an account of inputs and outputs to the fuel production system based on the technologies applied. For example, inputs to the production system might include crude oil, iron ore, and water while outputs might include emissions of greenhouse gases. Again, multiple choices are made by the life cycle practitioner at this stage, which have the potential to significantly impact the results of the analysis. Among the sets of choices in inventory analysis are selecting time periods and spatial scales for data gathering, strategies for filling data gaps, and computational considerations for managing the variety of products produced by the processes within the system. An example of how the time period for data collection may influence the results of an inventory analysis is provided by considering the petroleum-based fuel greenhouse gas emission baseline as of 2005, pursuant to Title II, Subtitle A, Sec. 201 of EISA. In 2005, disruptions due to Hurricanes Katrina and Rita had substantial impacts on refining operations. Other years without these disruptions may have different greenhouse gas emission characteristics, suggesting that the choice of the year of data collection may be significant. Petroleum refining also provides an example of the impact of choices for managing the variety of products produced by the processes in the system. A simple example is the allocation selection methodology associated with analyzing the greenhouse gas emissions associated with a refinery unit operation such as the crude oil distillation unit. Specifically, petroleum entering a refinery is separated into lighter (e.g. gasoline) and heavier (e.g., lubrication oils, heavy (bunker) fuels) components in a distillation unit that consumes energy and consequently has greenhouse gas emissions. If the unit produces a pound of gasoline for every pound of bunker fuel, should the energy use and emissions from the unit be assigned equally to the two products? Should the assignment be based on the relative economic value or the relative heating values of the products? The choice can influence the results of the analysis, as demonstrated in case studies cited in Section 5.0.

***Step 3*: Assess the climate change impacts of the life cycle inventory.** For greenhouse gas emissions, assessment of global warming potentials (GWPs) is usually performed using factors developed by the Intergovernmental Panel on Climate Change (IPCC 2007)[4]; however, choices that influence results are still made in analyses at this stage. For example, it is recognized that the altitude at which emissions occur can influence climate change impacts. Depending on the assumptions made regarding GWPs of emissions at altitude, aviation fuels that have different emissions at altitude may have very different greenhouse gas emission profiles. This issue is described in more depth in Section 3.0.

Further, many LCAs consider only high volume emissions (e.g., emissions of CO_2, CH_4, and N_2O), omitting consideration of other greenhouse gas emissions and the influence of land use changes. As the scientific understanding of climate change is still developing, typical and simplifying assumptions can influence the results of the LCAs. Specifically, land use changes (e.g., those associated with crop-based fuels) can result in changes in the ability of soils to store carbon, changing carbon balances, resulting in changes to the climate system. The time scales over which these changes occur are not well understood, so evaluating GWPs such as the 100-year time horizon global warming potential requires assumptions that may influence results.

Step 4: **Interpretation of the LCA results.** Interpretation explains the LCA results, including the investigations of data quality, parameter sensitivity, and data and model uncertainty within the context of the goal of the study. Important issues for interpretation are presented and discussed in Section 6.0.

2.3 Characterizing Uncertainties in Life Cycle Assessment of Transportation Fuels

Assumptions, methodological choices, strategies for filling data gaps, and other factors throughout the life cycle substantially influence the results of life cycle greenhouse gas emissions estimates for transportation fuels. Figure 1 provides an example assessment of estimates of the life cycle greenhouse gas emissions of diesel, depicting large variations in the LCA results.

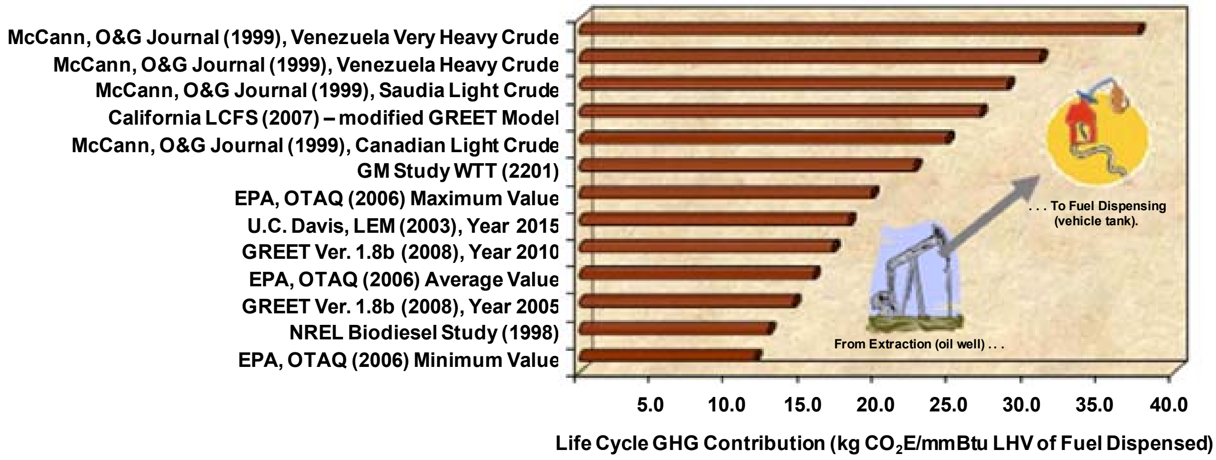

Figure 1. Greenhouse Gas Emissions (expressed as Global Warming Potential in Units of Equivalent CO_2 Emissions) for 13 Different Assessments of the Well to Tank Emissions for Diesel Fuel Production (Skone and Gerdes 2008)

Figure 1, developed by the U.S. Department of Energy's National Energy Technology Laboratory (NETL), shows the range of greenhouse gas emissions (expressed as Global

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[4] Available at: http://www.ipcc.ch/ipccreports/ar4-syr.htm

Warming Potential in units of kilogram equivalent CO_2 emissions) for 13 different assessments of the well to tank emissions for diesel fuel production. Values differ by a factor of 3 for well-to-tank emissions, translating to a difference of approximately 30% in well-to-wheels emissions. Some of these differences are due to differences in feedstock mix; some differences are due to the geographical or temporal scope of the study, and some differences are due to methodological assumptions. Later sections of this report will discuss the importance of methodological assumptions in more detail, and it will be demonstrated that methodological choices, even for petroleum fuels, can lead to a factor of two difference in well to tank greenhouse gas emission estimates (e.g., see Table 12). Clearly, if petroleum offers this level of variation by using different LCA assumptions, methodological choices, strategies for filling data gaps, and other factors, it can be expected to be challenging to assess the environmental benefit (or harm) of alternative fuels unless a standardized set of LCA guidelines are established (Skone and Gerdes 2008).

Even larger discrepancies in results may emerge when new feedstocks are considered, with the land use changes caused by the production of bio-based fuels at the forefront of current data and methodological discussions. The Publicly Available Specification for the assessment of greenhouse gas emissions of goods and services (PAS 2050 2008), issued by the British Standards Institute, the Carbon Trust and the UK Department for Environment, Food and Rural Affairs, provides estimates of GWPs for land use conversions (undeveloped land to agriculture land) that range from 1 ton of CO_2 GWP equivalents per hectare of land used per year for a South African Grassland to more than 30 tons for an Indonesian forest. It can be argued that global land use changes are introduced by changes in the allocation of any arable land, and therefore it is very difficult to determine exactly which land is being altered due to bio-fuel production. Selection of the appropriate GWPs is wrought with uncertainty, promising to produce variations in LCA results that are larger than those shown in Figure 1[5]. Since different potential feedstocks yield different fuel production potentials on a per hectare basis, understanding the uncertainty becomes a critical step in the comparison of different alternatives.

These few examples illustrate the challenges introduced by variations in assumptions, methodological choices, strategies for filling data gaps, and other factors inherent to LCAs of transportation fuels. In fact, the magnitudes of the discrepancies in the results can be larger than the changes in greenhouse gas emissions mandated in regulation. For example, the draft California Low Carbon Fuel Standard, available at the time this report was written, proposes a 10 year plan for reducing the GWP of greenhouse gas emissions associated with gasoline and diesel fuel by approximately 10%, which could easily be exceeded by variation in LCA results.

2.4 Models in Environment Regulatory Decision-Making

The mismatch between the variation in transportation fuel LCA results and regulatory emission reduction targets introduces challenges in both LCA modeling and in the development of related regulation. These challenges are not new. For example, complex atmospheric models are used to guide air quality management decisions for regulating emissions leading to criteria air pollutants, such as ozone. The U.S. Environmental Protection Agency provides model

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[5] If one hectare of land produces roughly 300 bushels of corn and corn yields 2.5 gallons of ethanol per bushel then a hectare of land yields an ethanol fuel with a LHV of 50-60 MMBTU, (Shapouri, Duffield and Wang 2002); in the units of Figure 1, the range of values recommended by PAS 2050 for land displacement for this corn-based ethanol example is 20 – 600 kg CO_2/mmBTU)

evaluation guidance that suggests criteria for model performance in predicting ozone concentrations. Specifically, model performance in predicting ozone concentrations is frequently in the range of 15% for normalized biases and 25% for normalized gross errors (EPA 2007). Yet these models are used to guide multi-billion dollar decisions that may influence ozone concentrations by just a few percent (e.g., reducing ozone concentrations from an 8-hour average concentration of 90 to 85 parts per billion) (National Research Council 2004).

Guidance in how to use models in these types of complex regulatory contexts was recently developed by the National Research Council at the request of the EPA's Council for Regulatory Environmental Modeling (National Research Council 2007). The NRC recommended model development, documentation, and evaluation processes that can improve the use of complex models in regulatory contexts. Specifically, the NRC report made recommendations related to:

- Peer review of models
- Communication of model uncertainty
- The effective integration of models and measurements
- Retrospective analyses of models
- Assessment of the balance between the level of detail incorporated into models and the ability to evaluate the performance of these model features (model parsimony)
- Overall model management.

These recommendations provide a framework for guiding the evolution of life cycle models for estimating greenhouse gas emissions and will be used in framing the recommendations made in this report.

2.5 Framework and Guidance for Estimating Life Cycle Greenhouse Gas Emissions for Aviation Fuels in the Context of Section 526 of EISA 2007

The purpose of this report is to provide a framework and guidance for estimating the life cycle greenhouse gas emissions for transportation fuels, specifically aviation fuels. The focus on aviation fuels was driven by the patterns of fuel use by the federal government. Policies such as those outlined in Section 526 of EISA 2007 cause federal agencies to institute enforceable guidelines for procuring low carbon alternative fuels. Federal consumption of fuels is dominated by the Department of Defense and the Air Force consumes more fuel than any of the other military services or federal agencies (Defense Science Board 2008). Thus, aviation applications may become early adopters of low carbon transportation fuels.

The U.S. Air Force convened a working group of individuals from government agencies, universities and companies actively engaged in assessing greenhouse gas emissions from transportation fuels, and requested that this group develop guidance on procedures for estimating greenhouse gas emissions in aviation applications, using currently available data and tools. The group also provided recommendations for model development and evaluation activities. A listing of the participants in this working group is provided at Appendix A: List of Attendees.

The working group met four times in the fall of 2008 and the spring of 2009 to define issues, review practices, and make recommendations. This report documents the findings and recommendations of the group.

The report is organized into major sections addressing:

- Guiding principles and functional units
- System boundary definitions and analyses
- Accounting for co-products
- Documenting data quality and uncertainty
- Life cycle model management

In each of these sections, the major questions and issues are defined, the work group's findings are described, and recommendations for future activities are made. The overall goal of the work group's activities and this report is to improve transparency and the quality of information available to decision-makers as complex life cycle models of greenhouse gas emissions begin to be used in regulatory and contractual contexts.

3.0 GUIDING PRINCIPLES AND FUNCTIONAL UNITS

3.1 Setting the Stage

As shown schematically in Figure 2, alternative fuels need to balance multiple objectives, including economic sustainability, energy diversity and environmental sustainability. Economic sustainability refers to a nation's ability to remain globally competitive, capacity to maintain a desirable standard of living, and resilience in handling volatile world market fluctuations. Economic sustainability also addresses inherent retention of other market sectors such as food production, manufacturing jobs, and natural resources. Energy diversity will help to ensure that sufficient energy resources are available and are being produced to support national needs. Environmental sustainability relates to the ability to reduce impacts resulting from energy consumption, such as reducing greenhouse gas emissions that contribute to climate change, as well as other elements that impact air, land and water quality, and place a demand on natural resources.

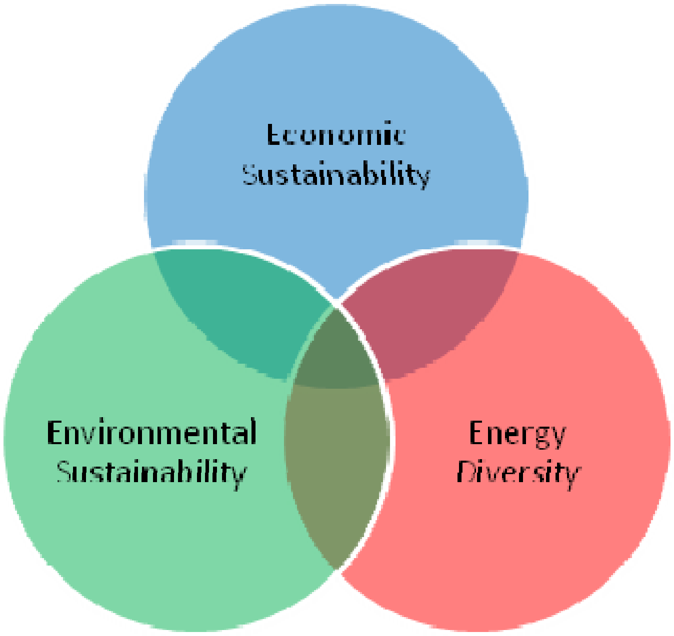

Figure 2. Three Objectives That Need to be Balanced With Alternative Fuels

The DOD and US civil aviation, including the Commercial Aviation Alternative Fuels Initiative (CAAFI), seek fuel choices that can be made from fossil, biomass, natural gas, or combinations of these resources that diversify and increase fuel supply, stabilize price, while reducing the overall environmental impact of aviation. To achieve this goal, a new alternative or synthetic fuel candidate must pass through a series of steps that assures the fuel meets aircraft safety, system performance and durability requirements. The finished fuel would preferably be a drop-in replacement, being fully compatible with the current fuel logistics infrastructure and aircraft operations, requiring no modifications for any aircraft or support equipment and affecting no loss in aircraft engine performance. With concerns about the pace of global climate change as well as the legislation that has been introduced as a consequence (e.g., EISA), an LCA of greenhouse gas emissions is increasingly becoming an important criterion for fuel acceptance.

3.2 Types of LCAs

LCA methodologies to evaluate life cycle energy and material flows associated with a product system or activity are commonly categorized based on the type of data used to characterize a system (average vs. marginal), approach used to address material and energy flows (attributional vs. consequential), and by resolution of analysis (screening, standard, or comprehensive). The following section provides a brief description of each of these LCA categories as they are used in this guidance document.

3.2.1 Average vs. Marginal LCA

An average LCA considers the energy and material flows that have occurred over an extended period of time and under conditions such that the inventory may be considered generally representative of, or "average", for a particular unit operation or industrial sector. A marginal LCA considers the "nth" product produced or process run and is representative of a very short period of time and/or very specific conditions. Any LCA model can be used to conduct either average or marginal LCAs, as it depends upon the data collected and used rather than the analysis itself. For example, if an alternative jet fuel were to be introduced such that it displaced some portion of conventional, petroleum-derived jet fuel, the alternative could be compared with the conventional fuel using an average LCA. In this case, data representing the average practice for this particular type of alternative jet fuel industry along with the average practices of the petroleum jet fuel industry would be gathered and used in the evaluation.

By contrast a marginal LCA assumes that the alternative jet fuel industry will, at the time of the analysis, contribute a small fraction of the total jet fuel used. The introduction of the alternative jet fuel will displace a subset of the conventional jet fuel industry. That is, the alternative jet fuel will displace conventional jet fuels at an economic margin. The data to be used in a marginal LCA should be gathered to represent the marginal production of the conventional jet fuel.

While marginal analysis, in theory, may better represent what could happen in the marketplace when the alternative jet fuel is introduced, it is difficult to identify which facilities producing conventional jet fuel operate at the margin and would be displaced by the new fuel. Characterization of marginal processes, including identification of appropriate parameters and data, is also likely to be a challenge.

3.2.2 Attributional vs. Consequential LCAs

LCA models may also differ in the approach used to address material and energy flows in cases where more than one output of value is produced. LCA models that assume an isolated system are termed attributional LCAs. In this instance, all flows and their associated environmental burdens are attributed by one of several available methods to each of the individual products. All of the attributed environmental burdens from all life cycle pathway stages for a product are aggregated as the total environmental burden of producing a target product and any co-products that are accounted for within the system. These attribution or allocation methods are described in more detail in Section 5.0.

In contrast, consequential LCAs assume an open product system and take a systems response approach in assessing impacts throughout the system as a result in a change in output of the functional unit under study. The most commonly used form of a consequential LCA (CLCA) relies on systems level economic models. These models track economic, material, and energy across economic sectors. Weidema (2003) and Ekvall and Weidema (2004) describe the CLCA methodology including consequential process identification and the use of marginal process data and supply and demand price elasticities to quantify the impacts of industrial processes outside the life cycle of interest but within the CLCA system boundaries.

This guidance document focuses primarily on average attributional LCAs for conventional and alternative aviation fuels.

3.2.3 Levels of Resolution

The LCA can be thought of as falling into three levels, listed in order of decreasing level of study completeness, data quality requirements, level of effort requirement, and confidence in analysis results[6]:

- Level I: Comprehensive
- Level II: Standard
- Level III: Screening

A Level III, or Screening, LCA is appropriate when performing a preliminary assessment of a technology alternative or informing research funding decision making. A Level II, or Standard, LCA examines all major unit operations, but with a lower degree of inventory completeness and data quality requirements than for a Level I LCA. A Level I, or Comprehensive, LCA, with its higher degree of accountability, is most appropriate for meeting the requirements of Section 526 of EISA 2007. Data, allocation, and system boundary definition requirements meeting the standard of a Level I LCA are discussed in this document.

3.3 Goals and Scope Definition

3.3.1 Programmatic Goals for Alternative Jet Fuels

The Air Force and the civil aviation sector have developed and published processes to assess the technical compliance of candidate jet fuels. The Air Force has documented the process in Military Handbook 510 (2008) and the commercial sector has documented their process in ASTM procedures (e.g., D4054). Both the Air Force and the civilian aviation sector have goals of approving and using alternative jet fuels, some of which are summarized in Table 1. To ensure full compatibility with existing systems in the near term, certification efforts have focused on alternative fuel blends with petroleum. For example, both the Air Force and the civilian aviation sector have focused on 50/50 blends of petroleum fuels with either Fischer-Tropsch (F-T) or Hydroprocessed Renewable Jet (HRJ) fuels. Since Section 526 of EISA 2007 mandates that any alternative fuel have a life cycle greenhouse gas profile less than or equal to an equivalent conventional petroleum-based fuel, the process of evaluating candidate fuels must also include some quantification of their life-cycle GHG emissions.

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[6] Section 6.6, entitled Assessing Data Quality, provides a thorough discussion of three levels of LCA analysis, Comprehensive, Standard, and Screening. These levels reflect varied levels of data quality and are meant to answer the needs of varied life-cycle analysis.

Table 1. Certification and Use Goals for the Commercial Aviation Sector (as Represented by CAAFI and the US Air Force)

Year	CAAFI Certification Goals	USAF Certification and Use Goals
2009	50% Fischer-Tropsch Syngas-based blends including biomass to liquid (BTL)	
2010	-50% Hydroprocessed Renewable Jet (HRJ) fuel from non-food sources, including algae	
2011		- Complete testing and certification on all aircraft and support systems for use of 50/50 alternative fuel blends
2013	-100% Hydroprocessed Renewable Jet (HRJ) fuel	
2016		- Competitively acquire 50% of the domestic aviation fuel requirement using certified alternative aviation fuel blends (50/50). - Procure 800 Million gallons of alternative renewable fuels

Several fuels are currently being considered for certification, such as Fischer-Tropsch, syngas-based fuels and HRJ fuels. HRJ fuels are produced from triglycerides which are broken into single chains and subsequently hydrotreated in order to eliminate oxygenated compounds. Both are termed Synthetic Paraffinic Kerosene (SPK) fuels. SPK fuels, as the name implies, are synthetic, (i.e., created from a source other than petroleum) kerosene fuels comprised of paraffinic hydrocarbons. In other words, they have similar composition and properties to conventional jet fuel, but with one major exception -- they do not contain aromatic hydrocarbon compounds. Other fuels, such as fatty acid methyl esters (biodiesel) and alcohols (ethanol and butanol), are not being proposed for aviation certification for a multitude of reasons, including safety, compatibility, and energy density. For these reasons, the guidelines presented in this document are focused on alternative jet fuels that have an SPK composition. It is, however, conceivable that, in the future, other fuel compositions will be considered for certification as jet fuel, and the guiding principles spelled out in this report should be broadly applicable to analysis of the life cycles of those novel jet fuel compositions and those of other transportation fuels.

3.3.2 Conventional Petroleum-Based Fuels: A Baseline for Comparison

Fuel baselines needed to judge whether or not a candidate alternative fuel has life-cycle GHG emissions that are "less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources." Section 526 of EISA, from which this quote was taken, does not define this comparative baseline fuel; however, Title II, Subtitle A, Sec. 201 of EISA 2007, which amends the Clean Air Act, defines the term "baseline life cycle greenhouse gas emissions" to be the average life cycle greenhouse gas emissions of gasoline and diesel sold or distributed as a transportation fuel in 2005. Although this Title II definition does not directly apply to Section 526, it will be assumed to be the relevant baseline for the purposes of this document.

A recent report by NETL (Skone and Gerdes 2008) provides one of the most rigorous examinations of the life cycle greenhouse gas emissions profiles from U.S. domestically sold and distributed conventional petroleum sources for the year 2005. This study reports the U.S. average life cycle GHG emissions of conventional gasoline, conventional diesel fuel with less than 500 parts per million of sulfur, and kerosene-based jet fuel. The reported central estimate of well-to-wake emissions for kerosene-based jet fuel was 88.1 g CO_2e/MJ (92.9 kg of CO_2 equivalents per million BTUs of Lower Heating Value, LHV, fuel consumed). CO_2 equivalent is determined by summing the weighted contributions from carbon dioxide, methane, and nitrous oxide, using the 2007 IPCC 100-year global warming potential CO_2 equivalent factors. The NETL study included both CO_2 and non-CO_2 emissions from the combustion of kerosene-type jet fuel. If non-CO_2 combustion emissions were excluded from the NETL estimate, as will be recommended later in this section, then the central estimate of well-to-wake emissions for kerosene-based jet fuel is 87.5 g CO_2e / MJ. This study, although based on some data that are not available for public review[7] and requiring additional data and boundary validation, provides perhaps the best basis for the development of baseline conventional fuel LCAs for EISA

3.3.3 LCA Study Goal and Scope Definition

The required level of detail appropriate for an LCA changes as a function of the question that the analysis is being developed to address. For example, to be compliant with Section 526 of EISA 2007, it is necessary to determine whether the fuel supplied produces life-cycle GHG emissions less than or equal to those produced from a baseline conventional fuel. Such an analysis would examine existing facilities (or those planned for the immediate future) and use high quality data with a minimum of assumptions as it will be used for compliance purposes. Another question that may be asked is whether or not it is to society's benefit to promote the development of a specific fuel industry. Such an analysis would examine a hypothetical future industry, such as large-scale algae production, that could replace a considerable quantity of all commercially consumed conventional jet fuel (e.g., 1.6 million barrels per day or more in the US alone, (Energy Information Administration 2007)). This analysis would more than likely have to rely on simulations rather than actual operational data and may also require a considerable amount of forecasting of technology performance. Both of these increase the uncertainty in the overall analysis.

This document is meant to provide guidelines for assessing the life-cycle emissions for fuel production at a typical, individual facility in the near term. This choice relates well to the needs of the DESC and other agencies responsible for procurement, but it also serves fuel manufacturers who would like to assess and certify the life-cycle GHG emissions of their specific fuel production pathway.

ISO 14044: 2006(E) (2006b) requires the goal and scope of a study to be clearly defined and consistent with the level of detail and intended use of the study results. The following questions provide guidance in defining the appropriate level of LCA to be conducted:

- **What is the purpose of the study?** The purpose of the LCAs required under Section 526 of EISA 2007 is narrowly focused toward the direct comparison of life cycle greenhouse gas emissions generated from alternative jet fuels produced at a specific facility through a specific production chain, as related to the purchase of synthetic and alternative fuels by the US government, with average greenhouse gas emissions from conventional, petroleum based sources.

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[7] Data used in this study are contained within the GaBi LCA software system which limits public publication of unit process data. Data can be reviewed with purchase of the software, see http://www.gabi-software.com/

- **Who is the intended audience?** The DESC purchases aviation fuel for the DOD and is expected to be the primary procurement agency that will oversee fuel vendor compliance with Section 526 of EISA 2007. It is also anticipated that prospective fuel producers, civilian fuel purchasers, and environmental interests may use this document as guidance in comparing or conducting their own LCAs as well.
- **What is the intended level of detail?** To meet the requirement of EISA 2007 (demonstrating that lifecycle greenhouse gas emissions associated with the alternative aviation fuel supplied to Federal agencies are, on an ongoing basis, less than or equal to those of conventional petroleum-derived jet fuel), it will be necessary for the fuel manufacturers and LCA practitioners to develop a comprehensive (Level I), high-quality LCA that is determined to sufficiently account for full lifecycle greenhouse gas emissions from all phases of alternative aviation fuel production, transport, and use.

Table 2 provides a summary of the information that might be included in specifying the LCA goal pursuant to EISA.

Table 2. Definition of Life Cycle Goal for Alternative Aviation Production/Consumption Chains

General Question	Specific Goal
Intended application	Department of Defense contracts for procurement of alternative or synthetic fuels covered by Section 526 of the Energy Independence and Security Act (EISA) of 2007.
Study purpose	To estimate and compare the life cycle greenhouse gas emissions associated with producing, transporting, storing, and using conventional petroleum with those of alternative or synthetic transportation fuels for purchase by the US government.
Intended audience	Decision-maker: The DESC, DOD or any entity who needs to ensure fuel vendor compliance with Section 526 EISA 2007
Intended level of detail: Comparative assessment status	The results from the LCAs will be used to make an absolute comparative assertion between a target (baseline/reference point) and an alternative or synthetic option with the ultimate goal of providing a reasonable estimate that the alternative or synthetic fuels have lower life cycle greenhouse gas emissions. For example, the modeler (the person performing the LCA) will need to demonstrate that the alternative or synthetic fuel being assessed has lower GHG emissions by: • showing improvement over baseline GHG emissions with some justification and knowledge of the uncertainty • showing consistency or discrepancy among case studies of similar alternatives

3.4 The Primary Fuel Process Chain

3.4.1 Defining Life-Cycle Stages

Assessments performed in accordance with these guidelines are to consider the full fuel life cycle from cradle-to-grave, i.e. from raw material production or extraction through the combustion of the refined fuel by the aircraft. A first step toward developing a robust and defensible LCA of a candidate synthetic or alternative aviation fuel is to explicitly define the primary production chain for which an LCA is to be developed. In the interest of standardization, and in keeping with specifications of ISO 14040 (2006a), the following six general life cycle stages are the preferred format for organizing inventory data and reporting of inventory/assessment results and representing the primary fuel production chain:

- Life Cycle Stage #1: Raw Material Acquisition
- Life Cycle Stage #2: Raw Material Transport
- Life Cycle Stage #3: Liquid Fuels Production
- Life Cycle Stage #4: Product Transport and Refueling
- Life Cycle Stage #5: Use/Aircraft Operation
- Life Cycle Stage #6: End of Life

3.4.2 Life-Cycle Boundaries

While details of system boundaries and level of detail necessary for developing life cycle inventories will be provided in subsequent sections, a brief description of the key activities and boundaries for each life-cycle stage of petroleum-based fuel production chain is provided as an example.

- **Life Cycle Stage #1**: Raw Material Acquisition
    - Including land-use changes, the extraction of raw feedstocks from the earth and any partial processing of the raw materials that may occur (e.g., oil seed harvesting and processing, upgrading to meet quality requirements for crude pipeline transport).
- **Life Cycle Stage #2**: Raw Material Transport
    - Starting at the end of extraction/pre-processing of the raw materials and ends at the entrance to the refinery facility.
    - Refinery feedstocks may be transported from both domestic and foreign sources to U.S. refineries.
- **Life Cycle Stage #3**: Liquid Fuels Production
    - Starting with the receipt of refinery inputs at the entrance of the refinery facility and ends at the point of aviation fuel input to the product transport system.
    - Emissions associated with acquisition and production of indirect fuel inputs (e.g., purchased power and steam, purchased fuels such as natural gas and coal, and fuels produced and subsequently used in the refinery) are included in this stage.

    - Emissions associated with on-site and off-site hydrogen production are accounted for in this stage, including emissions associated with raw material acquisition for hydrogen plant feedstock and fuel.
- **Life Cycle Stage #4**: Product Transport and Refueling
    - Starting at the gate of the petroleum refinery with aviation fuel already loaded into the product transport system and ends with dispensing the fuel into the aircraft.
    - Including the operation of the bulk fuel storage depot, transport of jet fuel from storage tanks to the aircraft, and aircraft refueling.
- **Life Cycle Stage #5**: Use/Aircraft Operation
    - Starting starts at the aircraft fuel tank and ending with the combustion of the liquid fuel.
- **Life Cycle Stage #6**: End of Life
    - It should not be necessary to include end of life, such as recycling or disposal, in the scope of jet fuel LCAs, since the final product is consumed in Life Cycle Stage #5. As such, Stage #6 is not discussed further in this document.

3.4.3 Example Primary Production Chains

Simplified process schematics provide a straightforward and visually intuitive means of representing the primary production chains through the five most significant life cycle stages. The following figures provide several commonly cited synthetic and alternative aviation fuel production chains and give examples of sub-processes within the life cycle stage framework. The five significant schematic processes reflect: (1) Petroleum, (2) Biomass, (3) Coal and Biomass to Liquid (CBTL), (4) HRJ Fuel, and (5) Hybrid Petroleum/Biomass fuel stages.

The case outlined in Figure 3 includes extraction of conventional and unconventional crude oil from domestic and foreign sources (Stage #1), pipeline, tanker, rail and truck transport of crude oil to refineries, domestic and foreign, serving in whole or part the domestic jet fuel market (Stage #2), refinement of crude oil to produce the primary products of gasoline, diesel fuel, and jet fuel (Stage #3), transport of jet fuel for U.S. consumption (Stage #4), and combustion of jet fuel (Stage #5).

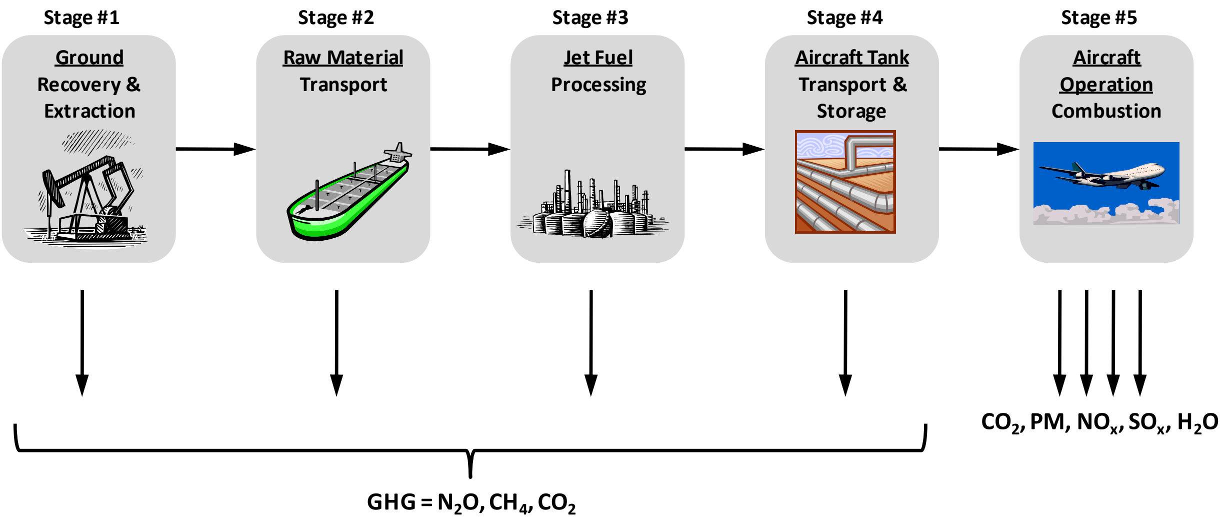

Figure 3. Simplified Schematic of a Life Cycle Primary Production Chain for a Petroleum-Based Aviation Fuels

The case outlined in Figure 4 incorporates raw material acquisition from cultivation and harvesting of biomass including inventory of GHG emissions that may result from changes in land use resulting from these activities, and processing of biomass to extract bio-oil for use as refinery feedstock, as well as other potentially salable co-products, e.g., soy bean meal (Stage #1). Bio-oil generated in the raw material acquisition stage is then transported (e.g., pipeline, tanker, rail or truck transport) to the refinery operation (Stage #2) where it is mixed with other refinery inputs and processed to bio-derived jet fuel and co-products (Stage #3). Following the jet fuel production stage, the fuel is blended with additives, transported to bulk storage, stored, transported to the aircraft refueling location and loaded into the aircraft fuel tank (Stage #4). Finally, the jet fuel is combusted in the aircraft (Stage #5).

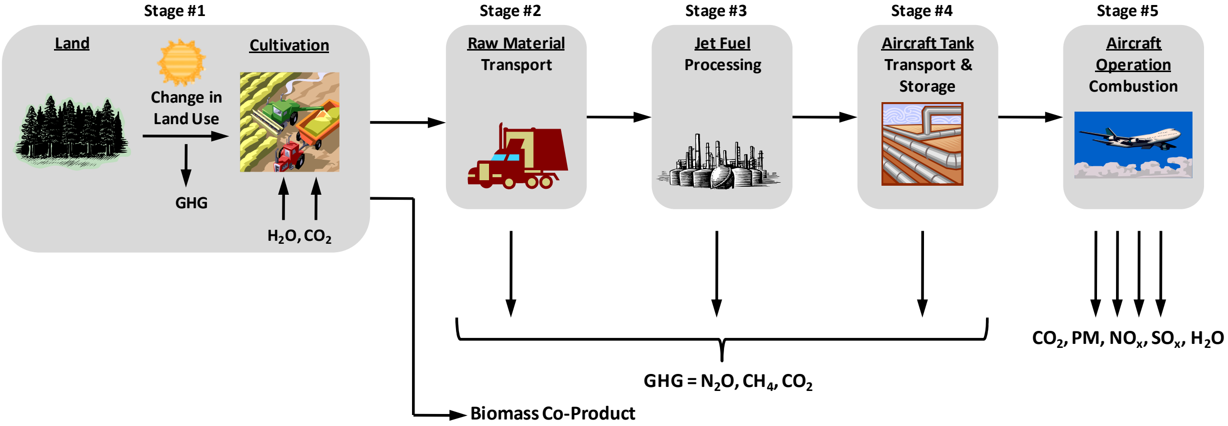

Figure 4. Simplified Schematic of Life Cycles Stages for the Primary Production Chain of a Conventional Bio-Oil to Jet Fuel

The case outlined in Figure 5 is representative of CBTL production. Stage #1 incorporates both coal extraction and biomass cultivation and harvesting. Coal extraction includes mining operations, on-site prewashing, sizing, and further preparation for utilization. Raw material acquisition from cultivation and harvesting of biomass will include inventory of GHG emissions that may result from changes in land use resulting from these activities and the further processing of biomass, e.g. pelletization, in preparation for utilization; (biomass preparation may also take place at the CBTL facility, taking advantage of process flow integration to increase efficiency). Processed coal and biomass are then transported to the CBTL facility by rail, truck, or barge and unloaded into feedstock loading facility (Stage #2). At the CBTL facility, feedstock may be further processed (e.g., comminution, drying, blending) to improve overall conversion and is then converted to synthetic jet fuel in the CBTL conversion process[8] (Stage #3). CBTL may be coupled with a variety of CO_2 management strategies to lower the overall life cycle greenhouse gas emissions profile of Stage #3. Following the synthetic jet fuel production stage, the fuel is blended with additives, transported to bulk storage, stored, transported to the aircraft refueling location and loaded into the aircraft fuel tank (Stage #4). Finally, the fuel is combusted in the aircraft (Stage #5).

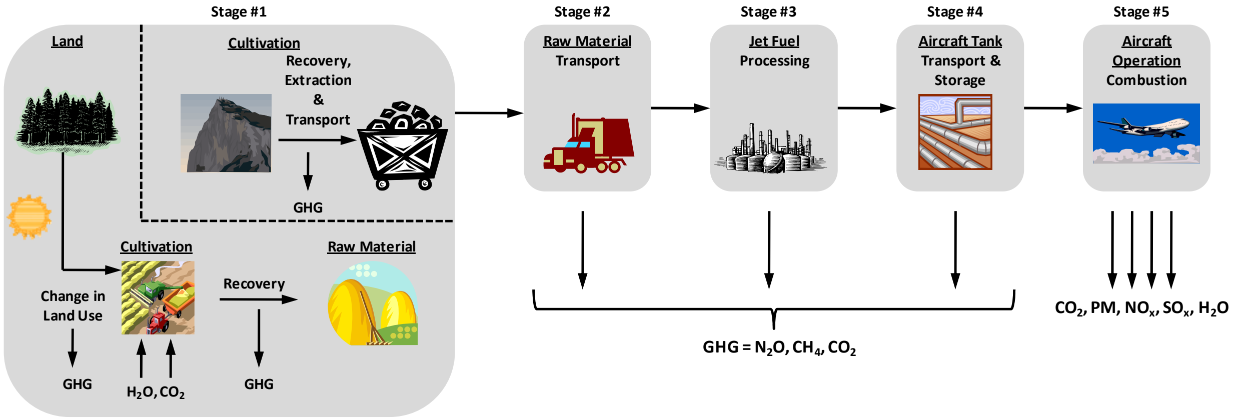

Figure 5. Simplified Schematic of Life Cycle Stages for the Primary Production Chain of a CBTL-Based Jet Fuel Production Chain

The case outlined in Figure 6 is representative of HRJ fuel production from algae. Stage #1 includes acquisition of bio-oil from cultivation, harvesting, and processing (e.g., algae dewatering and oil extraction) of algal biomass, including inventory of GHG emissions that may result from changes in land use resulting from these activities (Stage #1). Stage #1 will also include accounting for that portion of anthropogenic CO_2 capture (e.g., from coal or natural gas combustion) activity that is attributable to the algae production facility, should such operations be employed to facilitate algae growth. Also in Stage #1, algal biomass generated as a co-

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[8] In one embodiment of CBTL, the process of indirect liquefaction may be used to produce jet and diesel fuels. Indirect liquefaction refers to processes in which the coal and biomass carbonaceous feedstocks are first broken down by a gasification step to form a "synthesis gas" (syngas) comprising carbon monoxide (CO) and hydrogen (H_2) that is then converted to a liquid hydrocarbon stream via a Fischer-Tropsch (FT) catalytic synthesis. This relatively-long chain paraffinic hydrocarbon is then selectively hydrocracked to form jet fuel and other hydrocarbon products. (Indirect liquefaction differs from direct liquefaction and pyrolysis CBTL technologies in which coal and biomass feedstocks are liquefied directly through cracking of large molecules and H_2 addition.)

product of algae bio-oil production may be utilized for on- or off-site applications (e.g., fertilizer, animal feed, biomass co-firing, anaerobic digestion for methane production). Bio-oil generated in the raw material acquisition stage is then transported (e.g., pipeline, tanker, rail or truck transport) to the refinery operation (Stage #2) where it is mixed with other refinery inputs and processed to bio-derived jet fuel and co-products (Stage #3). Following the jet fuel production stage, the fuel is blended with additives, transported to bulk storage, stored, transported to the aircraft refueling location and loaded into the aircraft fuel tank (Stage #4). Finally, the fuel is combusted in the aircraft (Stage #5).

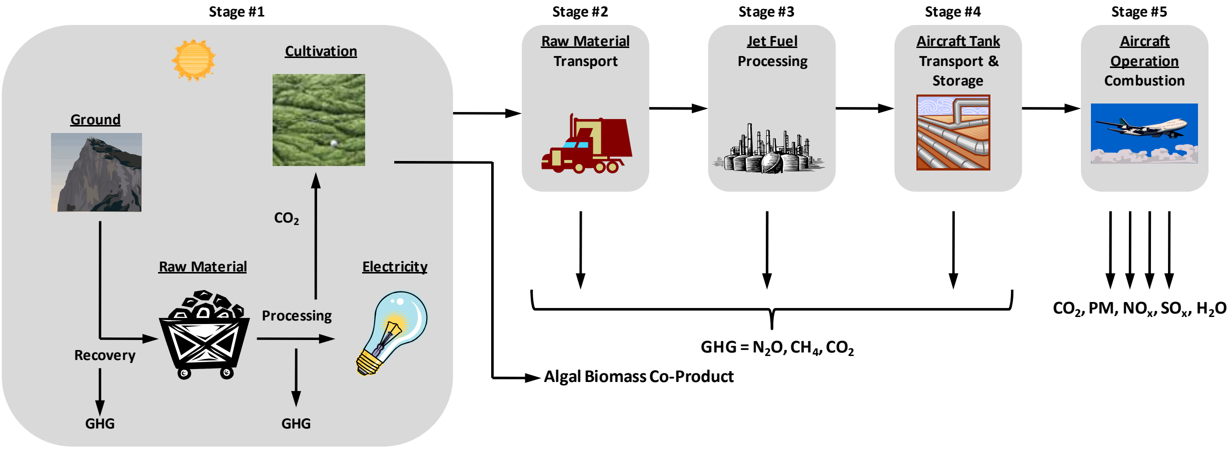

Figure 6. Simplified Schematic f Life Cycle Stages for the Primary Production Chain of an Algae-Derived Bio-Oil to Jet Fuel

The process shown in Figure 7 incorporates the first three life cycle stages of both the petroleum-derived and bio-derived jet fuels. At Stage #4 the intermediate product stocks are then transported to a blending facility to be combined into a single, blended product fuel for use. The blended product fuel is augmented with additional additives, transported to bulk storage, stored, transported to the aircraft refueling location and loaded into the aircraft fuel tank. Finally, the fuel is combusted in the aircraft (Stage #5).

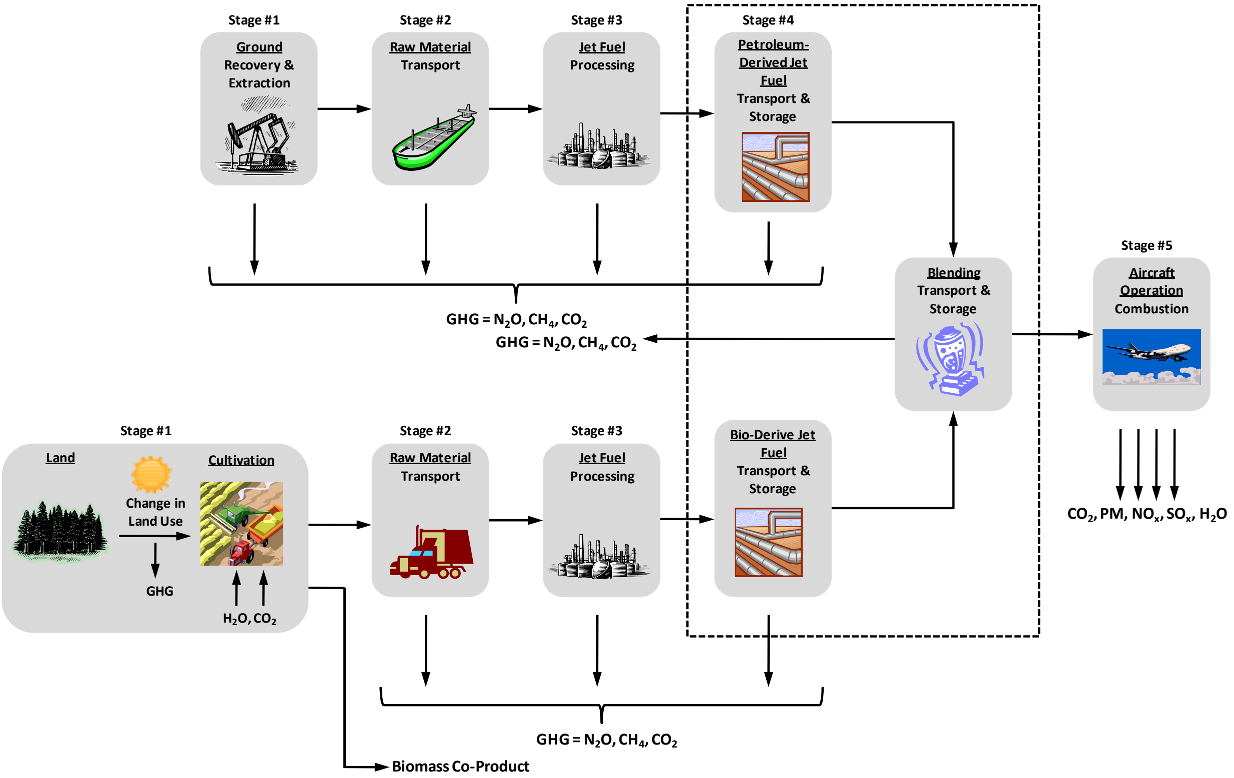

Figure 7. Simplified Schematic of Life Cycle Stages for the Primary Production Chain of a Jet Fuel Created From a Blend of Petroleum-Derived Jet Fuel Stock and a Bio-Derived Jet Fuel Stock

3.5 Examining the Life Cycle Stages

3.5.1 Primary Production Chain Inventory Modeling

Inventory modeling of the primary production chain ideally involves the preparation of a mass and energy balance for processes throughout the five life cycle stages. Ideally, such an analysis would examine existing facilities (or those planned for the immediate future) and use high quality data[9] with a minimum of assumptions as it will be used for compliance purposes. Such an analysis would examine a hypothetical future industry, such as large-scale alternative fuel production, that could replace a considerable quantity of, for example, all commercially consumed conventional jet fuel (e.g., 1.6 million barrels per day or more in the US alone, (Energy Information Administration 2007)). This analysis would more than likely have to rely on computational industrial models instead of actual operational data and may also require a considerable amount of forecasting, and both of these increase the uncertainty in the analysis.

In conducting an attributional LCA of an alternative jet fuel production chain, the simplified process schematics are expanded (disaggregated) to provide a higher fidelity of additional process and flow detail necessary to appropriately categorize the production chain and meet

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[9] The correct use of primary and secondary data as well as how to qualify the quality of data are both major components of the guidance that is provided in this document. Section 5.1 is devoted to this topic.

inventory requirements as defined by the system boundary and data requirements in subsequent sections.

3.5.2 System Boundary

A comprehensive LCA requires full accounting of all process-associated flows and activities, not only those within the processes of the primary production chains, but also activities and material/energy flows supporting necessary input to the primary production chain. For example, the operation of an oil well consumes fuels, electricity and processing chemicals and requires construction materials (e.g., steel tubulars and cement that make up the wellbore casing system), transport of drill rig and construction materials to the reservoir, well drilling and completion, intermittent well workovers during production, well plugging and abandonment, and well construction material end-of-life management (e.g., recycling of steel casing elements). The life cycles of all of these materials and activities are also included within the life cycle system boundaries. Furthermore, a very small fraction of the construction and materials associated with building of the plant where those construction materials, etc. were manufactured (e.g., the steel plant where the well casing was manufactured) could also be included in a complete LCA. Categorical exclusions from the system boundary would include low frequency, non-predictable catastrophic events, such as large spills, and human activities (e.g. workers' lunch breaks and commuting activities).

Definition of a life cycle assessment system boundary serves to constrain the life cycle assessment according to a set of clearly-defined geographic, temporal, and level of resolution thresholds that are consistent with the intended purpose of conducting the life cycle assessment. Greenhouse gas global warming impacts may be constrained to consider only those constituents that are recognized by the IPCC as having significant and well definable global warming potential, with global warming potential assessed using 2007 IPCC 100 year GWP factors. Land use GHG emissions may include both soil emissions from directly-impacted land as well as emissions arising from indirect land use, with land use emissions considered over a fixed time period following initial land perturbation (emissions effectively amortized over that time period). An appropriate system boundary will include the inventory of all relevant activities necessary to appropriately account for significant life cycle emissions. A succinct methodology has been developed to provide guidance in definition of appropriate system boundaries for analyzing an alternative aviation fuel pathway, and is presented in Section 4.0.

3.5.3 Disaggregation, System Expansion, and Allocation

In LCA, a co-product is defined as "any two or more products coming from the same unit process or product system" (ISO 2006a). Inevitably, some unit process co-products are used neither within the primary fuel production system nor within the additional processes within the life cycle. For example, in the production of petroleum jet fuel, gasoline, diesel, industrial chemicals, and other products are co-produced. ISO 14044 (2006b) states that inputs and outputs **shall** be allocated to the different co-products using methods in the following order:

1. **Process disaggregation:** dividing the unit process into two or more sub-processes and collecting the input and output data related to these sub-processes.
2. **System expansion:** expanding the product system to include the additional functions related to the co-products.

3. **Allocation by physical relationships:** inputs and outputs are partitioned between its different co-products in a way that reflects the underlying physical relationships (e.g., mass, volume, energy content) between them
4. **Allocation by other relationships:** when physical relationship alone cannot be established, inputs and outputs are partitioned between its different co-products in a way that reflects other relationships (e.g., economic relationships) between them.

Many fuel production processes produce co- products along with the primary product. Such multi-output processes complicate the development of a life cycle inventory because the inputs and outputs of the processes need to be divided, or allocated, between all the products. In some instances, a more detailed process model may be all that is required in order to disaggregate material and energy flows associated with specific products. If co-products substitute for other products in the economy, these substitutions can be integrated into the analysis through system boundary expansion. In other cases, the processes are co-mingled to the extent than more sophisticated methods of appropriately partitioning environmental burdens are required. Most desirable is to partition inputs and outputs between multiple products on the basis of an underlying physical relationship between them, such as mass or energy content. Challenges may be inherent in this approach, however, when the functions of the co-products are quite different, as is the case where products derived from biomass may consist of both fuels for their energy content and feed for nutrient value. In such cases, the most uniform common metric may be their final economic value. The choice of allocation approach can have a significant effect on the overall results. Clarity in the choice of allocation method and the implications of this choice are needed in order to provide a meaningful basis for comparison among fuels as well as other life cycle systems. Guidance on allocation is provided in Section 5.0.

3.5.4 Inventory Data

To meet the EISA 2007 requirement fuel producers must develop comprehensive, high-quality data for LCA. GHG life cycle inventories should completely represent all process life cycle stages and phases of operation, including consideration of all inherent system variability, and to account for emissions associated with all activities and material transformations back to elemental flows (i.e., flows drawn from the environment). In practice, the expectation is that a life cycle inventory will be developed using data of sufficient quality, representativeness (technology, temporal, geographic), and completeness as to be consistent with the stated goal and scope of the study: comparative analysis with baseline life cycle GHG emissions of comparable petroleum-based jet fuel. It is expected that data used to populate the life cycle inventory will be assembled from a variety of sources; while a substantial portion of these data are expected to be fuel producer-generated data providing detailed categorization of the range of fuel production technology performance, it will also be necessary to use data for raw material or energy inputs acquired from a number of secondary sources (e.g., data from publicly available reports of process or industry-level performance or aggregated cradle-to-gate profile data).

Variability in the sources and quality of data that may be considered for use in an LCA is almost inevitable. Some methodologies that could be used in selection of appropriate data, specific guidance on data quality requirements, and methodologies for reporting of results and incorporation of sensitivity/uncertainty analyses are provided in Section 6.0.

3.6 Scope Definition Parameters

Table 3 provides examples of some of the scope definition information that have been discussed above and elsewhere throughout this report.

Table 3. Example of an Alternative Aviation Fuel Life Cycle Greenhouse Gas Study Design

Life Cycle Boundary for the primary fuel production chain	Well-to-Wake
	(Raw Material Acquisition thru Fuel Use)
Temporal Representation	Year of Fuel Procurement
Technological Representation	Facility/Chain Specific
Geographical Representation	Transportation Fuel Sold and Distributed to DESC in the United States
Transportation Fuel Life Cycles Modeled	Kerosene-Based Jet Fuel
Impact Assessment Methodology	Global Warming Potential, IPCC 2007, 100-year time-frame Non-CO_2 combustion emissions not included
Reporting Metric	g CO_2e / MJ LHV of Fuel Consumed
Data Quality Objectives	Preferably Facility Technical Engineering and Operating Data. Publically Available Data (to the extent practicable)
	Full Transparency of Modeling Approach and Data Sources (to DESC)
	Accounting for a targeted uncertainty in Mass and Energy
	Accounting for a targeted uncertainty in Environmental Relevance
	Process-based ("Bottoms-up") Modeling Approach

3.7 Combustion Emissions (Tank-to-Wake)

The life-cycle emissions that result from the creation and use of a fuel have both a direct radiative impact on the atmosphere as well as an indirect effect by reacting chemically within the atmosphere to affect other compounds that have radiative impact. In this fashion, a life-cycle inventory of greenhouse gases is an accounting for all of the emissions that contribute to global climate change. It is important to note that an accounting of these emissions is a proxy for the actual physical impact of increased global temperatures as well as socio-economic impacts of changed weather patterns, sea level rise, ocean acidity, and other outcomes. These distinctions are especially important when considering emissions from the combustion of fuels within a jet engine.

As represented in Equation 1, the principal products resulting from the combustion of jet fuel are CO_2 and water vapor (H_2O), but the combustion also results in the creation of sulfur oxides (SO_X), nitrogen oxides (NO_X), carbon monoxide (CO), unburned hydrocarbons (UHC), and fine particulate matter (PM).

$$Fuel + Air\ (O_2 + N_2) \rightarrow CO_2 + H_2O + SO_x + NO_x + PM + CO + UHC \qquad (1)$$

The mass of emissions per mass of fuel consumed, a quantity known as an emissions index or emissions factor, have been compiled for all of the quantities listed in Equation 1 for commercial and military jet engines. It is important to note that the emissions indices of PM, CO, UHC, and NO_x vary with engine operation (e.g., idle, takeoff, and cruise operations), and there are recommended practices for estimating the time and fuel use in each operating mode. The interested reader is directed to Kim, et al. (2007) to learn more about the System for assessing Aviation's Global Emissions (SAGE) tool which is used to create annual emissions inventories for the US FAA.

The life-cycle analyst may be tempted to include estimates of methane and nitrous oxide emissions as they are discussed in the IPCC guidelines and are included in the well-to-tank portion of the LCA; however, as noted by the IPCC, these emissions have considerable uncertainty in whether or not these emissions are even being produced by modern gas turbine engines (quote from Page 3.56 of (IPCC 2007)).

> *Methane (CH_4) may be emitted by gas turbines during idle and by older technology engines, but recent data suggest that little or no CH_4 is emitted by modern engines. Emissions depend on the number and type of aircraft operations; the types and efficiency of the aircraft engines; the fuel used; the length of flight; the power setting; the time spent at each stage of flight; and, to a lesser degree, the altitude at which exhaust gases are emitted.*

IPCC also notes that modern gas turbine engines produce little to no N_2O emissions as well (IPCC 1999).

Alternative fuels may change the emissions produced by aircraft. For example, because the chemical composition of alternative fuels such as SPKs, produced either via the F-T process or hydroprocessing of renewable oil sources, differ from that of conventional jet fuel, there will be changes in the combustion products, as compared to petroleum-derived fuels. Our collective knowledge of these changes varies with our fundamental understanding of how these pollutants are created. The emissions of CO_2, H_2O, and SO_X can be estimated for any fuel composition, including SPK, based on complete combustion. These emissions indices are summarized along with the carbon mass fraction of the fuel and the fuel sulfur content in Table 4 (Hileman and Donohoo, 2009).

Table 4. Compositional Properties and Emissions Indices (EI) for CO_2, H_2O, and SO_x

Fuel	Carbon Mass Fraction	Fuel Sulfur Content (ppm)	Energy Content (MJ/kg)	CO_2 EI (g/kg)	H_2O EI (g/kg)	SO_X EI (g/kg)
JP-8	0.862	600	43.2	3,159	1,231	1.20
SPK	0.847	~0	44.1	3,105	1,363	~0

The emissions of NO_x may change with the use of SPK fuels relative to JP-8. NO_x results from the oxidation of atmospheric nitrogen during combustion, and for gas turbine engines NO_x formation is largely a function of combustion temperature. Estimation of other byproducts, such as PM, CO, and UHC (which are the result of incomplete fuel combustion) are less understood, even for conventional jet fuel; however, initial tests indicate that there is a decrease in PM emissions with the use of SPK fuels in gas turbine engines, ((Corporan, DeWitt and Klingshirn, et al. 2007a), (Whitefield 2008)). Recent tests conducted in February 2009 at NASA's Dryden

Flight Research Center under the name of the Alternative Aviation Fuels EXperiment (AAFEX) should shed more light on how these emissions change with SPK combustion.

Because it has a long life time in the atmosphere, the impact of a unit of CO_2 that is emitted by an aircraft in the upper atmosphere is, on average over the lifetime of the species in the atmosphere, essentially the same as if had been emitted by a car; however, for other emissions from jet fuel combustion in the upper atmosphere, both atmospheric lifetime and average radiative properties are important in determining their global warming potentials. As noted by Hileman, et al. (2009), most of these emissions have an impact on global climate.

> *Aircraft emissions that impact global climate change include the direct effects from CO_2 and water (H_2O) emissions, the indirect forcing from changes in the distributions and concentrations of ozone and methane as a consequence of NO_X emissions, the direct effects (and indirect effects on clouds) from aerosols and aerosol precursors, and the effects associated with condensation trails (contrails) and high-altitude (cirrus) clouds. Each of these emissions and effects has a varied residence time within the atmosphere; CO_2 has a life time of 50 to 200 years, methane of 8 to 10 years, ozone on the order of months, water vapor and NO_X on the order of weeks, and contrails and cirrus clouds on the order of hours. Taken together, these individual effects act to further increase the warming effect of aviation relative to that associated with CO_2 alone, although the relative amount of this additional warming is still the subject of scientific study ((IPCC 1999), (Sausen, et al. 2005), and (Wuebbles, Gupta and Ko 2007)).*
>
> *The non-CO_2 combustion emissions from aviation are known to have comparable influence on global climate change as the combustion CO_2 emissions ((IPCC 1999), (Sausen, et al. 2005), (Wuebbles, Gupta and Ko 2007), (Marais, et al. 2008)). SO_X emissions during cruise tend to cool the climate while NO_X emissions are generally predicted to warm the climate in terms of globally-averaged surface temperature. Depending on where it is emitted within the upper atmosphere, water vapor can be an important GHG (especially when emitted in the stratosphere, where approximately 20 to 40 percent of aircraft emissions are deposited ((IPCC 1999); (Hoinka, Reinhardt and Metz 1993); (Baughcum 1996); (Schumann 1997); (Gettelman and Baughcum 1999)). In contrast, water-vapor emissions at the ground and in the troposphere have a minor impact as a GHG because of the naturally large abundance of water in the hydrological cycle (IPCC 1999). If a fuel results in significant increases in water-vapor emissions when used in aviation, it might be advantageous from a global climate change perspective to use that fuel in ground transportation.*

As part of the Aviation Climate Change Research Initiative (ACCRI), several white papers were compiled to summarize the state of the science of aviation's impact on global climate change[10]. The interested reader is highly encouraged to review these documents. One of the white papers, by Wuebbles et al. (2008), summarizes the state of climate metrics for aviation. Wuebbles et al. (2008) note that "all of the well-accepted metrics of radiative forcing and GWPs … have major limitations that affect their interpretation when used to address many of the policy questions of interest to climate". The following excerpt from the conclusions of Wuebbles et al. (2008) further elucidates the problems with current climate metrics.

> *For example, the equivalent RF [Radiative Forcing] concept can be useful to address questions related to changes in climate for the atmospheric agents that have been emitted over a specific period of time. However, equivalent radiative forcing is not an emissions-based metric.*

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[10] As of February 13, 2008, the ACCRI white papers could be downloaded from http://www.faa.gov/about/office_org/headquarters_offices/aep/aviation_climate/

> *Emissions-based metrics are likely the primary choice for addressing most questions of interest for technological or policy considerations and/or trade-offs.*
>
> *GWPs [Global Warming Potentials] (and AGWPs [Absolute Global Warming Potentials]) are well established but may be difficult to apply to aviation emissions. We recommend that the existing concept be modified to include efficacies, and tests done to see if all effects can be conceptually included. While there have been many criticisms about this, no one has really attempted to see if the concept could be readily modified to include contrails and other cloud effects, e.g., by basing these effects in a more general sense on the emissions associated with fuel burn. Despite its limitations, the GWP concept is so well engrained in current international climate policy considerations that it might actually impede the progress of negotiations to promote use of an alternative metric. As a result, decision-makers are faced with weighing scientific precision relative to practical applicability (Fuglestvedt, et al. 2000).*
>
> *The answer may lie in using similar metrics that address some of the scientific concerns raised by GWPs. Specifically, the GTP [Global Temperature Profile] and the LTR [Linearized Temperature Response] approaches have some major advantages, but neither has been adequately tested. GTPs assume either pulse or sustained emissions while LTR generally uses a pulse of one year of emissions. Both may also be applicable to emissions scenarios.*
>
> *Additional research needs to be done to identify appropriate metrics for evaluating emissions from aviation and from other transportation and energy sectors. The application of existing metrics to aviation emissions needs to be evaluated individually and relative to each other. Some metrics such as the LTR approaches need further development to be scientifically robust. New metrics should also be considered.*

The preferred method for comparison of CO_2 and non-CO_2 life cycle greenhouse gas emissions (N_2O and CH_4) recommended in these guidelines is GWP reported on a CO_2 equivalents basis; however, as noted by Wuebbles et al. (2008) and summarized in Table 5, GWP may not be appropriate for examining aviation's non-CO_2 combustion emissions.

Table 5. Uncertainties, Gaps, and Issues for the Use of GWP to Examine Emissions From Aviation That Impact Global Climate Change. (Wuebbles, Yang and Herman 2008)

Metric	Uncertainties	Gaps	Improvement issues
GWPs -- Global Warming Potentials	Although commonly used in climate studies and policy considerations, it is not known how well this metric could be applied to aviation. Difficult to know what an appropriate time horizon should be, although the 100-year horizon has become the standard. Not clear if GWPs could be applied to regional analyses.	Not clear what time integration of radiative forcing means. Characterization of the impact of a gas is not robust with respect to the climate impact. Difficult to account for contrail formation and other non-emission related effects using GWPs. Not applicable in traditional configuration (fixed integration period integration) for fixed target policy analyses. Applicability for aviation needs to be evaluated.	Applicability for comparing aviation with other transportation / energy sectors needs to be tested. Testing needed using efficacies.

Given the uncertainty in estimating jet engine combustion emissions from alternative fuels, the state of the science of aviation climate change, and the lack of metrics to examine the non-CO_2 combustion emissions from aviation, **it is recommended that only emissions of CO_2 be included in the combustion stage of the LCA at this time, and that the emissions of CO_2 from bio-derived fuels be tracked separately from the CO_2 emissions from fossil-based fuels.** This will allow for a net contribution to atmospheric carbon dioxide to be estimated, while still allowing for data collection would serve multiple purposes. In addition, non-combustion CO_2 emissions should be tracked, to the extent that is practical, for future examination using an appropriate metric.

This approach, of collecting and documenting data that may be required as approaches to the estimation of life cycle greenhouse gas emissions of aviation fuels evolve, will be repeated in other parts of these guidelines, and can be viewed as a guiding principle. For example, recent research has shown that land use change may include both soil emissions from directly-impacted land as well as emissions arising from indirect land use, with land use emissions considered over a 30 year period following initial land perturbation (emissions effectively amortized over that 30 year period). As described later in this report, the guidelines recommended in this report suggest collecting data on land use impacts, in anticipation of the emergence of widely accepted methods for defining indirect land use impacts.

3.8 Functional Unit and Reference Flows

ISO 14040: 2006 (E) (ISO 2006a) defines a functional unit as the “quantified performance of a product system for use as a reference unit”. The function of an aircraft fuel is to provide energy to the gas turbine engine that powers the aircraft. Since the primary production chain has been defined here (and by EISA) to include aircraft operation (i.e., fuel combustion), the functional unit quantifies the propulsion of the aircraft. The preferred functional unit for a jet fuel is megajoules of the lower heating value (MJ (LHV)) of fuel consumed propelling the aircraft. The heating value is referred to as a lower heating value if the water in the exhaust is a vapor; it is referred to as a higher heating value if the water in the exhaust stream is a liquid. For stationary power plants, additional energy is often extracted from fuel combustion by condensing the water vapor to a liquid; however, it is impractical to extract this energy from jet exhaust, hence the choice of LHV.

Additional elements of the functional unit, implicit in the use of the product as jet fuel are a series of specifications summarized in Table 6[11]. The interested reader is directed to Hemighaus, et al. (2006) to learn more about these standards.

Table 6. Commercial and Military Jet Fuel Standards for the United States, United Kingdom and Canada

Jet A-1	British specification DEF STAN 91-91, ASTM D1655
Jet A	ASTM D1655
Jet B	Canadian Specification CAN/CGSB 3.23, ASTM D6615
JP4	Specification MIL-DTL-5624U Grade JP-4 (as of Jan 5, 2004, JP-4 and 5 meet the same US Military Specification) British Specification DEF STAN 91-88 AVTAG/FSII (formerly DERD 2454),where, where FSII stands for Fuel Systems Icing Inhibitor. NATO Code F-40
JP5	Military Specification MIL-DTL-5624U Grade JP-5 (as of Jan 5, 2004, JP-4 and 5 meet the same US Military Specification) British Specification DEF STAN 91-86 AVCAT/FSII (formerly DERD 2452). NATO Code F-44.
JP8	U.S. Military Specification MIL-DTL-83133E. JP-8 also meets the requirements of the British Specification DEF STAN 91-87 AVTUR/FSII (formerly DERD 2453). NATO Code F-34.

The overall goal of the life cycle assessments is to estimate greenhouse gas emissions for the functional unit, which is hereafter referred to as grams of carbon dioxide equivalents per megajoule of LHV **(g CO_2e / MJ)**.

Depending on the specific process used to create the alternative fuel, CO_2, CH_4, N_2O, and other greenhouse gases could result, and these will be reported as carbon dioxide equivalents. GWP provides a measure of the relative radiative effect of a particular greenhouse gas relative to carbon dioxide and should be used to place N_2O, CH_4 and CO_2 (and other long-lived GHG) on equal footing in the form of CO_2e mass. Table 7 presents GWP values based on a 100-year horizon from the IPCC fourth assessment report (IPCC 2007). GWP values have been changing over time as the state of climate science improves. Life cycle practitioners should use the most current GWP values by the IPCC.

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[11] From http://www.csgnetwork.com/jetfuel.html. See Hemighaus et al. (2006) for additional information on these differences and similarities of the fuels that result from these specifications.

Table 7. Global Warming Potential of Greenhouse Gases (IPCC, 2007)

Greenhouse Gas	GWP over 100 years
Carbon dioxide	1
Methane	25
Nitrous oxide	298

As described by Equation 2, the GWP coefficients are used with an emissions inventory to yield the mass of carbon dioxide equivalent.

$$Mass\ (grams)\ CO_2e = (gCO_2 + GWP_{CH_4} \cdot gCH_4 + GWP_{N_2O} \cdot gN_2O)_{WTT} + (gCO_2)_{TTW} \quad (2)$$

The life cycle emissions are based on reference flows from the processes in the life cycle required to fulfill the function expressed by the functional unit. For each specific primary fuel production chain (for a specific fuel), the amount of fuel required to fulfill the functional unit can be different. For example, aircraft operating on fuels providing reduced energy per mass (relative to conventional jet fuel) require more fuel to provide a MJ of energy delivery, as compared to the amount needed by a conventional jet fuel (see (Hileman and Donohoo 2009) and (Cooper 2003) for additional insight). Fuel additives, required for example to meet fuel standards related to freeze properties, may be different for different fuels and must also be quantified as part of the reference flows.

4.0 SYSTEM BOUNDARY DEFINITION AND ANALYSIS

4.1 Background

System boundaries are defined by specifying the unit processes that are to be included in the study and the level of detail to which each unit process is to be resolved. The selection of the system boundary, according to the ISO standards, shall be consistent with the goal of the study, which was defined in Section 3.0. Several methods have been used to determine life cycle system boundaries, all with their individual strengths and weaknesses. This section outlines a preferred method for a comparative aircraft fuel LCAs which is based on methods described in LCA literature. Note that it is assumed herein and as required by the EISA, an LCA to be used for making comparative assertions in the public domain will require quantification of life cycle impacts of a baseline or reference system as well as the alternative of interest.

4.2 System Boundary Determination Approaches

The definition of the goal, functional unit, and primary fuel production chain provide a starting place for system boundary determination. Reap, et al. (2008) provides some system boundary method descriptions and a level of critique. In general these authors warn that when appropriate boundaries are not selected, there is a danger that LCA results may either: (1) not reflect reality well and lead to incorrect interpretations and comparisons ((Graedel 1998); (Lee, O'Callaghan and Allen 1995)), or (2) provide the perception to the decision maker that there is a high degree of uncertainty that effectively lowers confidence in decisions based on the results.

Specifically, Reap, et al. (2008) identify four categories of approaches to boundary selection:

- Qualitative or semi-quantitative approaches
- Quantitative approaches guided by data availability
- Quantitative process-based approaches using cutoff criteria
- Input–output (IO) based approaches

Omitting consideration of the first two methods due to criticisms related to subjectivity, irreproducibility, and lack of scientific bases (Raynolds, Fraser and Checkel 2000), a focus on the latter two methods follows.

4.3 Quantitative Process-Based Approaches to Boundary Definition Using Cutoff Criteria

4.3.1 The ISO

Although noting that the ideal system includes all unit processes needed to ensure that only elemental flows (or inputs and outputs to nature) cross the boundary of the system, the ISO 14044:2006(E) suggests a method for boundary definition based on cutoff criteria that can be described with the following four steps (alluded to in section 4.2.3.3.2 of the ISO 14044:2006 (E) standard; (2006b)):

1. Make an initial identification of processes within the system boundaries using available data.

2. Given the initial process set, list material and energy flows between processes within the system boundary. This effort may be undertaken with data collected from specific sites or from published sources.
3. Apply cutoff criteria to add and remove processes within the system boundary. The standard suggests several cutoff criteria that may be used by LCA practitioners to decide which inputs are to be included in the assessment, and that these criteria can be based on mass, energy, or environmental significance:
    a. Cutoff criteria based on mass: requires the inclusion of unit processes for the production of all inputs and the management of all outputs that cumulatively contribute more than a defined percentage (e.g., $\geq 1\%$) of the mass input of the product system being modeled.
    b. Cutoff criteria based on energy: requires the inclusion of unit processes for the production of all inputs and the management of all outputs that cumulatively contribute more than a defined percentage (e.g., $\geq 1\%$) of the product's energy inputs.
    c. Cutoff criteria based on environmental significance: requires the inclusion of all unit processes for the production of all inputs and the management of all outputs that cumulatively contribute more than a defined percentage (e.g., $\geq 1\%$) of impact of the selected environmental relevant metric.
4. Refine the system boundary. Identify and document material and energy flows that are omitted during the course of the study.

Referring to the fourth step which reflects the iterative nature of LCA, the standard states that decisions regarding omitted data shall be based on a sensitivity analysis to determine their significance to the overall LCA, thereby verifying the initial analysis outlined in ISO 14044:2006 (E), section 4.2.3.3 (2006b). The ISO standard calls for documentation of the results of this iterative system boundary setting process and any sensitivity analysis performed. The sensitivity analysis demonstrates the significance of included or excluded unit processes on the overall results of the study. This procedure serves to limit the subsequent data handling to those inputs and output data that are determined to impact the goal of the LCA.

Implementation of cutoff criteria is investigated by Raynolds, et al. (2000). These authors define the Relative Mass-Energy-Economic (RMEE) method for system boundary selection, essentially assuming the modeler will move outward from the primary production chain which provides the functional unit. As the modeler moves outward, decisions are made as to whether or not each unit process providing a product or service is to be included in the system boundary using a "relative ratio" to determine inclusion. The ratio is intended to act as a proxy for the potential life cycle impact of the product or service on the overall system. Specifically, one ratio (Z_{RMEE}) is established for all mass, energy, and economic criteria as a percent of the total mass, energy, and economic value of the system functional unit, for example:

given $Z_{RMEE} = 1\%$,
if

$$\frac{\text{mass of the unit process input or output being tested (kg)}}{\text{mass of the functional unit (kg)}} \geq 1\% \text{ or}$$

$$\frac{\text{energy of the unit process input or output being tested (MJ)}}{\text{energy of the functional unit (MJ)}} \geq 1\% \text{ or}$$

$$\frac{\text{economic value of the unit process input or output being tested (US\$)}}{\text{economic value of the functional unit (US\$)}} \geq 1\%$$

then, the life cycle processes for the production of the unit process input or output being tested is included in the system.

Thus, starting with the unit process producing the product of interest, if the ratio of the mass, energy, and economic value of a process input or service to the total mass, energy, and economic value of the system functional unit is greater than Z_{RMEE}, then a unit process producing that product or service is included in the system. This process is repeated for all products and services needed by the unit process producing the product of interest, as well as those subsequently added to the system boundary, until all relative ratios are less than Z_{RMEE}.

4.3.2 Critique of Cutoff Criteria Approaches to Boundary Definition

Reap, et al. (2008) suggest that process-based approaches which use cutoff criteria such as the RMEE method essentially introduce truncation error that can be substantial. In other words, there is no guarantee that a small mass or energy contribution lost through use of cutoff criteria will always result in negligible mass, energy, economic value, or environmental impact across the product life cycle. For example and within the context of carbon footprinting, although an energy input associated with a land use change may fall below a cutoff criteria threshold, the greenhouse gas emissions of this land use change, as described in Section 2.0, can be substantial.

Further, the ISO standard states that if a study is intended for *comparative assertions* and is to be released to the public, a sensitivity analysis shall include mass, energy and environmental significance criteria relative to the system boundary. Such a system-boundary-level sensitivity analysis is intended to re-test the importance of a cutoff unit process flow to the cumulative system impact (e.g., to ensure that a cutoff flow deemed a small percentage of a unit process flow is not significant at the system-level). Such a system-level sensitivity analysis requires the total flows for the life cycle to be known (Reap, et al. 2008). If a practitioner has gathered all the data needed to establish the true final totals, why would some of the data be cut off? For this reason the guidelines proposed in this report eliminate the need to define a cutoff criteria.

4.4 Input-Output (IO) Based Approaches to Boundary Definition

The Economic Input-Output analysis-based LCA (EIOLCA) method uses economic input-output data derived from inter-industry transaction matrices for the US and publicly available environmental data to arrive at comprehensive, industry-wide environmental impacts ((Lave, et al. 1995); (Hendrickson, Horvath, et al. 1998); (Hendrickson, Lave and Matthews 2005)). For the US, the implementation of input-output (IO) modeling, including GHG emissions, is found in the EIOLCA model (available at www.eiolca.net). EIOLCA employs the 2002 U.S. Department of Commerce 426-sector industry-by-industry input-output matrix (Stewart, Stone and Streitwieser 2007), and publicly available environmental data, mostly from the U.S. Department of Energy and Environmental Protection Agency ((EPA 1995); (EPA 2002)). The power of this model is in its ability to determine system level environmental impacts with the goal of reducing cutoff error. The system includes the activities of all upstream suppliers (i.e., the product, the service suppliers of the product, the suppliers of the suppliers, and beyond) and thus upstream supplier environmental impact (e.g., GHG emissions) linked to the flow of interest by economic exchanges, measured in US dollars. While some of these suppliers are included in a typical process-based LCA, others remain elusive as they are too far up the supply chain from primary activities or are omitted based on cut off criteria.

The EIOLCA model has a number of weaknesses, however, that limits its utility for detailed analyses of a comparative nature where resolution between specific technologies is required. EIOLCA cannot resolve impacts on a product level (as in differences between types of organic chemicals or non-ferrous metals) but rather looks at sector impacts. In other words, the EIOLCA data have a high degree of product and service aggregation. For instance, the production of different organic fuel additives would map to the “Other Organic Chemicals” sector, yielding the impacts of the average manufacturer in the sector and not reflecting the difference in production technologies between different organic fuel additives. Also, the EIOLCA model reflects transactions occurring in the US economy, it treats imports (e.g. imported crude oil) as if they were produced in the US with US technologies and logistics. Further, the EIOLCA model cannot strictly account for use, disposal or recycling of the products.

To offset some of these limitations, a hybrid LCA modeling methodology has been developed (Suh, et al. 2004) that combines process modeling of the primary system with EIOLCA data for products and services needed by each primary system unit process. Hybrid LCA comes in two general forms: a combination of physical flows and monetary flows and a combination of sector and process data. Examples of these general forms include the tiered hybrid analysis, input-output hybrid analysis, and an integrated hybrid analysis. The latter two methods require the disaggregation of salient US sectors (for instance the electricity sector) or the addition of the detailed input-output model of the process under consideration to alleviate the need for product allocation during the analysis, respectively. **The tiered hybrid approach, the method suggested for possible use in this guidance, involves developing a detailed process model for first order and some lower order processes that have a recognized critical impact and using the EIOLCA model to quantify the other inputs.**

It is important to note that the EIOLCA methods do not explicitly select boundaries. The EIOLCA tool implicitly sets the boundaries at the level of materials extracted from the earth, referred to as elementary flows (note that these are not flows of chemical elements, but flows of materials extracted from the earth in the chemical form in which they are extracted). As pointed out by Suh and co-authors (2004) even though the ISO standard has a goal of defining a boundary where all inputs and output are elementary flows, this is a difficult goal for those conducting process-based analyses. The EIOLCA approaches this goal, at least to the level of the US economy.

4.5 System Boundary Guidance

Based on the above description of both quantitative process-based approaches using cutoff criteria and IO boundary definition approaches, a blended method leveraging the useful attributes of each method is presented here. The system boundary determination guidance in this report seeks to:

- Eliminate the use of subjective cutoff criteria
- Create reasonable data collection burdens in support of current fuel policies, including a quantification of the on-going unit process operation within the primary production pathway chain
- Extend the boundaries as close to elementary flows at the system boundary as possible (identified by the ISO standard as the ideal)
- Target data collection efforts towards what is needed for understanding and estimating significant impact contributors

It is important to remember the goal of the study: to provide a comparative assertion. It is assumed that the modeler will prepare or have access to a baseline system from which unit process and life cycle GHG emissions can be compared.

4.6 Recommended Method Details

The following decision tree outlines an iterative process for defining the system boundary. Each of these steps will be described below.

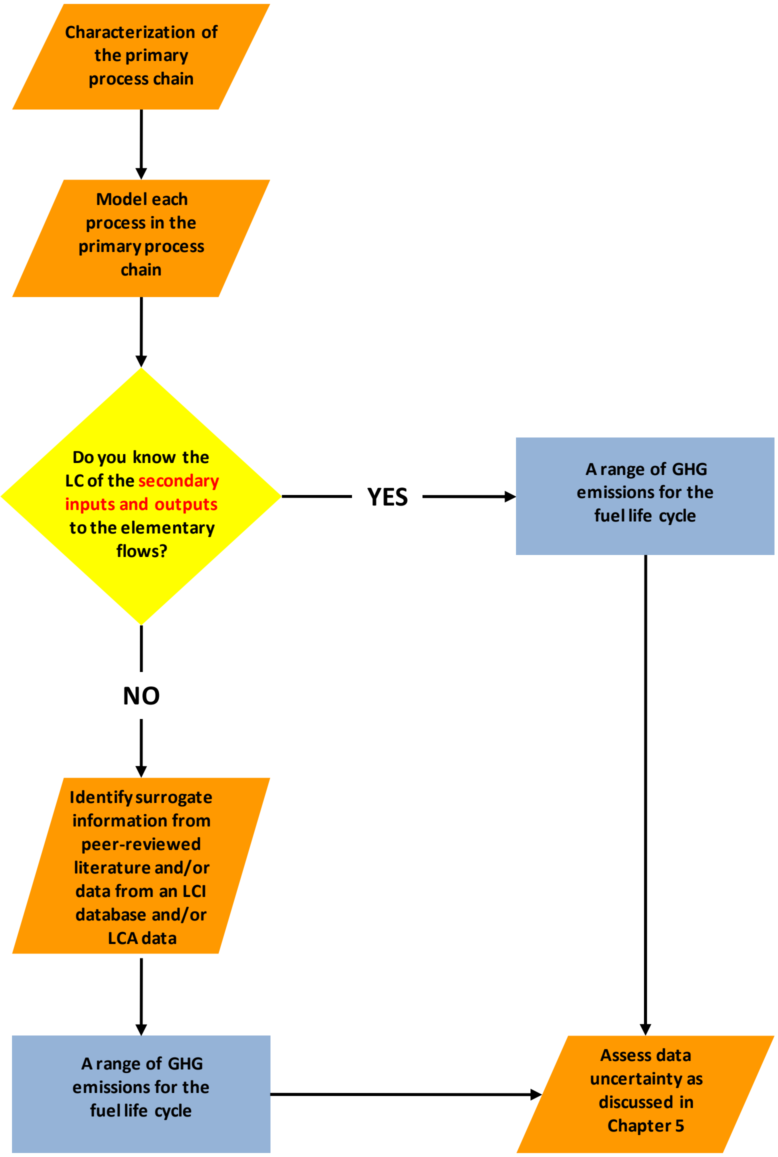

Figure 8. System Boundary Decision Flow

4.7 Characterization of the Primary Process Chain

Section 3.0 and Table 8 identify six life cycle stages that should be used in evaluating greenhouse gas emissions from aviation fuels and conceptual diagrams are provided for a number of conventional and alternative fuels. Section 4.2.3.3.1 of the ISO14044:2006(E) (2006b) standard notes that the deletion of life cycle stages, processes, inputs or outputs is permitted only if it does not significantly change the overall conclusions of the study.

> "Any decisions to omit life cycle stages, processes, inputs, or outputs shall be clearly stated, and the reasons and implications for their omission shall be explained.

Decisions shall also be made regarding which inputs and outputs shall be included and the level of detail of the LCA shall be clearly stated."[12]

4.7.1 Identification of the Initial System Boundaries/First Order Processes

The systems boundary defines the unit processes to be included in the analysis in such a way that inputs and outputs at the system's boundaries are the modeler's best determination of elementary flows. *For each unit process*, the following are to be considered (based on ISO 14041 (1998) methods and additional considerations for this guideline document):

- **Geographic specificity:** where the process is being executed, which will be specified in the study design; this relates to input and output characteristics.
- **Flows between industrial processes**
    - Construction of capital equipment, facilities and infrastructure
      The modeler may assume that some capital equipment, facilities and infrastructure exist but should consider whether or not maintenance or replacement is appropriate over the life defined in the functional unit
    - Transport and storage of product materials, ancillary materials, and waste materials
      This should include where each is coming from and account for the modes of transport used
    - Process operation: the operation of capital equipment and included energy use (fuels, heat, and electricity); product materials use; ancillary materials use (solvents, catalysts); products; co-products; wastes to air, water, and other management; and losses due to inefficiency or other factors.
    - Operation of facilities (materials management, lighting, heating) and infrastructure within the system boundary
    - Maintenance operations cleaning and part replacement
- **Environmental inputs and outputs**
    - The goal of studies covered under this framework document includes assessment of only GHG emissions. Future iterations may include consideration of other emissions, resource demands, and impacts.
- **Direct Land Use Changes**
    - Greenhouse gas impacts related to direct land use changes shall be included, and it is recommended that the modeler follow the guidance and use the factors provided by the IPCC. Direct land-use change occurs when a feedstock displaces a prior land-use (e.g. forest), thereby generating possible changes in the carbon stock of land. The IPCC Guidelines[13] provide a framework for quantifying and reporting methodologies as well as emission/removal factors (called the "Tier 1 Methodologies"). As noted by Agyemang-Bonsu, et al.(2005), although higher

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[12] See Section 3.3.2.

[13] Available at http://www.ipcc.ch/ipccreports/methodology-reports.htm

tier IPCC methodologies are based on more sophisticated methods for estimating emissions/removals and on the use of national or regional parameters that accommodate the specific national circumstances, these methods are not always described in detail in the IPCC Guidelines. Herein, as suggested by Agyemang-Bonsu, et al. (2005), the use of transparent and well documented methods consistent with those in the IPCC Guidelines is encouraged[14].

- **Indirect Land Use Changes**
    - Indirect land-use change occurs when the displacement of previous activity or land use induces land use changes on other lands. Indirect land use change (discussed below) should be considered once regulatory guidance of its calculation and impact is issued.

Keeping in mind the above unit process considerations, the identification of initial system boundaries involves specifying the first order processes (the primary process chain) in each of the life cycle stages, which will depend directly on the goal and scope of a given study. Several simplified process schematics defining first order or primary processes are available in Section 3.0. Table 8 defines the life cycle stages that are used throughout this guidance.

Table 8. Life Cycle Stage Descriptions

	Stage Name	Stage Abbreviation	Stage Description
1	Raw Material Acquisition	RMA	Boundary includes extraction of raw feedstocks from the earth and any partial processing of the raw materials that may occur (e.g., oil seed harvesting and processing, upgrading to meet quality requirements for crude pipeline transport)
2	Raw Material Transport	RMT	Boundary begins at the end of extraction/pre-processing of the raw materials and ends at the entrance to the refinery facility. Refinery feedstocks may be transported from both domestic and foreign sources to US refineries
3	Liquid Fuels Production (Manufacturing or Conversion)	LFP	Boundary starts with the receipt of refinery inputs at the entrance of the refinery facility and ends at the point of aviation fuel input to the product transport system. Emissions associated with acquisition and production of indirect fuel inputs (e.g., purchased power and steam, purchased fuels such as natural gas and coal, and fuels produced and subsequently used in the refinery) are included in this stage. Emissions associated with on-site and off-site hydrogen production (for hydrogen used in liquid fuels production) are included in this stage, including emissions associated with raw material acquisition for hydrogen plant feedstock and fuel.

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[14] Available at http://www.ipcc.ch/pdf/special-reports/srccs/srccs_chapter9.pdf

Table 8. Life Cycle Stage Descriptions *(Cont'd)*

	Stage Name	Stage Abbreviation	Stage Description
4	Product Transport and Refueling	PT	Boundary starts at the gate of the petroleum refinery with aviation fuel already loaded into the product transport system and ends with the dispensing of the fuel into the aircraft. Boundary includes the operation of the bulk fuel storage depot, transport of jet fuel from storage tanks to the aircraft, and aircraft refueling.
5	Use/Aircraft Operation	Use	Boundary starts at the aircraft fuel tank and ends with the combustion of the liquid fuel.
6	End-of-Life	EOL	Boundary starts when the value of the product to the end user has expired. This stage is excluded for the first order process when the primary reference flow is a fuel that will be combusted during Stage 5, the use stage.

An example of each life cycle stage is presented in simplified form for a hypothetical coal-to-liquid (CTL) aviation fuels process. Table 9 outlines the processes as well as the inputs and outputs for each stage. In the interest of simplicity of presentation, only select among the "flows between industrial processes," and the "environmental inputs and outputs" listed in Section 4.7.1 have been included in Table 9.

Table 9. CTL Process Primary Inputs and Outputs

LC Stage	Process	Inputs	Outputs
RMA	Coal Mining	Electricity, Diesel, Mining and Coal Preparation Equipment	Coal, GHG
RMT	Coal Transport by Rail	Coal, Diesel, Railcars and Railway Equipment	Coal, GHG
LFP	Fischer-Tropsch Facility for Coal to Liquid Fuel	Coal, Fuel Oil, Electricity, Chemicals [catalysts, solvents], Facility Equipment	Fuel, GHG
PT	Transport of Liquid Fuel by Pipeline	Fuel, Pipeline Equipment	Fuel, GHG
Use	Combustion of Liquid Fuel	Fuel, Chemicals (Jet Fuel Additives)	Fuel, GHG
EOL	Not applicable at the first order process level for this example		

4.8 Characterization of Second Order/Secondary Processes

First order process flows have their own life cycles which are provided by secondary or second order life cycle processes (using the terminology within this guideline document). Figure 9 provides an example of a simplified process schematic to define first order versus second order process distinctions.

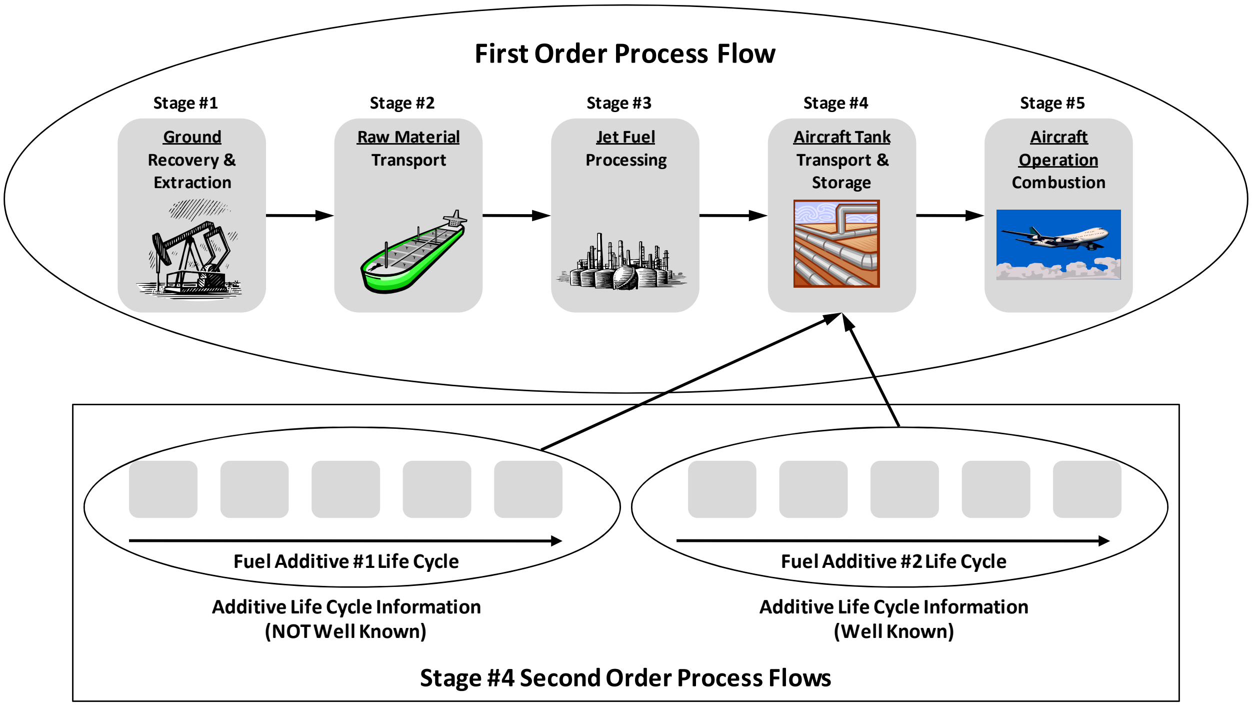

Figure 9. Simplified Process Schematic Defining First and Second Order Process Flows

In the example shown in Figure 9, additives #1 and #2 are mixed with the fuel prior to use. As these additives are material flows input into a primary process of the system, they are considered to be first order process flows. The inputs into the life cycles of these additives (e.g., electricity used in the production of the additives) are second order process flows. Some of these second order flows may be "well known" if inventory data for the processes used to manufacture the additives are available. Here, "well known" refers to situations in which the LCA of a higher order unit process has been prepared following the guidelines described in the entirety of this document and matches the goal and scope definition for the study at hand in a way that meets the data quality requirements. In such a case, referring back to the decision tree in Figure 8, then the answer to "do you know the life cycle of the secondary inputs and output flows to elementary flows" is yes. For other additives, the processes used to manufacture the additives may be less well known.

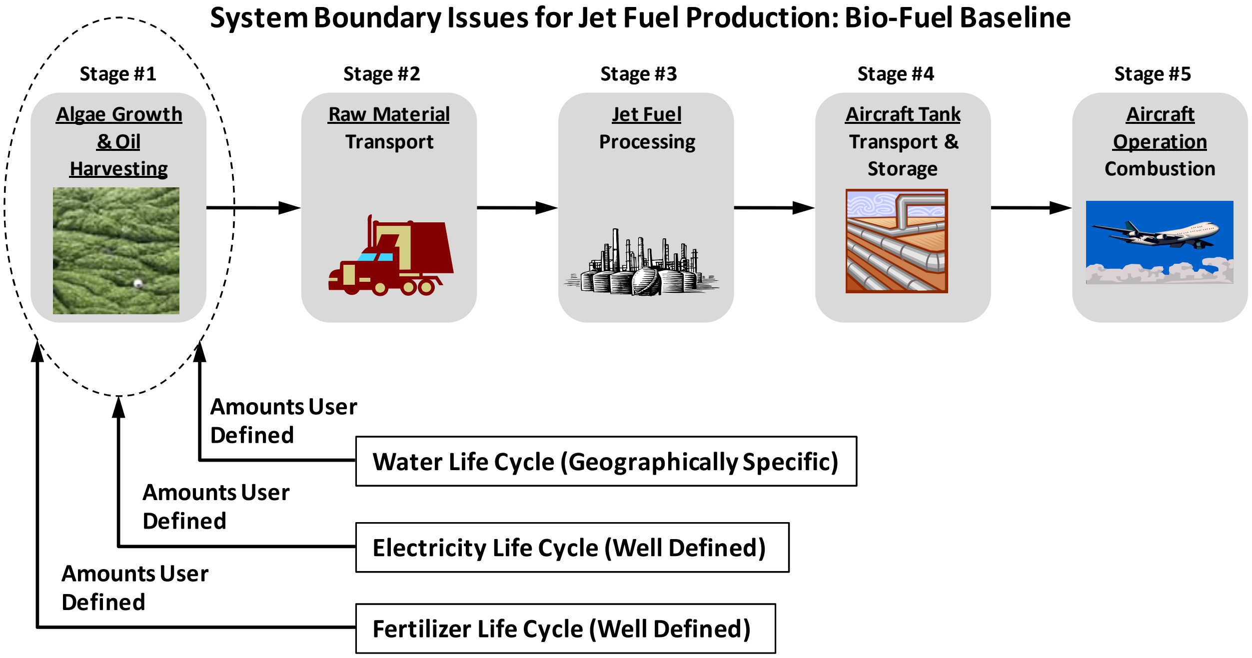

Figure 10. Second Order Process Flows in Algae Production

Another example of second order process flows is given in Figure 10, in which the primary process flows of electricity, fertilizer and water are used in algae production. In this case the second order process flows would be the inputs to electricity production, fertilizer and water. Life cycle data for the electricity and fertilizer second order flows are likely to be well known. In this case, referring back to the decision tree in Figure 8, the answer to “do you know the life cycle of the secondary inputs and outputs to the elementary flows” is yes, and thus characterization of this secondary flow is straight-forward. In contrast in this example, the inputs required to provide water for algae production depend on local sources and water quality requirements for the algae production and may not be well known. At this juncture, the modeler must search for the data needed to characterize the life cycle of the production of water. A methodology recommended for use in identifying surrogate higher-order process data is provided below.

4.9 Identification of Surrogate Higher Order Process Information

This guideline document recommends **two** sources of surrogate data for use beyond the primary process chain when life cycle data are not readily available. Both approaches should be used, documented, and verified during the LCA critical or peer review, resulting in a range of potential values for life cycle GHG emissions.

- **Data source 1: peer reviewed documentation of the life cycle of surrogate processes** in archival literature, in a project report, or in a LCI database. Although striving to achieve the closest match to the system at hand, these data may not match geographic, temporal, technological, or other specific characteristics of the higher order process of interest. Examples of LCI databases include, but are not limited to, national database projects (such as the National Renewable Energy Laboratory’s US LCI database or the database at the University of Washington[15]) or those maintained by private organizations such as within the GaBi (see http://www.gabi-software.com/) or SimaPro (see http://www.pre.nl/simapro/) LCA software tools. Note also that although such studies or data sets can provide the modeler with an inventory of life cycle data for many compounds and processes, often times these data are based on proprietary information subject to data aggregation to protect the original data source. These data are considered herein to be not transparent enough for a comprehensive LCA to be used as the sole source of life cycle GHG emissions without further investigation.

- **Data source 2: EIOLCA data for the life cycle of the sector in which the higher order flow is produced**. Specifically, the modeler can apply the EIOLCA model, including the sector-based sensitivity analysis described by Hendrickson, Lave, and Matthews (2005)[16], or use the high end of the range for the relative standard error for the sectors of 10% to 20%, to determine the range of life cycle GHG emissions for the flow. The resulting range of GHG values provided by the EIOLCA sensitivity analysis presumably contains within it the US value for the higher order flow of interest, thus providing the best currently available conservative estimate of a process-based LCA extended to elementary flows.

Given these two data sources, if multiple studies or data sets describe viable surrogates, all identified surrogate data sets should be included in the continuing steps in the boundary definition assessment. Since the EIOLCA model covers the entire economic sector and can provide a range of values, there should not be a case in which applying these data will not result in a range of possible values for any given flow. Thus, if the modeler is not able to define surrogate life cycle GHG emissions using these methods the higher order process should be modeled as if it were a primary process (i.e., following the steps outlined in the section above). Finally, it is the responsibility of the modeler and peer review team to ensure all such data have been peer reviewed.

Once the range of surrogate life cycle GHG emissions are determined, the modeler can decide to accept the range, proceed with the characterization of the remaining higher order processes, and move forward to sensitivity analysis as defined in Section 6.0. Alternatively the modeler could determine that this range of values is not sufficiently representative, will unduly impact the study results, and collect more detail on the higher order process.

At this point in the boundary definition process the modeler either has a value for the life cycle GHG emissions of the fuel (because they answered yes to "do you know the life cycle of the secondary inputs and output flows to elementary flows") or a range based on the two surrogate LC data methods described above. The system boundary will be defined, and the modeler will proceed to sensitivity and uncertainty analysis as described in Section 6.0.

4.10 Surrogate Data Example

Alternative aviation fuels may have less sulfur and other heteroatoms than conventional petroleum-derived jet fuels and therefore require the addition of additives for lubricity (sulfur and other heteroatoms in traditional jet fuels aids in lubrication). In this example the modeler

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[15] Available at: http://faculty.washington.edu/cooperjs/Research/database%20projects.htm

[16] See Appendix 4 of the reference for method.

does not have specific data concerning lubrication additives but finds that QPL-25017-22 that recommends the use of 22.5 mg DCI-4A (a proprietary jet fuel additive (Lacey and Westbrook 1997)) per liter of alternative jet fuel. The modeler does not know/ have access to the chemical composition of DCI-4A nor the life cycle data for the production of DCI-4A. The modeler however does have access to information from Octel, a distributor of DCI-4A, whose website links to a material safety data sheet (MSDS) for DCI-4A. The DCI-4A MSDS specifies the chemical is 60-80% proprietary material, 20-40% dimethyl benzene, and <5% diethyl benzene. Given these data, the modeler, who needs to identify surrogate data for the life cycle GHG emissions of DCI-4A proceeded as follows:

- Review of Available Peer Reviewed Literature: The modeler was unable to find a peer reviewed LCA of a chemical with characteristics similar to DCI-4A that provided life cycle GHG results in a transparent form. The modeler did however find that Capello, et. al. estimated the life cycle GHG emissions for 50 organic solvents, including dimethyl benzene, to range from approximately 0.8 to 6.2 kg CO_2e/ kg solvent. Using these data as a surrogate for the additive and assuming 22.5 mg DCI-4A is needed per liter of alternative jet fuel equates to a range of 0.018 to 0.14 g CO_2e per liter of alternative jet fuel (or 0.00052 to 0.0040 g CO_2e per MJ of alternative jet fuel assuming a LHV of 54 kJ/m^3).
- EIOLCA Model***:*** The modeler used the Carnegie Mellon EIO-LCA model which is available to use free of charge from the following website: ***http://www.eiolca.net/***. The modeler needed an approximation for the cost of the lubricant so they called Octel, a distributor of DCI-4A and received a cost value of 2.10$/lb of DCI-4A. Using EIOLCA for the sector "Other Organic Chemical" the life cycle GHG emissions were estimated based on a 90% confidence interval to be 0.0011 ± 0.00036 g CO_2e/MJ alternative jet fuel (i.e., at a range of 0.00077 to 0.0015 g CO_2e/MJ).

Using the method depicted in Figure 8, the life cycle GHG emission range for the additive finds the EIOLCA data fitting within the data presented by Capello, et. al. and thus applying the Capella, et. al. range of 0.00052 to 0.0040 g CO_2e per MJ of alternative jet fuel for the life cycle. Should the use of the high end of this range (0.0040 g CO_2e per MJ of alternative jet fuel) in the alternative fuel LCA result in superior performance when compared to the convention fuel, no refinement of the DCI-4A life cycle data would be needed.

4.11 Modeling GHG Emissions For Indirect Land Use Change

4.11.1 Background

Estimation of the GHG emissions of alternative jet fuels using bio-based feedstocks requires consideration not only of growth and soil processes on the land used to produce the fuel feedstock (the direct land use) but also processes on land which would through price changes result in a change in land use elsewhere throughout the globe (the indirect land use). Most notably, the conversion of cropland to the production of biofuel feedstocks can be expected to cause the conversion of non-cropland (grassland, forest, pasture) to cropland somewhere else which must be considered in biojet LCAs.

Guidance on how to estimate the GHG impact for indirect "land use change" (LUC) can be gained from the California Air Resources Board (ARB) "Staff Report: Proposed Regulations to Implement the Low Carbon Fuel Standard" [1] and the US EPA's "Draft Regulatory Impact

Analysis: Changes to Renewable Fuel Standard Program" [2]. They suggest a framework based on five key questions:

- How much land is converted?
- Where does land use change occur?
- What types of land are converted?
- What are the GHG emissions from that land conversion?
- How do we account for the variable timing of land use change GHG releases?

Guidance on how to respond to these questions is provided within the USEPA document [2], and is the subject of on-going research and policy discussions. As follows, an example of the estimation of indirect LUC GHG emissions within a hypothetical biojet LCA is presented, with attention paid to uncertain decisions and the limitations of assumptions throughout.

4.11.2 LUC Illustrative Example

Suppose the intent is to produce biojet as a replacement to conventional jet fuel and that the feedstock of interest is to be grown on land that was previously used for production of *crop A*. The increase in the demand for crop A causes a shortage in the first growing season. In subsequent growing seasons, the supply of crop A and the supply of substitute crops (e.g., crops B, C, and D) increase to meet the new demand, such that prices eventually equilibrate and finally decrease over time - supply outstripping demand. The final increase in supply means that new lands are brought into the production of crops A – D (the "new crop mix") at varying levels of production efficiency (i.e., in the new crop mix, it is possible that crop A will be produced more or less efficiently than the original production of crop A). These phenomena combine to form a "market-mediated response," which is discussed conceptually by Hertel, et. al. (2009) [3] with related sources of uncertainty described by the EPA in detail [2] and in a public EPA fact sheet [4]. The land used to produce the "new crop mix" for the final increase in supply is the indirect LUC.

For this example, the assumptions used for purposes of illustration in the estimation of the GHG emissions from the indirect LUC are presented in Table 10. Limitations for each assumption are noted, which in all cases deal with the ability of the modeler to be confident in the relevance and comprehensiveness of land use types, management regimes, and the associated data. Ongoing indirect land use change research (e.g., as part of EPA's Renewable Fuel Standard rulemaking) will provide further insight and guidance on how to appropriately determine the assumptions/values described in Table 10.

Table 10. Indirect Land Use Assumptions Used in the Example (For Illustrative Purposes Only)

	Indirect land use assumptions for the example	Assumption notes and limitations
How much land is converted?	**500 liters of biojet are produced per ha of direct land** (which at 5.23 mmBTU/bbl (LHV) equates to 30.4 liters/mmBTU) or **0.061 direct ha producing *crop A*/ mmBTU of biojet produced per year** **0.011 indirect ha producing *the new crop mix*/ mmBTU of biojet produced per year**	The land area indirectly converted must consider a range of factors that affect global agricultural commodity markets, and the modeler must be confident their choice is relevant and comprehensively describes subsequent indirect land uses.
Where does land use change occur?	In a temperate, dry region	Indirect LUC impacts can occur in many different regions. Regional variations in GHG emissions data are wide, and the modeler must be confident their choice is relevant and comprehensively describes subsequent indirect land uses.
What types of land are converted?	**The previous use of the indirect land before conversion:** A coniferous, unmanaged, continental forest with above-ground biomass at 50-150 tonnes/ ha and low activity soils is cleared with fire **The use of the indirect lands after conversion:** Cropping system containing perennial species (long-term cultivation, full tillage)	A wide range of forest, grassland, and pastureland types could be affected by indirect LUC; thus, assuming that all land conversion results in deforestation provides an extreme example for illustrative purposes only. The modeler must be confident their choice is relevant and comprehensively describes previous land uses. A wide range of crop and cultivation/ tillage practices are possible, and the modeler must be confident their choice is relevant and comprehensively describes subsequent land uses.
What are the GHG emissions from that land conversion?	Use IPCC default data and methods to calculate: • Change in the life cycle emissions from crop production, • Change in biomass carbon stocks, • Non-CO2 emissions from land clearing, • Lost forest sequestration, and • Change in soil carbon stocks	GHG emissions estimation must match region and types of lands converted and the conversion methods, and the modeler must be confident their choice is relevant and comprehensively describes subsequent indirect land uses. Default IPCC data should be considered a general approximation (or Tier I approach) due to coarse resolution. Precision can be added with higher resolution data sets from the scientific literature.
How do we account for the variable timing of land use change GHG releases?	Physical life cycle GHG emissions, including emissions resulting from indirect land use change, are displayed from 2010 to 2040 (over 30 years)	GHG emissions from biofuel-induced land use changes can vary considerably over time. The modeler should show how emissions vary over time. If the modeler aggregates emissions over time, the modeler must be confident their choice of time horizon and accounting methods are relevant and appropriate.

Based on the information presented in Table 10, Figure 11 depicts the market interactions given the dissemination of the biojet production system and the resulting scope of the example biojet LCA. As shown, the current system, based on the production of 1mmBTU of conventional jet and the production of *crop A* on 0.061 ha of land, is replaced by a system producing 1mmBTU of biojet and *the new crop mix* on 0.011 ha of land. On the crop side, the production of the "new crop mix" is assumed to meet the final increase in supply resulting from the increase in demand for crop A.

On the fuel side, it is assumed that the biojet is added to the jet fuel market resulting in changes, or "rebound effects," in fuel markets. In a manner similar to the market changes considered for indirect LUC, rebound effects account for market changes that might result from new production of biojet. Several rebound effects could result. For example, an increase in jet fuel supply when could result in a subsequent drop in the price of jet fuel and an increase in its use, such that prices eventually equilibrate and finally increase over time – demand outstripping supply. A second rebound effect would involve a decrease in the production of jet fuel from crude oil which would have oil refineries blend the portion of the crude oil that would have been used for the production of jet fuel into “other crude oil refinery products” (gasoline, diesel, chemical precursors, etc.) and resulting in an increase in the supply and a decrease in the price of the “other crude oil refinery products.” A third rebound effect would also involve a decrease in the production of jet fuel from crude oil but would have the oil refineries use the jet fuel (or some version of the portion of the crude used as jet fuel feed) as a fuel to support refining processes. Other rebound effects are possible, and a mix of rebound effects is likely.

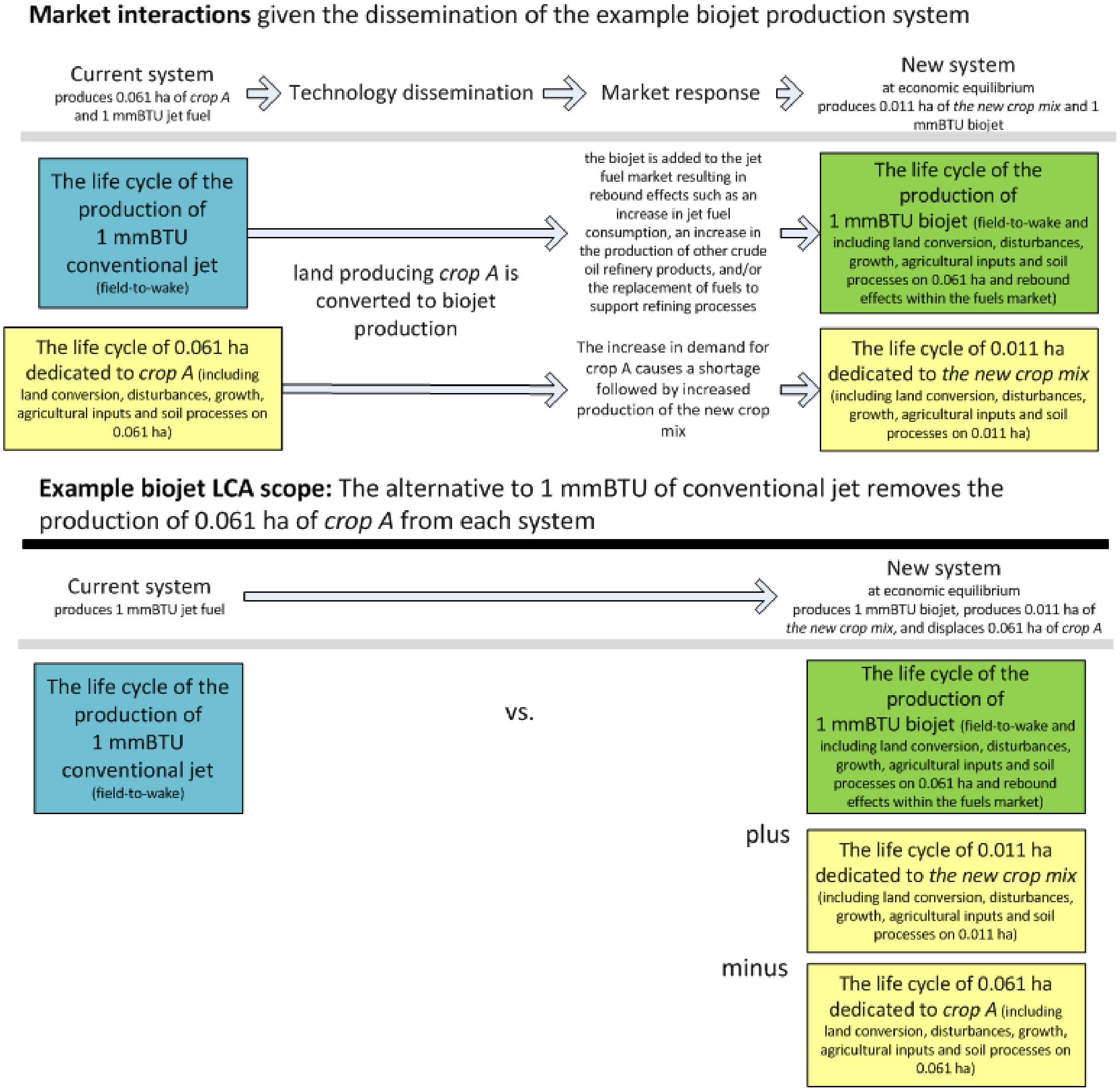

Figure 11. Market Interactions and the Scope of the Example Biojet LCA

In the bottom portion of Figure 11, the LCA scope is depicted. For the LCA, it is assumed that the desire is to compare **only** the life cycle of conventional jet (as field-to-wake) to the proposed system based on the life cycle of biojet. Computationally, this means that the life cycle impacts of the production of 0.061 ha of *crop A* are credited to the proposed system based on the life cycle of biojet, as they no longer occur. Thus, as depicted in Figure 11, the scope of the proposed biojet LCA includes the life cycle of the production of biojet (as field-to-wake and including land conversion, disturbances, growth, agricultural inputs and soil processes on direct lands and rebound effects within the fuels market), the conversion of 0.011 ha from forest to *the new crop mix*, and the life cycle of *the new crop mix* production on 0.011 ha, less the life cycle of the production of 0.061 ha of *crop A*. Further, it is very important to note that any crop produced in the current system will likely be replaced by a mix of different agricultural products (e.g., food crops, livestock feed crops, livestock themselves, etc.), as opposed to replacement by a single *the new crop mix* as assumed here.

Next, Table 11 and Figure 12 present the data used in the example biojet LCA, based on equations and data from the IPCC presented in Table 12. In general, the calculations follow the US EPA's approach [2]. As shown, in 2010 indirect emissions represent the change in the life cycle emissions from the switch from *crop A to the new crop mix* as well as the non-CO_2 emissions from land clearing and the change in biomass carbon stocks in the forest on indirect lands. In 2010 and beyond, lost forest sequestration and changes in soil carbon stocks are accounted for. As shown in Figure 12, the cumulative indirect LUC contribution decreases as time proceeds, with the majority of the benefit coming from the change in the life cycle emissions from crop production. Essentially, this can be thought of as the movement of the agricultural markets towards more efficient practices (from *crop A* to *the new crop mix*) as a result of an increased demand for the biojet feedstock.

Table 11. GHG Emissions Associated With Indirect Land Conversion for the Biojet LCA Example (Per Indirect Ha Converted, See Table 12 for the Data and Equations Used)

	Indirect land use change GHG emissions assumptions for the example
Change in the life cycle emissions from crop production (i.e., production of 0.011 ha of *the new crop mix* minus production of 0.061 ha of *crop A*)	-18.3 tonne CO2e/ year for each indirect ha converted
Non-CO2 emissions from land clearing	10.6 tonne CO2e in year 0 for each indirect ha converted
Change in biomass carbon stocks	444 tonne CO2e in year 0 for each indirect ha converted
Lost forest sequestration	8.27 tonne CO2e/ year for each indirect ha converted
Change in soil carbon stocks	0.792 tonne CO2e/ year for the first 20 years for each indirect ha converted

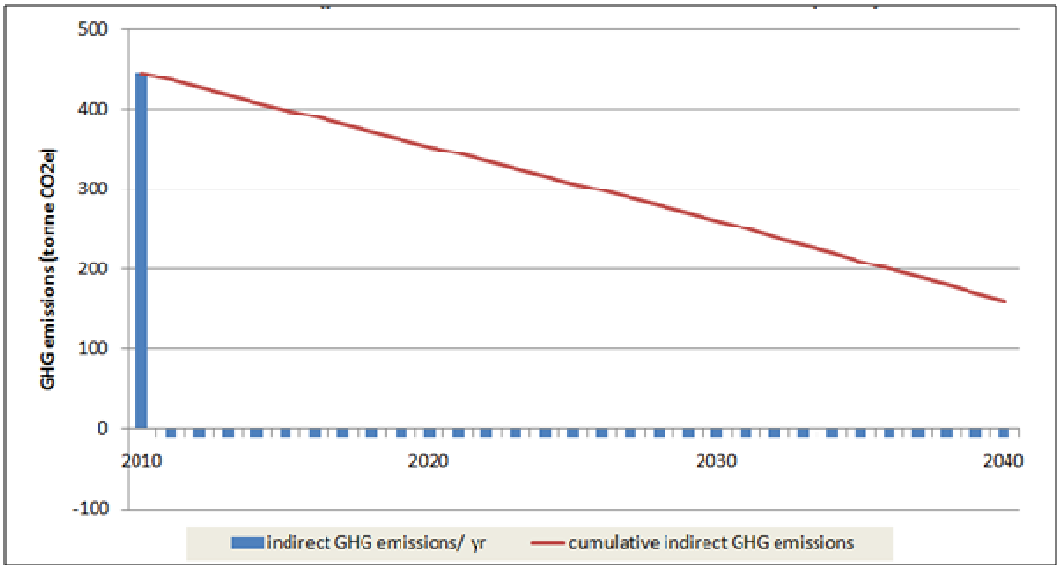

Figure 12. Example Indirect LUC GHG Emissions (Per Indirect Ha Converted From Forest to *the new crop mix*)

Table 12. Estimation of GHG Emissions for Indirect Land Conversion (Per Indirect Ha Converted)

	Indirect land use assumptions for the example
Change in the life cycle emissions from crop production	**Change in the life cycle emissions from crop production = -18.3 tonne CO2e/ yr for each indirect ha converted** Estimated as: Change in the life cycle emissions from crop production = $\frac{(LCIC*IA)-(LCDC*DA)}{IA}$ assuming • LCIC= the life cycle GHG emissions for *the new crop mix* produced on indirect lands during biojet production is 4.6 tonnes CO2 e/ha/yr • IA = the ha of indirect land used for *the new crop mix* production is 0.011 ha/ mmBTU biojet • LCDC= the life cycle GHG emissions for *crop A* produced on direct lands prior to biojet production is 4.0 tonnes CO2 e/ha/yr • DA = the ha of direct land used for biojet production is 0.061 ha/ mmBTU biojet
Non-CO2 emissions from land clearing	**Non-CO2 emissions from land clearing= 10.6 tonne CO2e in yr 0 for each indirect ha converted** Assuming the forest is cleared by fire, non-CO_2 GHG emissions were estimated using Equation 2.27 of the IPCC AFOLU [6] assuming: • **The fuel (dead organic matter plus live biomass) biomass consumption is 50.4 tonnes dry matter/ ha** (for non-Eucalyptis forests temperate forests from Table 2.4 of the IPCC [6]) • **The emission factors for CH4 and N2O are 7.1 and 0.11 g/kg dry matter combusted** respectively (from the IPCC [7] Table 3A.1.16, on page 3.185); and • **The GWPs of CH4 and N2O are 25 and 298 tonne CO2e/ tonne emitted** respectively (as suggested in the IPCC AR4)

Table 12. Estimation of GHG Emissions for Indirect Land Conversion (Per Indirect Ha Converted) *(Cont'd)*

	Indirect land use assumptions for the example
Change in biomass carbon stocks	**Change in biomass carbon stocks = 444 tonnes CO2e in yr 0 for each indirect ha converted** Again assuming above-ground biomass is removed from the forest by burning (to clear the land), the initial change in biomass carbon stocks on land converted to another land category (e.g., from forest to cropland) was calculated as: Change in biomass carbon stocks = A* CF *44/12 where: • **A= amount of above-ground biomass is 257.5 tonnes dry matter/ ha** (as "Dry Matter in Aboveground Biomass in Temperate and Boreal Forests" from the IPCC [9] Table 5-6 on Page 5.30); and • **CF= the carbon fraction of above-ground forest biomass is 0.47 tonnes C/tonne dry matter** (for a temperate forest from the IPCC [6] Table 4.3 page 4.48)
Lost forest sequestration	**Lost forest sequestration emissions = 8.27 tonne CO2e/ yr for each indirect ha converted** Estimated as: Lost forest sequestration emissions= [A* CF* (1+ R)] *44/12 assuming • **A= above-ground net biomass growth in natural forests is 4.0 tonnes dry matter/ha/yr** (for a temperate, continental forest from the IPCC [6] Table 4.12 which includes the average above-ground biomass of forest areas affected by disturbances; net average annual above-ground biomass growth; and the net volume annual increment values); • **CF= carbon fraction of above-ground forest biomass is 0.47** (for a temperate forest from the IPCC [6] Table 4.3 page 4.48); and • **R= Root-to-Shoot ratio is 0.2** (for conifers in temperate forests from the IPCC [9])
Change in soil carbon stocks	**Change in soil carbon stocks = 0.792 tonne CO2e/ yr for the first 20 yrs for each indirect ha converted** Estimated using equation 3.3.3 in the IPCC [7] assuming • **the inventory time period is 20 yr** (as the default value) • **the reference carbon stock is 24 tonnes C/ ha** (for low activity soils in a warm, dry, temperate region from the IPCC [7] Table 3.3.3 on page 3.76) • **stock change factor for land use or land-use change type is 0.82** (as "long-term cultivated predominantly annual crop; for an area that is continuously managed for <20 yrs" from the IPCC [7] Table 3.3.4 on page 3.77) • **stock change factor for management regime is 1.0** (for full tillage from the IPCC [7] Table 3.3.4 on page 3.77) • **stock change factor for input of organic matter is 1.0** (for medium input from the IPCC [7] Table 3.3.4 on page 3.77)

To interpret the results, next assume there is an interest in including the indirect LUC GHG emissions presented above in a LCA of 1 mmBTU of biojet to be produced from 2010-2040. Again, the 1 mmBTU of biojet is assumed to displace 0.061 ha producing *crop A* and to bring into production 0.011 ha producing *the new crop mix* per year. Also, assume that the life cycle of the conventional jet fuel emits 92.9 kg CO$_2$e/ mmBTU (~3kg CO$_2$e per liter) and that the life cycle production of the biojet (from field-to-wake and including the conversion of 0.061 ha from *crop A* to fuel production; disturbances, growth, agricultural inputs and soil processes on direct lands for fuel production; and the rebound effects within the fuels market) emits 30 kg CO$_2$e/ mmBTU (~1 kg CO$_2$e per liter). Figure 13 presents the results for this illustrative example, with the cumulative net GHG emissions for the project decreasing over time such that the net GHG benefits begin to accrue in approximately 2039.

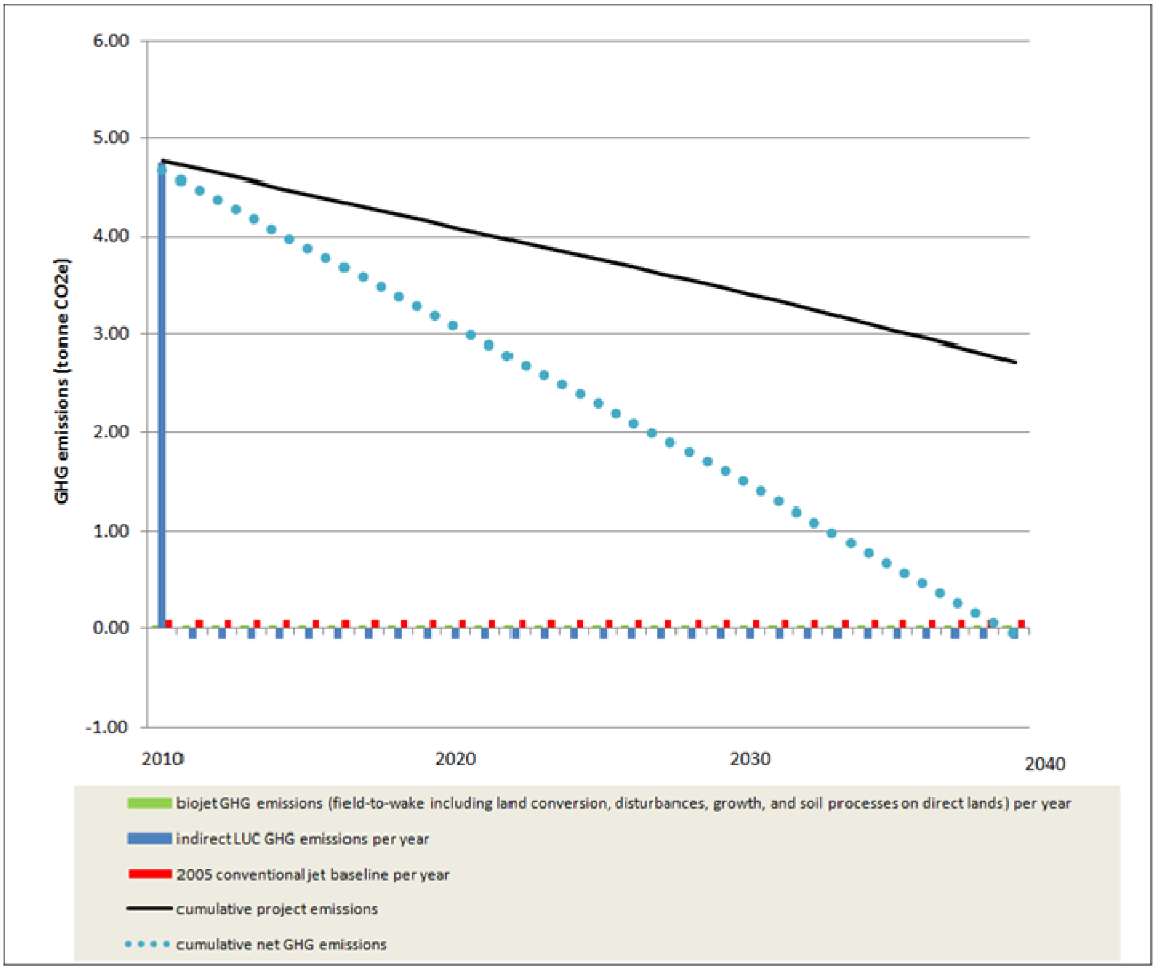

Figure 13. Example Project Life Cycle GHG Emissions: Per mmBTU (30.4 Liters) Produced Per Year

Further interpretation is presented in Figure 14, in which the GHG emissions for the life cycle production of biojet is varied from -100 to 30 kg CO_2e/ mmBTU (-3.3 to 1 kg CO_2e per liter). As shown, improvements in the life cycle production of biojet move the point at which the net GHG benefits begin to accrue to an earlier year (i.e., payback occurs sooner).

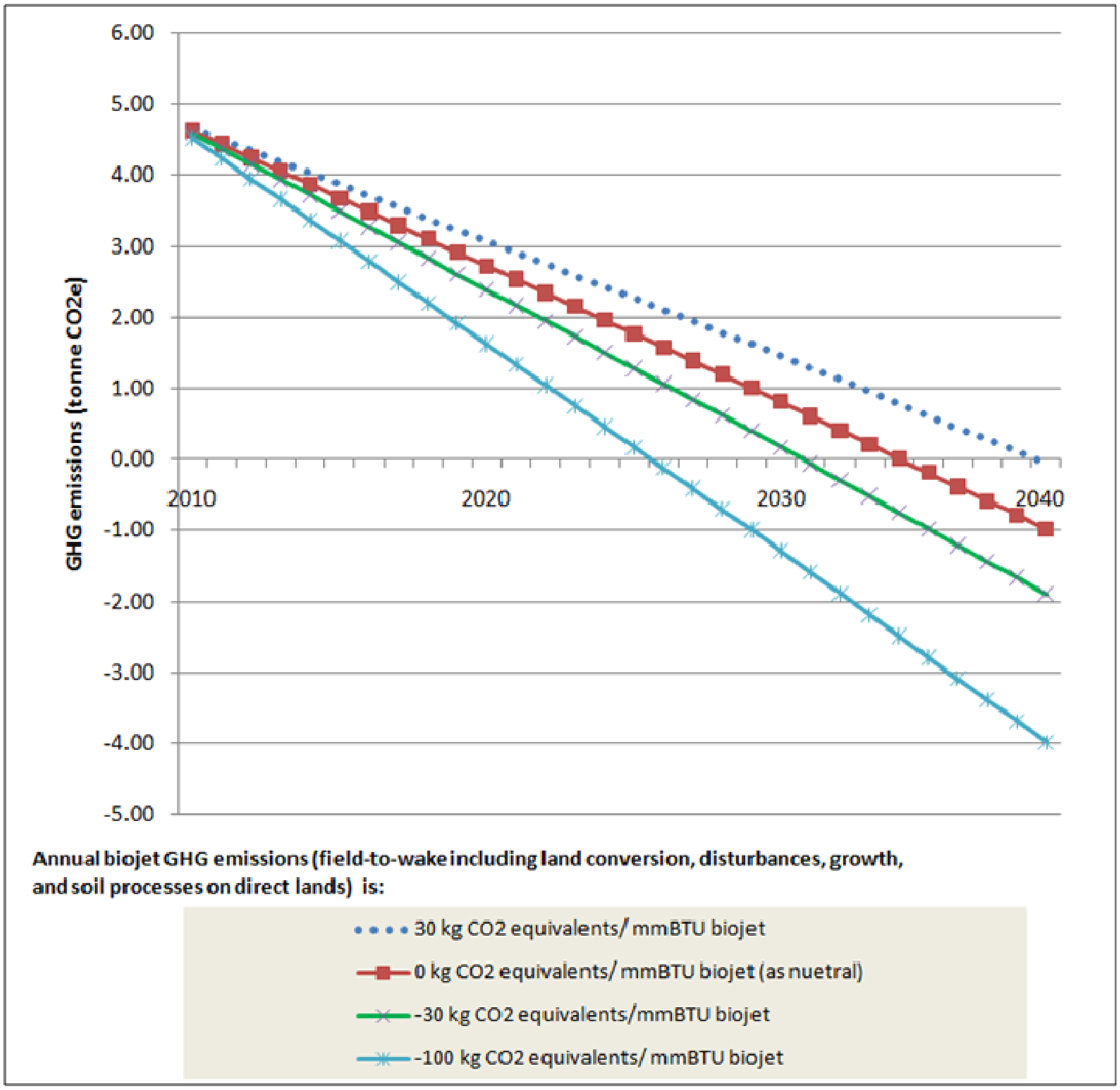

Figure 14. Cumulative Net Jet GHG Emissions With Variation in the Life Cycle Biojet Production GHG Emissions: Per mmBTU (30.4 Liters) Produced Per Year From 2010-2040

Due to these types of trends, the USEPA [2] calculates a net present value (NPV) of emissions to provide a common metric for direct comparison of life cycle emissions from alternative and conventional fuels. Guidance on the estimation of NPV for biofuel GHG emissions is provided by O'Hare, et al. [5] who offer a methodology for discounting physical quantities using a damage function based on the contribution of GHG emissions to radiative forcing over time. To estimate the NPV, the modeler must be confident that their damage function, discount factor, and assumed time frame are relevant and comprehensively describe direct and indirect GHG emissions. For example, whereas the California ARB [1] uses a time horizon of 30 years and a 0% discount rate, the USEPA [2] presents results with time horizons of 30 and 100 years and discount factors of 0% and 2% in the estimation of NPV for GHG emissions. Neither describe the damage function used.

The intended purpose of the example described above is to provide guidance on the system boundaries and information needs for consideration of indirect LUC within a biojet LCA. The related policy, science, and assessment methodology are in a state of flux, with the USEPA and researchers throughout the globe working towards consensus. Given this, the example presented here uses GHG emissions data for a single condition, with the goal of demonstrating the use of data accessible directly from the IPCC guidance documents [6,7]. Specifically, in contrast to the US EPA's methodology [2]:

- **In the example presented here,** a single land area and a single type of land conversion are assumed (specifically, the conversion of 0.011 ha / mmBTU of LUC in a temperate, dry region from a coniferous, unmanaged, continental forest with low activity soils' to a set of long-term cultivated, full tillage perennial cropping systems for *the new crop mix*),
- **In the USEPA GHG assessment [2],** the Farm and Agricultural Policy Research Institute (FAPRI) and the Forestry and Agriculture Sector Optimization Model (FOSOM) agricultural models are used to estimate domestic and international crop expansion respectively for a wide variety of agricultural products, with the type of land conversion then matched to the ecological zone and management practices in specific countries or regions, based on recent land use change patterns observed in satellite imagery.

As the USEPA continues to prepare guidelines and data for a wide range of biofeedstocks, the modeler's role in formulating answers to the 5 key questions, and in the development of data to represent the wide range of land types and crops ultimately affected, will be reduced.

4.11.3 Matching Methodological Assumptions For System Boundary Definition

As noted in Section 3.2.2, this guidance document focuses primarily on average attributional LCAs for conventional and alternative aviation fuels representing "an isolated system." As defined above, indirect LUC is a *consequence* of alternative fuels production and is thus outside such an attributional LCA's isolated system. Consequential LCA, also mentioned in Section 3.2.2, includes assessment of not only the consequences of LUC but also the consequences other economic aspects of the alternative fuel's life cycle.

In a consequential LCA, "consequential processes" are added within the system as resources enter or leave economic markets, thusly change the supply and demand characteristics of the markets, and, like LUC, cause the potential for a change in resource use and waste and associated environmental impact. A consequential LCA assumes market interaction either as a result of process multi-functionality, as a result of the use or production of open loop recyclables (as a special case of multi-functionality), or when production of a resource is constrained (i.e., a resource for which there is competition in the market, caused by market forces, natural limitations on the availability of the resource, or due to an intervention such as a government regulation) (Ekvall and Weidema [8]). Such processes are included in a consequential LCA using system expansion as described in Section 3.5.3 with the ultimate computational goal of only the product that leaves the system boundaries is the product of interest. For example, in an algae-to-jet consequential LCA, the desire is that only jet fuel is produced. This means for example that the use of recycled wastewater for algal growth may result in the **replacement** of land applied wastewater with irrigation and fertilizers; the use of methanol for algae oil transesterifcation may result in the **replacement** of the use of methanol as a chemical precursor; and the co-production of diesel and gasoline with jet by hydrocracking may **displace** the use of other fuels in mobile and stationary energy generation. Further, in an ideal consequential LCA model, the performance of consequential processes is modeled using marginal data and is accounted for on the bases of price elasticities of supply and demand.

This presents the modeler with a **continuum of system boundary choices.** At one end of the continuum is a "mostly attributional" system boundary using average production data, some combination of allocation and system expansion as described in Section 3.5.3 and considering market interactions only for LUC. At the other end of the continuum is a "fully consequential" system boundary using marginal production data and considering market interactions for LUC, multi-functional processes, open loop recycling, and constrained production throughout the biojet life cycle.

This guidance document describes preparation of alternative aviation fuel LCA as "mostly attributional," which is the approach described by the California ARB (6). However, the "mostly attributional" formulation represents a mismatching of methodological assumptions for system boundary definition: LUC is modeled differently than other market interactions. Since wide scale production of alternative aviation fuel is likely to be accompanied by substantial market interaction throughout the life cycle, it is not certain that the use of attributional LCA as described herein will be at the forefront of fuels research and LCA practice during the coming years.

4.11.4 Recommended Steps For Modeling GHG Emissions For Indirect Land Use Change

In support of a "mostly attributional" or a "fully consequential" biojet LCA, steps used in the estimation of GHG emissions for indirect LUC are:

Step 1. **Determine how much land is expected to be converted**, including the areas of land needed for biojet production and for indirect activities outside the biojet life cycle (e.g., the relevant combinations of conversions of forest, grassland, or pasture to other agricultural uses.

Step 2. **Determine where land use changes occurs,** either by ecological zone or as specific countries or regions.

Step 3. **Determine the types of land conversions**, as the previous uses of the indirect lands before conversion and each associated use after conversion, and including specification of species, soil types, and land or crop management practices (e.g., the portion of the indirect LUC converted from an "unmanaged forest" to a "full-tillage perennial cropping system," from a "prairie grassland" to a "no-tillage perennial cropping system," etc.)

Step 4. **Determine the GHG emissions from each land conversion**, including any relevant Change in the life cycle emissions from crop production, change in biomass carbon stocks, emissions from land clearing, lost sequestration, and changes in soil carbon stocks.

Step 5. **Plot the cumulative net biojet GHG emissions as a function of time, based on the time period over which biojet fuel production is expected to continue.** Then, report the net GHG benefits that accrue along with the time period over which the emissions reductions occur.

Step 6. **Quantify the uncertainty in indirect land use change estimates**. Present uncertainty estimates for each Step 1-4, and cumulatively. See the uncertainty protocol in Chapter 5 for further guidance.

In the absence of reliable information and data for domestic and international crop expansion or for any of the items listed above, the modeler should prepare a worst case scenario, assuming for example an acre- for-acre crop expansion (i.e., 1 ha indirect LUC/ ha direct LUC), based on a worst case set of GHG emissions from the land conversion based on the IPCC data [6,7], and using the data quality and uncertainty protocol described in Chapter 5. Again, as the USEPA and researchers throughout the globe continue to prepare guidelines and data for a wide range of biofeedstocks, the modeler's role in modeling the GHG emissions from indirect LUC will be reduced.

4.11.5 References

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4.12 Unit Process Exclusions

For the purpose of completing an LCA that meets the goals outlined in this guideline document, the inclusion of the following data is not expected:

- Although activities such as commuting to and from work and producing food for consumption during working hours may be omitted, activities that humans perform while on the job, such as driving a tractor or using facilities such as lighting while at work (which will impact the overall auxiliary power needs of the facility) should be included within the system.
- Low-frequency, high-magnitude, non-predictable environmental events (e.g., non-routine/fugitive/accidental releases) are not included in the system because such circumstances are difficult to associate with a particular product; however, more frequent or predictable events, such as material loss during transport, are included in the system boundary. Also, low frequency, high magnitude events that occur on a predictable basis are included in the system boundary.

5.0 APPROPRIATE MANAGEMENT OF CO-PRODUCTS

5.1 Background

Many industrial processes produce more than one product. For example, a petroleum refinery produces jet fuel, gasoline, diesel fuel and a range of other products. The extraction of soybean oil from soybeans to make soy-based biofuels also produces soybean meal which is used as animal feed. Multi-output or multi-functional processes such as these complicate the development of a lifecycle inventory because, if they are not used within the system, they essentially represent additional system products beyond that specified by the functional unit. Since a comprehensive LCA seeks to compare equivalent systems, systems producing product in addition to those specified by the functional units are not on an even playing field. Figure 15 illustrates, in general, how process energy or any other process input or output can be allocated between two co-products. Process energy and material inputs result in co-products 1 and 2. If the mass of product 1 produced is twice that of product 2, a mass-based allocation methodology could result in two-thirds of the process inputs allocated to co-product 1 and one third to product 2; however, a different allocation methodology could result in a different allocation. This section discusses the allocation options that are available to the life cycle practitioner and the consequences of choosing various options.

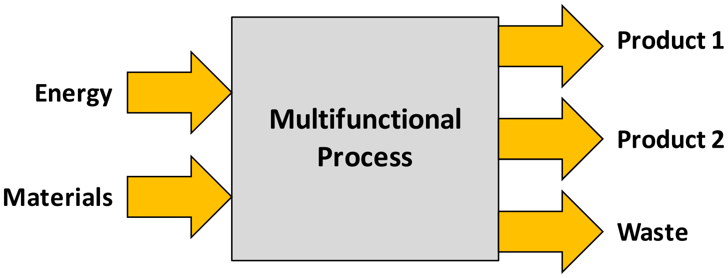


Figure 15. Processes With More Than One Product Require Decisions About How the Inputs and Outputs of the Process are to be Allocated to Each Product

5.2 Methods for Allocating Inputs and Outputs Among Co-Products

ISO 14044 (2006b) states that inputs and outputs **shall** be allocated to the different co-products using process disaggregation, system expansion, or allocation. These methods are described below.

5.2.1 Allocation by Mass, Energy, or Economic Value of Co-Products

When a process produces more than one product, inputs and outputs of the process can be partitioned on the basis of an underlying physical relationship between them, such as mass, volume, or energy. If no such relationship is evident, economic value (either cost or market value) may be used instead of, or in tandem with, a physical relationship. For example, if production of soybean oil results in 82 kilograms of soybean meal for every 18 kilograms of oil, then with mass allocation, 82 percent of the inputs and outputs would be attributed to the soybean meal and 18 percent of the inputs and outputs would be attributed to the oil. With allocation based on energy content of the co-product, the relative energy (calorific) content would be used to allocate the inputs and outputs. With an economic allocation, the relative cost of their production or fair market price of co-products could be used to allocate the inputs and outputs; however, these choices result in a different allocation of emissions. All of these approaches have been used in assessments of biofuels, and the implications of different choices of allocation basis will be discussed in Section 5.3.

5.2.2 Disaggregation

Disaggregation involves dividing the unit process into two or more sub-processes and collecting the input and output data related to the sub-processes. Disaggregation is possible when there are clearly defined sub-processes, and is recommended by ISO 14044 as an alternative to allocation ((ISO 2006b), section 4.3.4.2). Figure 16 illustrates disaggregation of the process shown in Figure 15. The figure shows the same overall process as in Figure 15, but disaggregated into sub-processes.

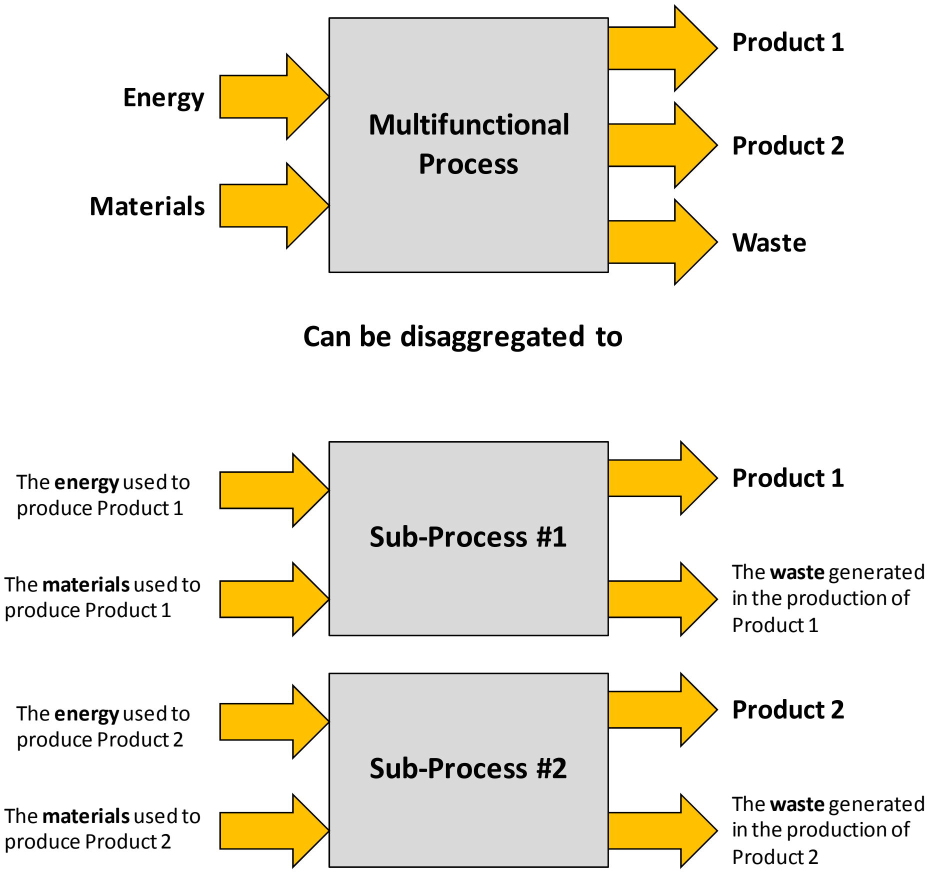


Figure 16. Disaggregation Into Sub-Processes May Reveal Additional Insight Into Co-Product Allocations

5.2.3 Expansion of System Boundaries

System boundaries can be expanded to include additional product systems related to the co-products. If one of the co-products, or a similar or substitutable product, is produced by another process, system boundary expansion involves the inclusion of both product systems in the LCA. If increased production in one product system causes decreased production in the other, a technique referred to as substitution or displacement can be used. This is the main system expansion approach for allocation that will be discussed here.

In a displacement calculation, the mass and energy that would have been used and the emissions that would have been generated during production of the displaced product are counted as credits for the co-product. These credits are subtracted from the total mass and energy used and emissions associated with the product (e.g. an aviation fuel) under evaluation (Huo, et al. 2008). For example, if glycerin is produced as a by-product of bio-diesel production, that glycerin may displace glycerin that is made from an alternate process. The emissions that would have been generated in the alternate process, that are now being displaced by glycerin as a co-product from bio-diesel manufacturing, are counted as emission credits. Figure 17 illustrates an example of a displacement calculation.

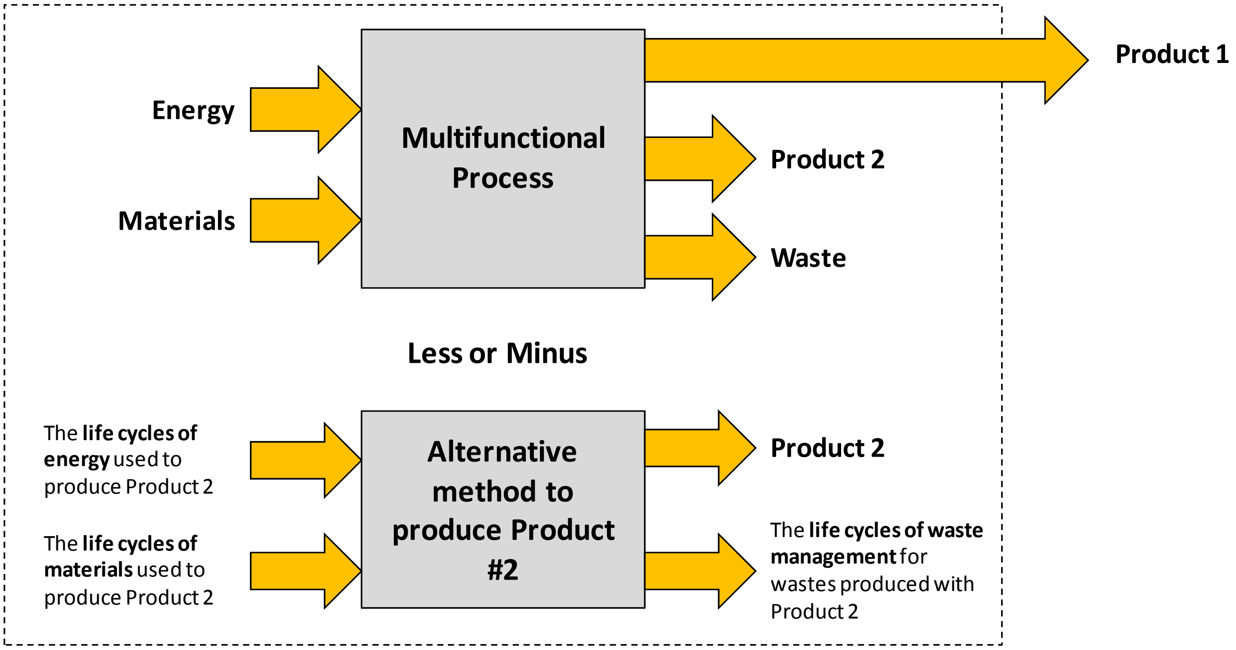


Figure 17. An Alternate Process That Produces Product 2 That is the Same as, or Can be Used as a Substitute for, the Co-Product 2

5.3 Discussion of Approaches

5.3.1 Discussion of Allocation by Measures Such as Mass, Energy or Value

The advantage of allocation by measures such as co-product mass, energy or economic value is that the calculation is based just on the physical properties of the process streams and data from the production facility, and the allocation parameter can generally be quantified easily. In contrast, economic allocation metrics are dependent on markets which fluctuate on time scales that are different than the time scales for the design of production facilities.

The co-products of soy-derived fuels have been allocated in a number of different ways in different studies. Hill, et al. (2006) allocated the processing energy between soybean oil and soybean meal on the basis of mass. In contrast, Shapouri, et al. (2006) allocated by energy (calorific) value for co-products used as food or agricultural feed. Pradhan, et al. (2008)

reviewed studies of soy biodiesel and found that allocation was responsible for most of the difference between studies.

Table 13. Allocation of Emissions Between Soy Oil and Soybean Meal (Wong 2008)

Allocation Approach	Soy Oil (%)	Soybean Meal (%)
Mass	18.2	81.8
Market Value[1]	41.8	58.2
Energy[2]	45.6	54.4
Notes: (1) Market of soy oil and soy meal are \$0.84/kg and \$0.26/kg (Wang 2008) respectively (2) Energy content of soy oil and soy meal are 37.2 MJ/kg (UOP, 2005) and 9.88 MJ/kg (Wang 2008) respectively		

Table 13 illustrates the application of mass, energy, and market value allocation to the products of soy oil production: soy oil and soybean meal (Wong 2008). The table shows that the choice of allocation can significantly affect the results. In this case, application of mass methodology results in allocation of the smallest percentage of the inputs and outputs to soy oil and the largest percentage to soybean meal. This means that a calculation of greenhouse gas and other inputs and outputs of fuel derived from soy oil will indicate smaller environmental impact if mass allocation is used instead of energy or value allocation.

As a second example, the products of petroleum refineries, i.e. diesel, kerosene, gasoline and other products, can also be allocated in a number of ways, with varying results. To develop a lifecycle inventory for one product, kerosene for example, the fraction of energy and other inputs and outputs of the refinery processes that will be allocated to kerosene must be determined. Table 14 illustrates the application of mass, energy, and market value allocation to the products of a petroleum refinery, with an analysis carried out at the level of the entire plant (Wang, Lee and Molberg 2004). The table shows that, depending on the allocation methodology, the portion of the emissions associated to any one product can vary widely or perhaps not at all. As an example, gasoline can vary by 20 percentage points (37.5% versus 57.6%) while the emissions associated with diesel fuel are relatively unchanged with only a variation of two percentage points.

Table 14. Allocation Based on Mass, Energy and Value for a Refinery
(Wang, Lee and Molberg 2004)

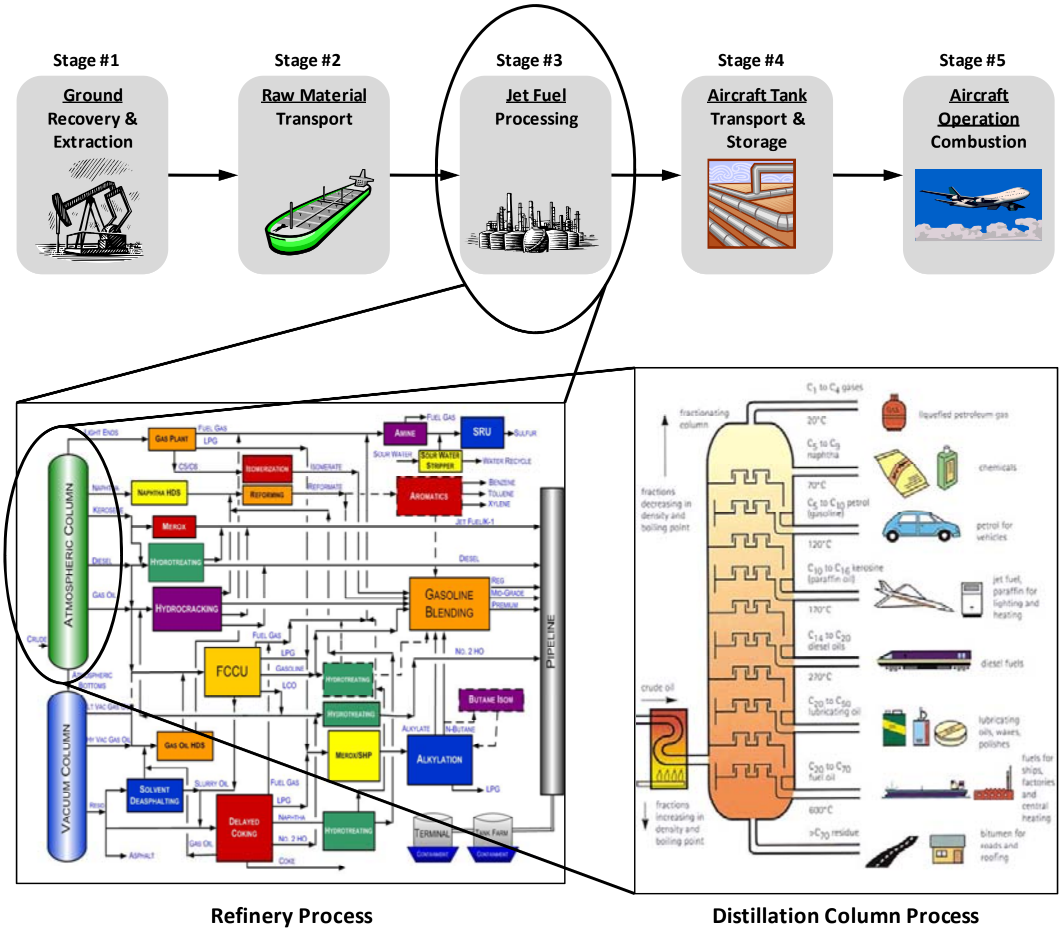
Product	Refinery Plant Level (%)		
	Mass	Energy Content	Market Value
Residual Oil	5.2	5.3	1.9
Diesel	19.1	19.9	21.2
Kerosene	8.9	9	5.3
Gasoline	37.5	41.6	57.6
LPG	7.1	8.8	8.4
Others	22.2	15.4	5.7

For different situations, different allocation approaches might seem more reasonable. At a refinery or chemical plant, allocation by mass or energy may seem physically most appropriate, especially for products with similar chemical structures. Skone and Gerdes (2008) allocated refinery products based on the energy content of products that are energy carriers (e.g. fuels) and allocated based on mass or volume for all other types of products. Allocation by economic value may be more appropriate for products that are very different from each other. In addition, allocation by economic value can be used as an exploratory approach to distinguish "products" from "wastes".

An upper limit on the environmental impact of a fuel can be determined by allocating all of the inputs and outputs to the fuel (Larson 2006). Determining this upper limit can provide a transparent starting point for evaluating the implications of choices to allocate some inputs and outputs to co-products.

5.4 Discussion of Disaggregation

Within an industrial facility that produces a number of products, some products may receive special processing, different from the other products. In this situation, rather than allocating all facility inputs and outputs equally among all of the products, it may be possible to disaggregate the accounting of the production process. For example, in a petroleum refinery, some fuels such as gasoline require extensive hydro-processing to reduce sulfur concentrations. This processing would not be done for other categories of fuels, such as bunker fuels. If the processes of the refinery can be disaggregated, as shown in Figure 18, then the greenhouse gas emissions associated with the hydro-processing of gasoline could be appropriately assigned to the fuel products that require sulfur removal, rather than all process streams. In general, disaggregation can more accurately reflect process flows than an aggregated analysis, and can eliminate, or at least reduce, the need to allocate inputs and outputs of the entire facility among the products. Figure 18 also shows, however, that even if disaggregation is done to the maximum extent possible, some level of allocation is often required. In the refinery crude unit, for example, multiple product streams are produced from a single device and some level of allocation will be required



Refinery Process

Distillation Column Process

Figure 18. Tracking the Flow of Products Through Specific Unit Operations at the Refinery Allows Some Disaggregation of the Inputs and Outputs Among Products and Eliminates Some of the Need for Allocation (Derived From (Skone and Gerdes 2008))

Table 15 and Figure 18 illustrate the result of disaggregation of processes in a petroleum refinery (Wang, Lee and Molberg 2004). The table shows a refinery-plant-level allocation based on mass, energy content, and market value, as was shown previously in Table 14, and also shows the results of disaggregating process inputs and outputs within the refinery, with allocation applied after the disaggregation. The table shows that the disaggregation results in significantly different allocation to the different refinery products as compared to allocation among co-products of the aggregated refinery process. Disaggregation results in a tighter allocation range for all of the refinery outputs, but the results are most pronounced for gasoline. With disaggregation, there are only 5 percentage points of variation among mass, energy and market value; this is considerably less than the 20 percentage points of variation among these options for the aggregated plant analysis. In addition, the overall variation between the allocation approaches is smaller after disaggregation than before, especially for gasoline.

Table 15. Allocation of Energy Use Based on Plant- and Process-Level Analyses of a Petroleum Refinery (Wang, Lee and Molberg 2004)

Product	Refinery Plant Level (%)			Refining Process Level (%)		
	Mass	Energy Content	Market Value	Mass	Energy Content	Market Value
Residual Oil[1]	5.2	5.3	1.9	3	2.7	0.9
Diesel	19.1	19.9	21.2	6.6	6.7	8.2
Kerosene	8.9	9	5.3	8.3	8.5	6.8
Gasoline	37.5	41.6	57.6	53.7	53.3	58.7
LPG	7.1	8.8	8.4	3	2.7	3
Others[2]	22.2	15.4	5.7	25.4	26.2	22.3

Notes:
(1) For the refining-process-level-based allocation, energy use for residual oil and heavy fuel oil were added together.
(2) The 'others' category includes many refinery products. Here we use residual oil's energy content and market value as weights to allocate energy use to this category.

5.5 Discussion of Displacement

In the displacement method, a co-product is assumed to displace a product with the same function and produced by a different process, typically at an unrelated facility. The mass and energy that would have been used and the emissions that would have been generated during production of the displaced product are counted as credits for the co-product. These credits are subtracted from the total material, energy use and emissions associated with the fuel under evaluation (Huo, et al. 2008).

The advantage of the displacement approach is that it attempts to evaluate the actual changes in environmental inputs and outputs due to production of the co-product. When co-product creation results in reduced production of another product, that reduced production will have energy and environmental implications, which should be incorporated into the LCA.

There are a number of issues related to displacement calculations. These are: (1) completeness of the displacement; (2) identification of appropriate substitute production processes; (3) displacement uniqueness; (4) system boundary consistency; (5) time dependence; and (6) consistency with other GHG protocols. These issues are considered in more detail below.

5.5.1 Completeness of the Displacement

Displacement calculations typically assume that the displacement of a product with a co-product with the same function is complete. Production of the original product may decline, but it is unlikely to decline on a one-for-one basis so as to exactly offset the co-product production. Displacement can in general be expected to be partial (not complete) and will depend on the elasticity of demand for the product (Thomas 2003). When the co-product quantities are large compared to the total market demand for the product being displaced, only a fractional displacement of the co-product would be expected.

This concept of fractional completeness of the displacement is especially important when co-product credits are large. If the amounts of co-products are relatively large compared with the amount of primary product from a given process, as is the case for renewable diesel and renewable gasoline (Huo, et al. 2008), the displacement method can produce results that have a large impact on the LCA of the fuel. It is mathematically possible for displacement calculations to result in negative energy and environmental impacts for the fuel chain, if the co-products are calculated as having less environmental impact than the product that they are displacing (Table 16).

Table 16 shows six different approaches to allocation between soy oil and soybean meal. The first three rows show allocation by mass, market value, and energy, as was previously shown in Table 13. The rest of the table shows displacement calculations in which soybean meal is assumed to displace barley, corn, or soybeans. Because production of barley and corn, in this illustration, have greater GHG emissions than production of the corresponding amount of soybean meal, the displacement of these products by soybean meal is calculated to be greater than all the inputs and outputs of the soy oil/soybean meal production process. The result is that in some cases, production of soy oil is calculated to have a negative allocation, meaning that the soy oil is calculated to have a net environmental benefit.

Table 16. Allocation of GHG Emissions Between Soy Oil and Soybean Meal (Wong, 2008, Table 56)

Allocation Approach		Soy Oil (%)	Soybean Meal (%)
Mass		18.2	81.8
Market Value[1]		45.6	54.4
Energy[2]		41.8	58.2
Displacement of barley (1kg soymeal = 4kg barley)[3]	LUC included from soybeans and barley	-5	105
	LUC included from soy but not barley	71	29
	no LUC	-217	317
Displacement of corn (1kg soymeal = 5.3kg corn)[3]	LUC included from soybeans and barley	-233	333
	LUC included from soy but not barley	64	36
	no LUC	-301	401
Displacement of soybean (1kg soymeal = 1.2kg soybean)[3]	LUC included from soybeans and barley	4.3	95.7
	LUC included from soy but not barley	95	5
	no LUC	45.3	54.7

Notes:
(1) Market of soy oil and soy meal are \$0.84/kg and \$0.26/kg (GREET, 2007) respectively
(2) Energy content of soy oil and soy meal are 37.2 MJ/kg (UOP, 2005) and 9.88 MJ/kg (Wang, 2008) respectively
(3) Equivalency between soymeal and displaced product was done on protein equivalency
(4) Lifecycle GHG emissions from soybean faming and soy oil extraction are 60.3gCO_2e/MJ of fuel produced
(5) LUC refers to land use change

For a fuel system, the use of co-products to substitute for other products can be tracked over time, although robust data are likely to be available only after major industrial development of the fuel system. Moreover, substitution effects will be intertwined with economic changes in the demand for the co-products and its substitutes that may be independent of the fuel production system. Quantification of the extent of substitution/displacement is likely to be uncertain; this uncertainty should be acknowledged in the analysis.

5.5.2 Identification of Substitute Production Processes

Some co-products do not have existing alternative production chains. Examples may include a range of petroleum products including jet fuel, gasoline, and diesel fuel. In theory it is possible to identify alternative production processes or near-substitutes: for example gasoline might be substituted by corn-derived ethanol, and diesel might be substituted by soy-derived diesel. But these near-substitutes have very small production volumes and may not provide a plausible basis for evaluating the environmental impact of petroleum refineries. This issue might technically be considered as a limiting case of the discussion of substitution completeness: when there is no primary production process that can plausibly be displaced, a displacement calculation may not be appropriate.

5.5.3 Displacement Uniqueness

There may be more than one substitute for a product. For example, soy meal can displace barley, corn, or soybeans. An analysis of the soy oil extraction process, based on Wang (2008), provides an illustrative example. As shown in Table 16, the variation of allocation of emissions to the soy oil from using soy meal to displace barley, corn and soybeans on a protein equivalency basis is from -301% to 45.3%. A displacement calculation must reflect the actual displacements that will occur. This could involve fractional displacement for different substitute products.

5.5.4 System Boundary Consistency

A fourth issue with displacement calculations is that system boundary guidelines may indicate that more than one level of displacement effect should be taken into account. Displacement calculations typically have evaluated the direct impact of displacing the co-product with its displaced product; the calculations typically have not extended to secondary changes in industrial production resulting from the substitution.

5.5.5 Time Dependence

Displacement assumptions may be most salient for the first few years of the activity. Over time the assumptions on which the displacement calculations were originally based may be less salient. Co-product displacement calculations are inherently time dependent. Over time, as production volume goes up, the displacements may change. For example, as biodiesel production has increased, the glycerin co-product has been produced far in excess of market demand (Johnson and Taconi 2007). In addition, if the energy efficiency or material efficiency of the alternate process improves, the energy and material displaced by the co-product would decrease.

5.5.6 Consistency With Other GHG Protocols

There are a number of protocols for calculating greenhouse gas emissions of institutions, facilities, and organizations. Typically credits for greenhouse gas savings can be claimed only by the organization or facility directly responsible for the emissions savings. Displacement calculations may, therefore, not be consistent with existing greenhouse gas emission protocols and those that may be established under national or international greenhouse gas legislation and regulations. Further research is needed to compare typical displacement calculations with existing and developing greenhouse gas regulation protocols. For example, a facility might reduce system-wide greenhouse gas emissions by selling biomass to another facility that would use the biomass for fuel to displace diesel. In a displacement calculation, this might be counted as a greenhouse gas emission credit. In other protocols, however, the facility selling the biomass may not be able to count that biomass as a greenhouse gas credit, because the reductions would be counted in the greenhouse gas emission inventory of the facility that uses the biomass as a fuel ((The Climate Registry 2008), (Rich 2008)).

5.6 Guidance for Attribution and Allocation

Figure 19 below provides a decision tree summarizing the recommended methodology for selection of an appropriate allocation approach for a product system. The decision process is discussed in further detail below.

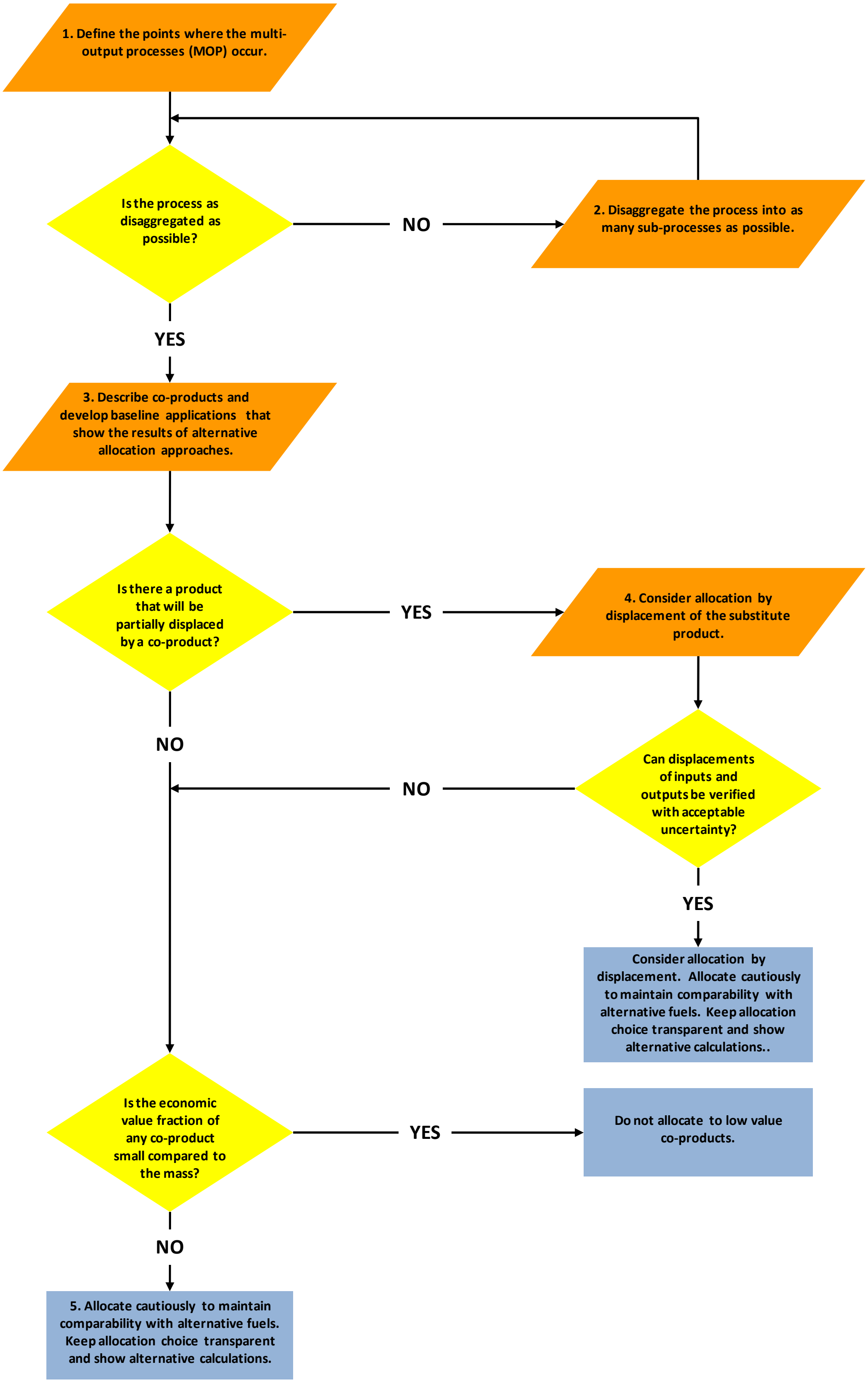


Figure 19. Illustration of the Process for Developing an Allocation Approach for a Product System

1. Identify the points where multi-output processes occur: The first step in allocating among co-products is to identify the points at which more than one product is produced.
2. Disaggregation: The second step is to determine if the process flows can be disaggregated to more clearly identify how inputs and outputs should be allocated to each co-product. If there is sufficient information about the sub-process inputs and outputs, the process should be disaggregated.
3. Describe co-products and develop baseline alternative allocation calculations: The third step is to develop a baseline allocation that can be used as a point of reference for developing a more refined analysis. The mass fraction, potential use and substitutes, energy content (for energy carriers), and economic value should be identified and described. Clearly showing what allocations might be used, and how this would affect the results, will provide a basis for comparing results with other studies and indicating how allocation choices affect the outcome.
4. Displacement: The fourth step is to determine if any of the co-products can be characterized as displacing another product. This involves:
   a) Determining what product or products is displaced, and the quantitative relationship between the co-product and the displaced product;
   b) Determining how much of the co-product would be used for the same purpose as the displaced product; and
   c) Determining the extent to which production of the displaced product will decrease per unit increase in supply of the co-product.

   Substitution calculations should include an estimate of the completeness of the displacement (fraction of displacement f), and should indicate the uncertainty in the completeness estimate. The fraction of the co-product that does not displace the alternate product (1-f) should not be subtracted from the inventory. These determinations should be clearly documented and verified if possible, and the uncertainty should be characterized. Displacement calculations may introduce considerable uncertainty into the calculation and may not be feasible for all products and co-products. Ekvall and Finnveden (2001) have argued that, due to the difficulties of developing an accurate displacement calculation, allocation procedures based on mass, energy, or other physical relationships may in many cases be the preferred approach. If the displacement cannot be adequately validated, displacement should not be used.
5. Allocate cautiously, if justified, by property such as mass, energy or economic value: The general recommendations for allocation as presented in ISO 14044 are as follows (ISO 2006b):
   - The inputs and outputs shall be allocated to the different products according to clearly stated procedures that shall be documented and explained together with the allocation procedure.
   - The sum of the allocated inputs and outputs of a unit process shall be equal to the inputs and outputs of the unit process before allocation.

- Whenever several alternative allocation procedures seem applicable, a sensitivity analysis shall be conducted to illustrate the consequences of the departure from the selected approach.

In addition, we offer the following guidance for allocation calculations:

For processes that produce mostly or entirely fuels, the standard practice is to use energy content as the basis for allocation. This is particularly relevant for products of petrochemical refineries, to the extent that disaggregation cannot resolve co-product allocation issues. As is shown in Table 15, allocation by mass and energy give approximately the same result for products of petroleum refineries.

Allocation by mass has the advantage of being easy to apply to a wide range of co-products; however, mass allocation inherently ascribes most of the environmental impact to the heaviest products. In the case of soy-derived fuels, mass allocation is the choice that shifts most of the impact away from the fuel. In cases such as this, mass allocation should be used with caution.

Moreover, mass allocation has the potential to be applied to materials that might otherwise be classified as wastes. Process inputs and outputs should never be allocated to wastes, that is, to products that are not used in the economy; however, innovation can provide new uses for what were formerly considered wastes, and the development of productive uses for wastes can have environmental benefits (Allen and Behmanesh 1994). Accordingly, allocation of inputs and outputs to co-products that might formerly have been considered wastes is potentially acceptable, but should be carried out with caution.

Allocation by economic value has the advantage of attributing most of the environmental impact to the most valuable products. A disadvantage of using economic value to allocate inputs and outputs is that prices fluctuate over time. At times of low fuel prices, a value-based allocation would result in the environmental impacts being shifted to co-products; at times of high fuel prices, a value-based allocation would allocate inputs and outputs more to the fuel. Price volatility could be addressed by taking a time average of prices over several years.

LCIs are typically developed to compare one product with another. Regardless of the method used, allocation inherently divides the inputs and outputs of processes that are in fact physically linked. Methods to separate, attribute, or allocate one product from another involve approximations and in some cases adoption of conventions for calculations. In interpreting the results of these calculations, it is important to acknowledge the limitations of these approximations. All forms of co-product allocation introduce significant limitations to the interpretation of the results.

Clearly, when comparing products made with a similar process, the allocation needs to be done the same way for both processes in order to compare them. When comparing two products made with different processes, even more care is needed in comparing the products. For petroleum, the choice of allocation method does not greatly affect the overall greenhouse gas emission calculation, because most of the emissions are directly related to combustion of the fuel itself, rather than due to the process energy used in the refinery; however, for a biofuel, the allocation method can dominate the calculation, because most of the emissions are associated with growing and processing the fuel.

In comparing multiple alternative fuels, it may be helpful to evaluate all of the fuels with the same allocation method; however, for some fuels it may be relatively straightforward to use a displacement calculation, whereas for other fuels a displacement calculation may not be feasible because data are not available about the co-product substitution. This could result in one fuel appearing to have a much different environmental footprint than another, due entirely to the way the calculation was done, rather than due to the underlying environmental impact. Because of this potential for different calculations to be used for different fuels, developing several allocation calculations would provide a basis for comparing fuels.

6.0 DOCUMENTING DATA QUALITY AND UNCERTAINTY

6.1 Background

Inventory data is the fundamental element that determines the quality of an LCA. The ability to compare alternative aviation fuels to evaluate their relative difference in life cycle greenhouse gas emissions is dependent on how the data selected to model each process throughout the life cycle match the defined goal and scope of the study.

As stated in Section 2.0, the purpose of this guidance document is to provide a framework for developing comparative LCAs that can be used to inform decisions on alternative aviation fuels. A high level of data quality is required to meet this purpose.

The guidance in this section introduces a framework for assessing the quality of the data used to model processes, for evaluating the completeness and representativeness of the life cycle, and for documenting whether the study meets the intended goal and scope

6.2 Data Quality

"Good data", "bad data", "high quality data", "low quality data"…these are common terms used out of context to describe data that are used to model unit operations in a life cycle. The reality is that there are no absolutely "good" or "bad" data. The appropriate issue is "Is the data quality sufficient to meet the goal and scope of the study?" This question provides insight into the real objective of assessing data quality: to ensure that data used in development of an LCA accurately reflects the purpose of the study, the temporal, technological, and geographical representation, and the study data quality objectives. Table 17, a reproduction of Table 3 in Section 3.0, provides an example of study design parameters and includes data quality objectives

Table 17. Example Alternative Aviation Fuel Life Cycle Greenhouse Gas Study Design

Life Cycle Boundary	Well-to-Wake
	(Raw Material Acquisition thru Fuel Use)
Temporal Representation	Year of Fuel Procurement
Technological Representation	Facility/Chain Specific
Geographical Representation	Transportation Fuel Sold or Distributed to DESC in the United States
Transportation Fuel Life Cycles Modeled	Kerosene-Based Jet Fuel
Impact Assessment Methodology	Global Warming Potential, IPCC 2007, 100-year time-frame Non-CO_2 combustion emissions not included
Reporting Metric	g CO_2e/MJ LHV of Fuel Consumed
Data Quality Objectives	Preferably Facility Technical Engineering and Operating Data Publically Available Data (to the extent practicable)
	Full Transparency of Modeling Approach and Data Sources (to DESC)
	Accounting for a targeted uncertainty in Mass and Energy
	Accounting for a targeted uncertainty in Environmental Relevance
	Process-based ("Bottoms-up") Modeling Approach

6.3 Data Sources, Types, and Aggregation

Various types of inventory data can be used to characterize unit processes within the system boundary of the life cycle. The following are examples of sources of data that could be used in a typical LCA (adapted from (SAIC 2006)):

- Meter readings from equipment
- Equipment operating logs/journals
- Industry data reports, databases, or consultants
- Laboratory test results
- Government documents, reports, databases, and clearinghouses
- Other publicly available databases or clearinghouses
- Journals, papers, books, and patents
- Reference books
- Trade associations
- Related/previous life cycle inventory studies
- Equipment and process specifications
- Best engineering judgment

The type of data selected to model each unit process should be examined, and documented, to ensure the data meets the goal and scope of the study. For the purposes of this guidance document, data of the highest quality should be used in accordance with the recommendations for a Level I: Comprehensive LCA. Examples of data types include (*starting with the highest priority*) (adapted from (SAIC 2006)):

- Measured continuously, over a time period adequate to represent continuous operation
- Sampled intermittently, using a representative sample size
- Modeled, using a well documented, peer reviewed computational method
- Equipment vendor data or patents
- Data representing a similar site or similar technology (i.e., surrogate data)

The level of aggregation of data should also be documented, for example, whether data are representative of one process or several sub-processes. When measured data are not used, data should be collected from a variety of sources. Whenever possible, it is best to get well-characterized process data. Note also that processes often become more efficient or change over time, so it is important to seek the most current data available. Inventory data can be facility-specific or more general and still remain current.

Several levels of data aggregation are often used in inventories (starting with the *most* disaggregated) (SAIC 2006):

- *Individual process- and facility-specific data* from a particular operation within a given facility that are not combined in any way

- *Composite data* from the same operation or activity combined across locations
- *Aggregated data* combining more than one process operation
- *Industry-average data* derived from a representative sample of locations and believed to provide a statistically accurate description of the typical operation across technologies
- *Generic data*, while it may not be known how well the data set represents the system flow, these data sets are qualitatively descriptive of a process or technology

6.4 Dealing With Confidential Data

The protection of confidential business information should be weighed against the need for a full and detailed analysis or disclosure of information. Information disclosed in a public forum may require aggregation with other data (i.e., aggregation of unit processes) to protect a business's intellectual property (corresponding to competitive advantage in the marketplace); however, detailed information may require disclosure in a non-public forum with the primary decision maker (e.g., purchasing agent) to verify the results presented in the final study report. This type of information should be made available under a form of confidentiality agreement determined acceptable by both parties. Life cycle data purchased from a data provider may have licensing restrictions that also prevent the direct public release of the raw data; however, the data can typically be reported in a public study when aggregated with other data or combined to calculate the global warming potential of the operation. It is important in all cases to ensure data use restrictions are not compromised.

6.5 Assessing and Documenting LCA Quality

Uncertainty can take many forms, including a lack of knowledge about the true value of a quantity; the true form of a model; or the appropriateness of a modeling or methodological decision (Reap, et al. 2008). The guidance provided in this report recognizes that it is not necessary to quantify all uncertainty in data, modeling and scenarios, for the purpose of comparing life cycle greenhouse gas emissions to a baseline value. Instead, it should be shown that the uncertainty does not affect the final results. The following factors should be considered when assessing and documenting data and uncertainty in life cycle analyses:

- The quality of data used to model each unit process as described in ISO 4.2.3.6.2
- The uncertainty in modeling choices
- The uncertainty in scenario choices (e.g., future systems)
- The sensitivity of key processes or data elements that contribute significantly to the well-to-wake results and total life cycle results
- The overall quality of the life cycle study and known data limitations

Figure 20 outlines the process to effectively assess and document the data used to model the life cycle when conducting a Level I "Comprehensive LCA".

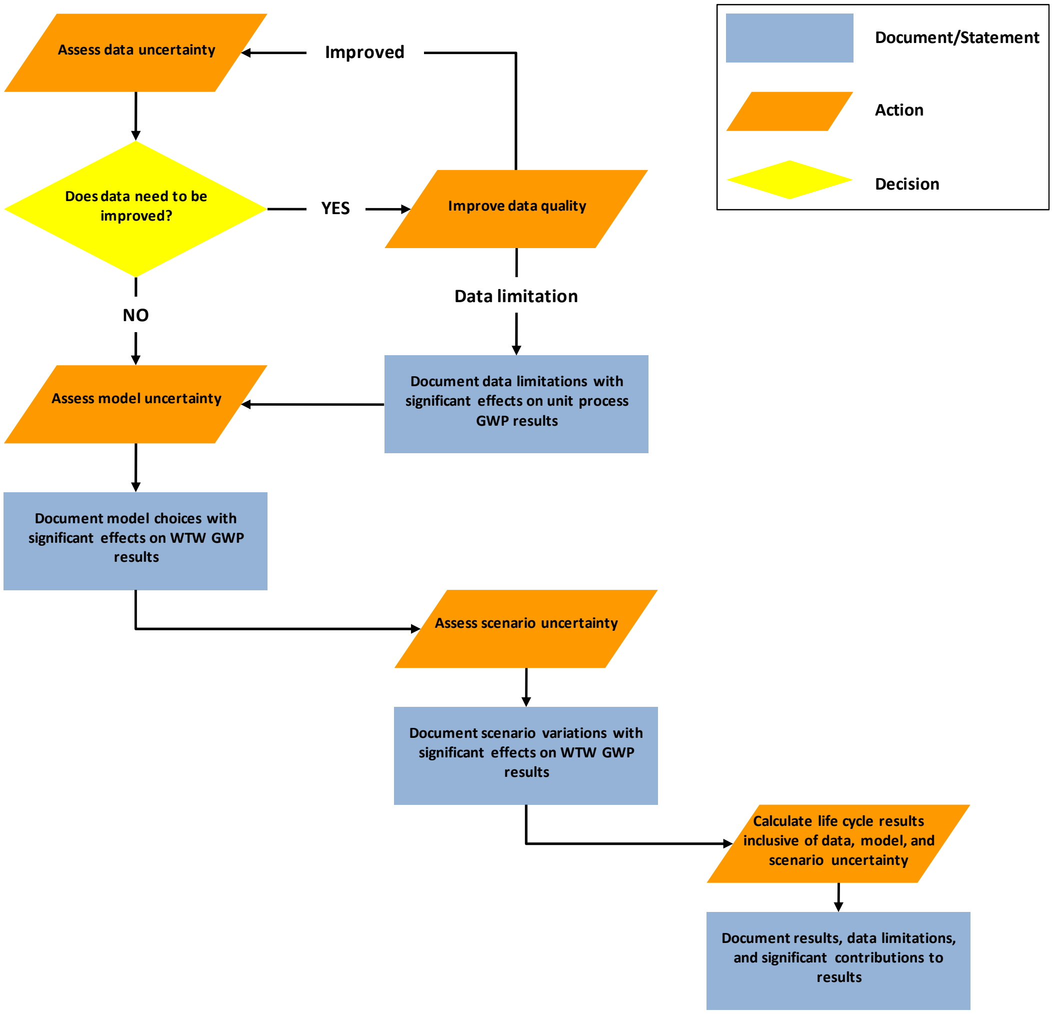


Figure 20. Process for Assessing and Documenting Uncertainty in LCA

The purpose, scope, and boundary of the inventory help the LCA modeler determine the level or type of information that is required. For example, even when the LCA modeler can obtain actual industry data, in what form and to what degree should the LCA modeler show the data (e.g., the range of values observed, industry average, plant-specific data, and best available control techniques)? These questions or decisions can usually be answered if the purpose or scope (of the life cycle analysis) has been well defined. Typically, most publicly available life cycle documents present industry averages, while many internal industrial studies use plant-specific data. Recommended practice for external life cycle inventory studies includes the provision of a measure of data variability in addition to averages. Frequently, the measure of variability will be a statistical parameter, such as a standard deviation (SAIC 2006). Guidance for assessing each type of uncertainty (data, model, and scenario) is discussed below.

6.6 Assessing Data Quality

The first step in characterizing and documenting data quality and uncertainty, as outlined in Figure 21, is to assess and document data quality. Figure 21 summarizes a process for assessing data quality. Each step in this process is described in more detail below.

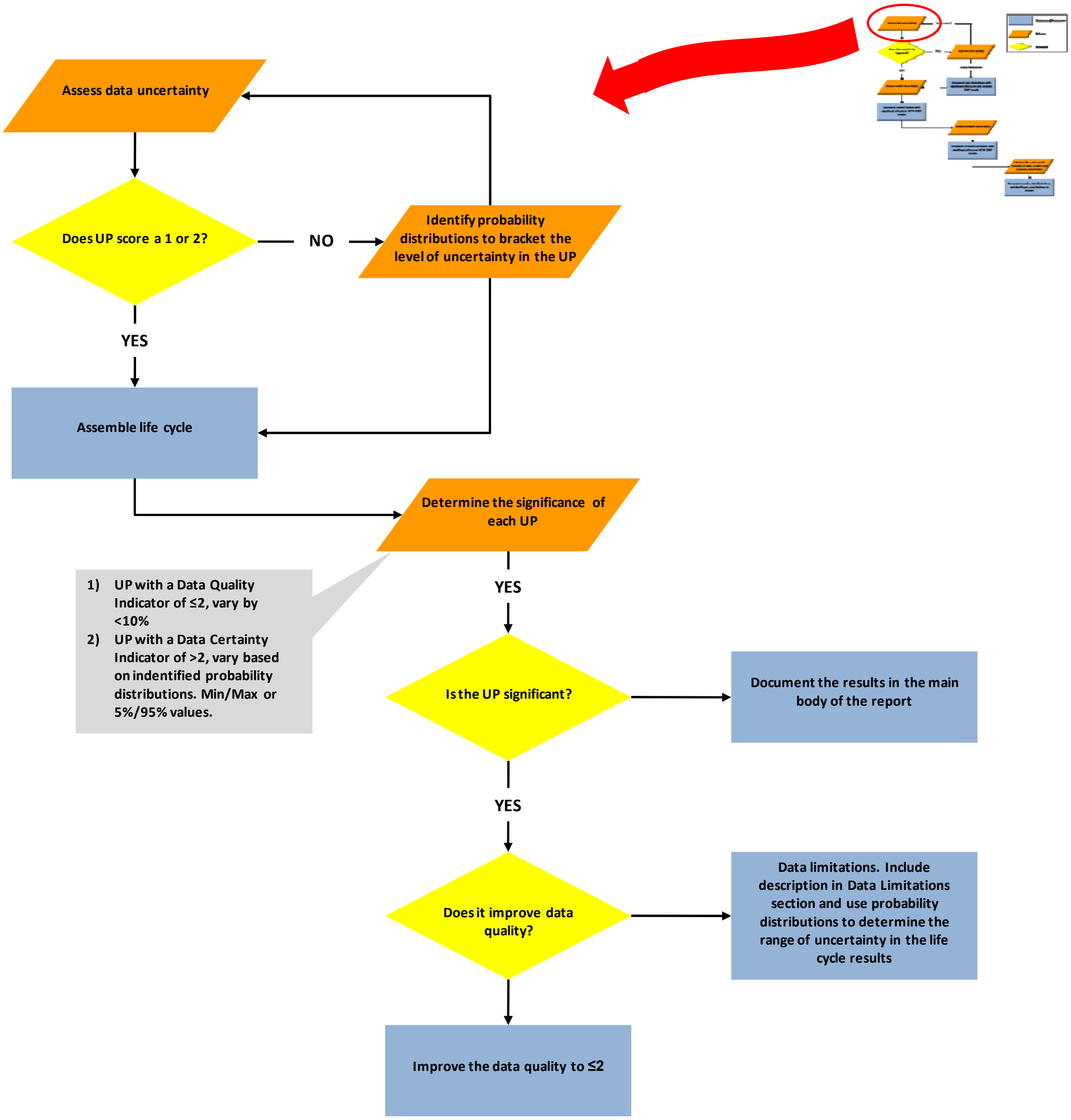


Figure 21. Process for Assessing and Documenting Data Uncertainty

Step 1: Calculate Data Quality Indicator (DQI) Scores for Each Unit Process (UP)

Uncertainty is inherent in all data used to model the life cycle of a process. It is critical to understand how the data used to model the life cycle effects the confidence of the final results. The first step in this process is to qualitatively rate the data for each unit process to determine its applicability to the goal and scope of the study. The following *Data Quality Matrix* is recommended to characterize the quality of data used in each unit process. The resulting characterization is referred to as a *Data Quality Indicator*.

Table 18 outlines a pedigree matrix for a qualitative indication of LCI data quality for each unit process used to characterize the life cycle of interest. This matrix was developed by Weidema and Wesnaes (1996) and has been modified to reflect criteria specific to this guidance document. The approach developed by Weidema and Wesnaes has been used in multiple studies and variations on the matrix have been used in several uncertainty approaches ((Sonnemann, Schuhmacher and Castells 2003); (Maurice, et al. 2000)), including the European LCI database "ecoinvent" (Frischknecht, et al. 2005). The text in this table is meant to serve only as a guide from which to assign indicator scores. In many cases, especially when two or more factors affect an indicator, professional judgments will need to be considered when assigning scores. For some indicators, determination of the score has rigid qualifications, and for others determination is more subject to professional judgment. It is the modeler's discretion which scores to assign in these cases, although rationales used should be documented when they are subjective (or include an element of subjectivity). Definitions of terms used in the data quality matrix and clarifications follow the table.

Table 18. Example Data Quality Matrix (Adapted From (Weidema and Wesnaes 1996))

Indicator	Score				
	1	**2**	**3**	**4**	**5**
Source Reliability	Data verified based on measurements	Data verified based on some assumptions and/or standard science and engineering calculations	Data verified with many assumptions, or non-verified but from quality source	Qualified estimate	Non-qualified estimate
	Source quality guidelines met		Source quality guidelines not met		
	Data cross checks, greater than or equal to 3 quality sources	Two or less data sources available for cross check, or data sources available that do not meet quality standards		No data available for cross check	
Completeness	Representative data from a sufficient sample of sites over an adequate period of time	Smaller number of site but an adequate period of time	Sufficient number of sites but a less adequate period of time	Smaller number of sites and shorter periods or incomplete data from an adequate number of sites or periods	Representativeness unknown or incomplete data sets
Temporal Representativeness	Less than three years of difference to year of study	Less than 6 years of difference	Less than 10 years difference	Less than 15 years difference	Age of data unknown or more than 15 years difference
Geographical Representativeness	Data from area under study	Average data from larger area	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area or area with very different production conditions
Technological Representativeness	Data from technology, process or materials being studied	Data from a different technology using the same process and/or materials		Data on related process or material using the same technology	Data or related process or material using a different technology

Source Reliability – This indicator relates to the quality of the data source and the verification of the data collection methods used within the source.

- **Data Verification**: Source data that have been verified within error bounds by either the source author (with a high level of transparency) or the LCA modeler. Verification can be done by measurement including on-site checking, recalculation, or mass or energy balance analysis. If the source data cannot be verified without making assumptions (i.e., not enough data are available to close the mass/energy balance), then the score should be a two or three, depending on the number of assumptions. If no source data are available, a qualified estimate from an expert in the field should receive a score of four, and an estimate from a non-expert should receive a score of five.

- **Source Quality Guidelines**: The highest quality source should meet the following criteria.
    - Be from a peer reviewed journal or a government sponsored study. If the source is an LCA, it must meet ISO requirements.
    - The source is publicly available either for free or at cost, or directly representative of the process of interest.
    - The source is written/published by an unbiased party.
    - The source is an unbiased survey of experts or process locations.

  When the source used for data is a reputable model that does not specifically meet the above criteria, it is the discretion of the modeler to determine the rank of the source. An example for justification would be if the data have been used in published reports that met the data quality standards.

- **Data Cross Check**: The number of sources that verify the same data point or series, within reason. As a general benchmark, a high standard is greater than or equal to three data cross checks with quality approved sources.

Completeness – This indicator quantifies the statistical robustness of the source data. This ranking is based on how many data points were taken, how representative the sample is to the studied process, and whether the data were taken for an acceptable time period to even out normal process fluctuations. The following examples are given to help clarify this indicator.

- *Pollutant output data were collected from all available power plants within a region from 11 pm to 12 am.* This would be sufficient sampling but for inadequate periods of time, so it would receive a ranking of three.
- *Natural gas use data at one power plant for a year.* This data would be assigned a rank of two, because the sample size is not representative but the time period is.
- *Efficiency of a new bio-refinery system using two types of biomass, and the source reports error within five percent.* The ranking of these data would range from two to four, subject to the judgment of the modeler both on acceptable error and because it is a new technology (multiple sampling sites would not be available). However, it is important to note that using these data for a biomass type not tested would affect the technological appropriateness ranking, defined below.

Specific numbers for amount of data or sample size are not given; these should be determined using the modeler's best professional judgment based on the type of data (new or existing technologies) and the reported error.

Temporal Representativeness – This indicator represents how well the time period in which the data were collected corresponds with the year of the study. If the study is set to evaluate the use of a technology from 2000 to 2040, data from 1970 would not be very accurate. It is important when assigning this ranking to take notice of any discrepancies between the year the source was published and the data were collected.

Geographical Representativeness – This indicator represents the appropriateness between the region of study and the source data region. This indicator becomes important when comparing data from different countries. For example, technological advances might reasonably be expected to develop differently in different countries, so efficiency and energy use might be very different. This is also important when looking at best management practices for carbon mitigation.

Technological Representativeness – This indicator embodies all other differences that may be present between the study goals and the data source. From the above example, using data for a type of biomass that is not being studied in the LCA should result in a lower technological representativeness ranking.

Step 2: Uncertainty Distributions for Unit Processes with Low Quality Data

Unit processes with data quality indicator scores of one or two for all five data quality indicator categories outlined in the data quality indicator matrix (e.g., 1, 2, 1, 2, 2) is considered high quality because the data meets the goal and scope of the study. Uncertainty estimates using probability distributions for data would generally not be necessary to meet the objectives of the study, however, if uncertainty information is known for one or more of the unit processes (i.e., provided with the data or derived from sampling data) the probability distributions should be included in the documentation to further improve the interpretation of the study results.

All unit processes that scored a three, four, or five in any of the five data quality categories should be further evaluated to properly assess the uncertainty introduced by data that failed to meet the goal and scope of the study. Uncertainty should be expressed in terms of a probability distribution (e.g., uniform, triangular, normal, lognormal, or other appropriate distribution). This information will be used in Step 4 below when determining the significance of each unit process.

Below are brief descriptions of some common distribution types, and when each might be used. Many other sources, such as Morgan and Henrion (1990) and IPCC (2006), address this subject in more detail.

- A *uniform distribution* is one of the simplest ways to represent uncertainty about a model input. All values between an upper and lower bound are equally likely; this could be from expert judgment or physical limitations.
- The *triangular distribution* represents knowledge of upper and lower bounds, as well as a most likely value somewhere between the two. This can also be used to represent expert judgment.
- The *normal distribution* is commonly used to represent the additive effect of various data points with unknown levels of uncertainty that are believed to be acting in a random manner. The normal distribution represents a symmetric continuous distribution that is unbounded on both ends (i.e., from infinity to infinity).
- The *lognormal distribution* is often used to represent the value of a process where the percent change in the value is random or independent of other parameters. For example, the oil industry uses lognormal distributions to represent oil reserve potential. The

lognormal distribution is also different from the normal distribution such that the values are always positive; they range from zero to infinity.

Step 3: Assemble the Unit Processes to Model the Life Cycle

The next step is to assemble each of the unit processes into the five life cycle stages (see Section 3.0) and link them to generate the functional unit of the study.

Step 4: Determine the Significance of Each Unit Process

At this point, an analysis of the model response to each unit process is performed to assess the significance of each unit process. The inputs for each high quality unit process (DQI 1 or 2) should be individually varied by ±10 percent, and the inputs of low quality unit processes (DQI 3-5) should be varied to the minimum and maximum values or 95 percent confidence interval of the uncertainty range. If the change in the final result from a single unit process is greater than a threshold value, for example 0.1 g CO_2e/MJ, then the processes should be flagged for possible additional data quality refinement. This approach determines which unit processes could potentially contribute a significant amount of uncertainty to the final result of the study. The value of 0.1 g CO_2e/MJ is approximately 0.1 percent of the anticipated baseline of conventional aviation fuel (Skone and Gerdes 2008). In general, the threshold value should be selected to represent a contribution of 0.1 percent to the comparative baseline or 0.1 percent of the life cycle under study if not intended for comparative assessment. In both cases, the selected threshold value must be clearly stated to support the data quality assessment.

While this is similar to a sensitivity analysis, it would be more accurate to say that the model response to uncertainty is being tested in each unit process, with an assumed uncertainty of ±10 percent in cases where high quality data is used. Sources for more information on conducting a sensitivity analysis include Morgan and Henrion (1990) and the EPA Models Guidance Draft (Council for Regulatory Environmental Modeling 2003).

Step 5: Improve Data Quality of Significant Processes with Low Quality Data

If a unit process is based on low quality data and contributes an uncertainty of greater than 0.1 g CO_2e/MJ, an attempt should be made to find additional data and reduce the uncertainty range. In cases where energy or mass limitations were used to determine the uncertainty bounds, this could be additional sources that allow for a tighter bracketing of the uncertainty.

Step 6: Document Data Quality

In cases where uncertainty due to poor data quality cannot be reduced (or reduced enough to lower the model response below the threshold) a discussion regarding the impact of the uncertainty on the study outcome should be included with final presentation of results. When high quality data inputs are determined to have a minor impact to the final results (i.e., below the 0.1 gCO_2e/MJ threshold), the data sources should be documented within the report.

6.7 Model Uncertainty

Once the quality of data used to develop the life cycle has been assessed and improved to meet the goal and scope of the study (to the extent possible) the next step is to assess and document the effects of model uncertainty on the life cycle results. This is the second phase mapped in Figure 20. Model uncertainty is classified within this guidance document as any modeling choice that could not be adequately supported by data (i.e., professional judgment was required to determine the modeling choice). Examples include:

- More than one allocation method could be applied to products and co-products.
- Ratio of conventional crude oil production to unconventional (heavy oil) crude oil production is undefined in the available data.
- Data on carbon changes to a specific soil type used to grow food crops is not available and model estimates must be used.
- System boundaries could not be tracked to elementary flows (see Section 4.0).

The following procedure is recommended to evaluate model uncertainty. The uncertainty introduced from all modeling choices should be included with the final results in both tabular and graphical format (e.g., error bars). Figure 22 outlines a recommended procedure for identifying, assessing, and documenting model uncertainty within the life cycle results. A brief description of each step is provided below.

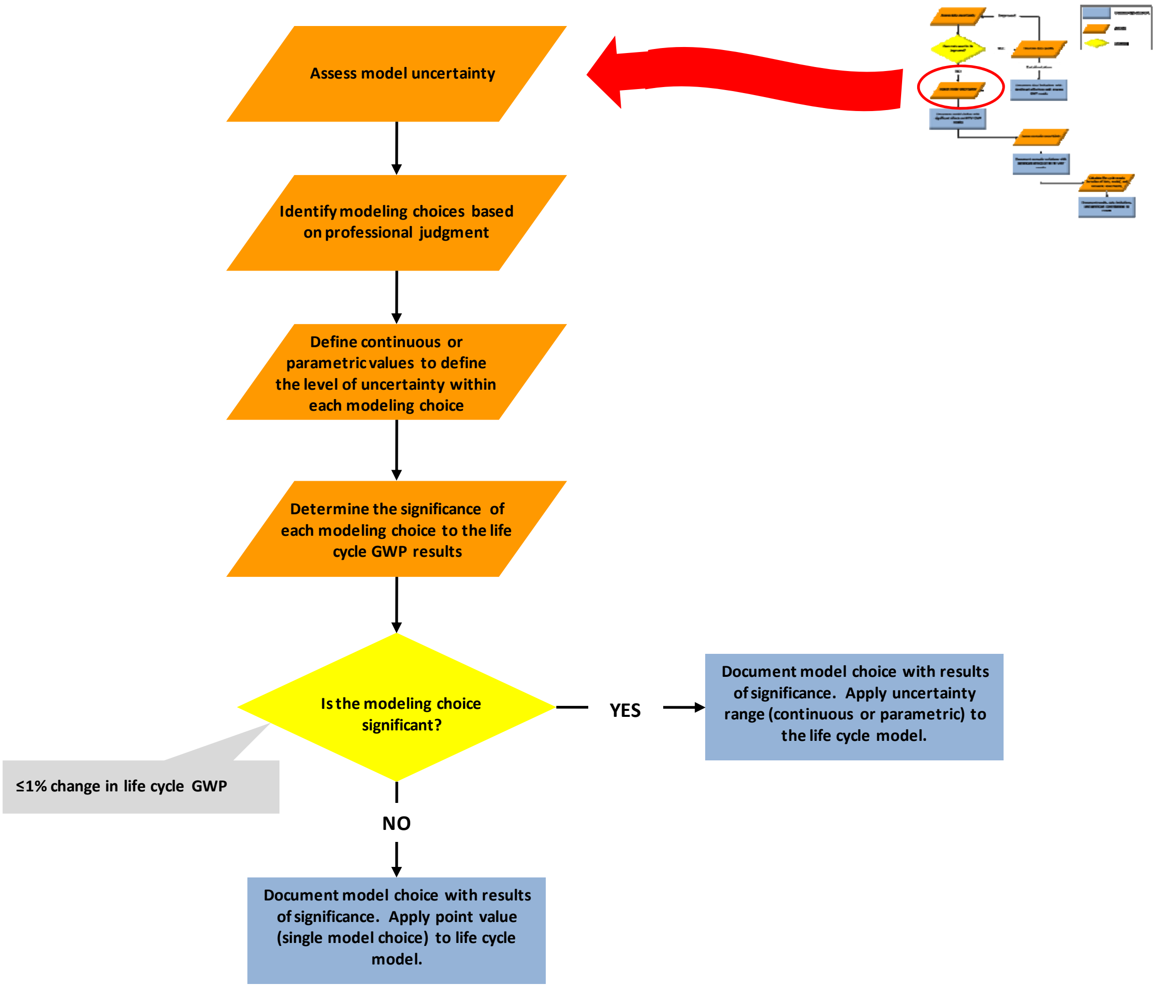


Figure 22. Process for Assessing and Documenting Model Uncertainty

Step 1: Identify Modeling Choices Based on Professional Judgment

Throughout the process of assembling the life cycle, choices were required by the LCA modeler on how to represent the life cycle. Most of these choices were supported by data or other information to guide the selection. In some cases, professional judgment may have been required to overcome inadequate detail in available data or more than one selection choice could have been selected (e.g., method of allocation). All modeling choices that required professional judgment to be used in selecting the appropriate choice should be identified and then evaluated in the following step.

Step 2: Determine Uncertainty Distributions or Parametric Values for Modeling Choices

Modeling choices can be either represented as a probability distribution or a set of parametric choices (distinct model values). The selection of different allocation methods is an example of distinct parametric choices. An example of a modeling choice that would use a probability distribution is where the ratio between two quantities is unknown (for example, the types of specific sub-bituminous coals fed to a gasification unit), but there are reasonable boundaries (e.g., technical limits) with or without a most likely (i.e., probable) value. The uncertainty of all modeling choices should be evaluated to determine the significance to the total life cycle GWP results.

Step 3: Determine the Significance of Each Modeling Choice

The effect of model uncertainty should be measured against the well-to-wake (WTW)[17] life cycle GWP using a form of sensitivity analysis (sometimes referred to as "scenario analysis"). Point values (mean, average or most probable) contained within the current model should be used to assess the effect of model uncertainty. The effects of data uncertainty and model uncertainty, as well as scenario uncertainty, should be included in the final life cycle study results interpretation and reporting section.

Results of the modified sensitivity analysis can be graphed and ranked to display the modeling choices and identify the choices with a significant effect (greater than 1% change in the life cycle GWP results).

Step 4: Document Modeling Choices and Known Data Limitations

Any modeling choice that causes a change of 1% or greater to the total life cycle GWP results should be discussed as a data limitation with the final results.

Modeling choices that are determined to affect the final results by less than 1% should be briefly discussed in the report but are not required to be noted as a data limitation that impacts the comparability of the results.

6.8 Scenario Uncertainty

When forecasting operations that will occur in the future there is a level of uncertainty associated with the source of electricity, the methods of biomass collection, and potential regulatory

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[17] The point of comparison for determining sensitivity is on the full life cycle basis (well-to-wake), unlike the data uncertainty section that requires the evaluation be conducted at the well-to-tank perspective. The full life cycle basis (well-to-wake) equates to the functional unit of the study and therefore is the primary comparison point for decision-making purposes. This value has yet to be determined when evaluating data quality when using the systematic process outlined within this guidance document. Therefore, the only relative point of reference to ensure adequate data quality is the unit process.

changes; to mention only a few examples. These are not modeling choices; they are distinct changes in how the life cycle is modeled when technology choices or other future aspects are unknown. Evaluating scenario uncertainty is a method to capture and report this form of uncertainty when forecasting future operations. These are referred to as variants of different scenarios within this document (the term “choices” was avoided to prevent confusion with the term “modeling choices”). Examples of scenario variants are:

- Future Energy Mixes
- Technology Differences
- Carbon Sequestration Options
- Biomass Handling Options

The following procedure is recommended to evaluate scenario uncertainty. The uncertainty introduced from all modeling choices should be included with the final results in both tabular and graphical format (e.g., error bars). Figure 23 outlines a recommended procedure for identifying, assessing, and documenting scenario uncertainty within the life cycle results. A brief description of each step is provided below.

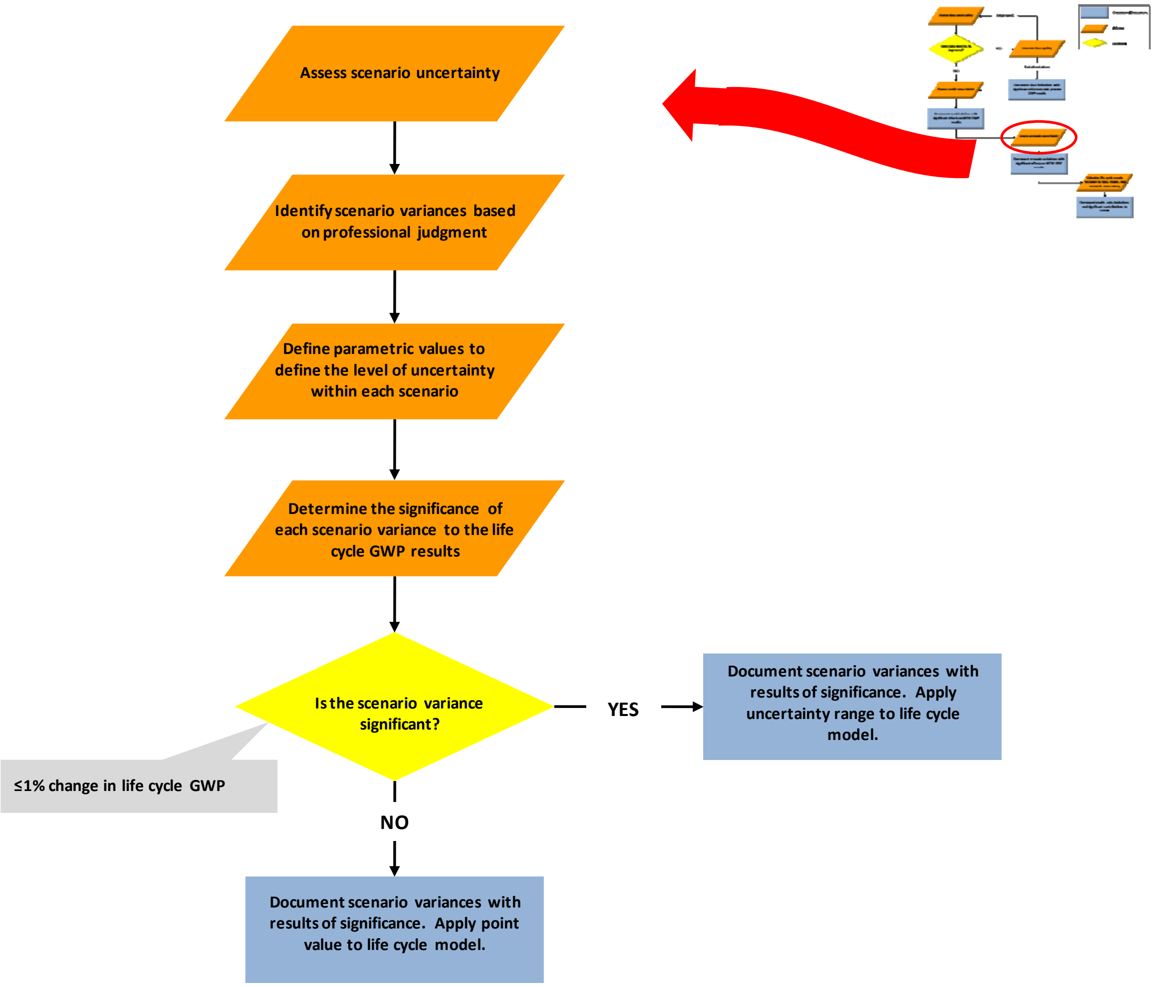

Figure 23. Process for Assessing and Documenting Scenario Uncertainty

***Step 1*: Identify Scenario Variants Based on Professional Judgment**

All scenario variations that are employed to capture the probable range of variations in modeling future operations should be identified and assessed to convey the potential effect on the final life cycle GWP results.

***Step 2*: Determine Uncertainty Distributions or Parametric Values for Scenario Variants**

Scenario variations are commonly represented as a set of parametric choices (distinct model values). For example the electricity profile in year 2030 is modeled with or without a carbon constrained profile. Variations of the change in energy efficiency of biomass harvesting or energy production would also be examples of scenario uncertainty. The uncertainty of all scenario variants should be evaluated to determine the significance to the total life cycle GWP results.

***Step 3*: Determine the Significance of Each Scenario Variant**

The effect of scenario uncertainty should be measured against the WTW life cycle GWP using a form of sensitivity analysis (sometimes referred to as "scenario analysis"). Point values (mean, average or most probable) contained within the current model should be used to assess the effect of scenario uncertainty. The effects of data uncertainty, model uncertainty, and scenario uncertainty, should be combined in the final life cycle study results, interpretation and reporting section.

Results of the modified sensitivity analysis can be graphed and ranked to display the scenario variances with the greatest to least effect and identify the variants with a significant effect (greater than 1% change in the life cycle GWP results).

***Step 4*: Document Scenario Variants and Known Data Limitations**

Any scenario variance that causes a change of 1% or greater to the total life cycle GWP results should be discussed as a data limitation with the final results.

Scenario variances that are determined to affect the final results by less than 1% should be documented, but are not data limitations that impact the comparability of the results.

6.9 Documenting LCA Study Quality and Known Data Limitations

Once the three primary forms of uncertainty have been identified and assessed (data, model, and scenario), the three uncertainty distributions need to be combined into a single model and evaluated using a form of Monte Carlo analysis to determine the cumulative uncertainty in the final GWP results.

Results should be presented for each life cycle stage, well-to-tank basis, and the total well-to-wake life cycle GWP results. All results should be presented in both a tabular and graphical format in the LCA report. Results of the sensitivity analyses conducted throughout the overall LCA should be reported on the significant unit process and/or data elements with the discussion of final results.

6.10 Data Limitations

It is imperative to report all known data limitations identified throughout the study to ensure decision-makers are fully informed when interpreting the final study results. A separate section entitled "Data Limitations" should be included with the final results to highlight each form of data, model, and scenario uncertainty included in the study. The data limitations should address the cause and effect of each form of uncertainty included within the study.

6.11 Data Quality Assessment

An assessment of the overall study quality should also be included with the final results to document whether or not the study met the goal and scope and is suitable for the intended purpose. Table 19 identifies the data quality requirements identified by the International Organization for Standards (ISO) 14044 (2006b) as appropriate metrics for evaluating the quality of study results with respect to the study goal and scope. The table should be completed for each life cycle modeled within the study (i.e., Baseline, Alternative A, Alternative B, etc.).

Table 19. Data Quality Assessment of Study Methodology and Results (Adapted From (ISO 2006b))

Quality Metric	Qualitative Assessment
Time-related Coverage	This statement should summarize the timeframe (year of collection, and time range of collection) during which the data were collected, or any reference to the frequency at which the data are collected.
Geographical Coverage	The statement should describe the geographical area from which data are collected (e.g. district, country, region). This statement should provide clarity to reviewers any geographical and thus environmental impacts that needed to be considered when the collected data were applied to the study.
Technology Coverage	This statement should provide insight into whether the data collected relate to a specific technology or a compilation of technologies. This statement can provide the reviewer with insight into knowledge that exists regarding the evolution of technology relating to the data collected.
Precision	Measure of the variability of the data values for each data expressed (e.g. variance)
Completeness	The percentage of data that is measured, and the degree to which the data represent the population of interest (is the sample size large enough, is the periodicity of measurement sufficient, etc.) • % of Mass and Energy Included • % of Environmental Relevance
Representativeness	Qualitative assessment of the degree to which the data set reflects the true population of interest (this is a composite of geographical coverage, time period and technology)
Consistency	A qualitative assessment of whether analysis of the selected data set was carried out uniformly. This statement should reflect whether a study was conducted methodically while remaining consistently detailed.
Reproducibility	A qualitative assessment of the extent to which information about the method and data values would allow an independent practitioner to reproduce the results reported in the study.

Table 19. Data Quality Assessment of Study Methodology and Results (Adapted From (ISO 2006b)) ***(Cont'd)***

Quality Metric	Qualitative Assessment
Sources of Data	A reference to the primary or secondary nature of the data. This statement should reflect whether the data collected represent a industry average, measured site-specific data, etc.
Uncertainty of the Information	Overall statement that summarizes the level to which uncertainty has been examined, and the resulting conclusion.
Study Quality/Applicable Uses	A qualitative statement assessing the level to which data quality was preserved and whether the study remained applicable to the original goal and scope of the project. The statement should also cite industry areas where the study might be applicable.

6.12 Minimum Guidelines for Reporting Comparative LCA Results

Table 20 provides an illustrative example of a completed data quality assessment from the Department of Energy (DOE), NETL report on petroleum-based fuels (Skone and Gerdes 2008).

Table 20. Example of Completed Data Quality Assessment of Study Methodology and Results

Quality Metric	Qualitative Assessment
Time-related Coverage	Crude oil extraction profiles for all countries are technologically representative of year 2005 operations. Year 2005 industry data, reported to the EIA, were used to characterize sources of refinery feedstock material, refinery energy usage, refinery production data, and imported product data. Energy intensity and modes of transport were derived from Oak Ridge National Laboratory, Transportation Energy Data Book for year 2005 which are compiled from Department of Transportation statistics. Vehicle emission profiles (from fuel combustion) are based on the average 2005 U.S. passenger vehicle fleet. Aircraft emission profile are not specific to 2005 operations, but are consistent with the aviation standard for reporting GHG emissions for the year 2005.
Geographical Coverage	U.S. specific models were constructed to represent all US operations. Country specific crude oil extraction profiles were used to represent 90% of the total crude oil consumed at U.S. refineries. Foreign refining operations are based on the NETL US Petroleum Refining Model. Results were compared to non- US studies of foreign refining operations. Due to high variability in results of non- US studies, sensitivity analysis was conducted to determine the impact of utilizing the US model.

Table 20. Example of Completed Data Quality Assessment of Study Methodology and Results *(Cont'd)*

Quality Metric	Qualitative Assessment
Technology Coverage	Petroleum refining technology has not changed significantly in the past 15-years. All data were evaluated to accurately represent energy consumption and emission rates relative to year 2005. Petroleum refining unit process capacity utilization data were based on a 1996 survey of the US petroleum industry. Unit process throughput allocation to the product categories was based on a survey of recent literature. Sensitivity analysis was conducted on these parameters and determined to have minimal impact on the final results.
Precision	Precision was managed by subject matter expert review and quality assessment of data sources and subsequent selection of the best available data representing actual operations in year 2005. Key parameters were evaluated through sensitivity analysis to assess the impact to the final results.
Completeness	Completeness is achieved within the study's defined cutoff criteria of mass, cost, and environmental relevance consistent with ISO 14044 LCA standards. This includes analysis and selection of carbon dioxide, methane, and nitrous oxide as the three types of GHG emissions that have environmental relevance to the total life cycle of petroleum-derived transportation fuels. The refinery model was balanced to 100% based on an iterative calculation procedure to balance both the energy and hydrogen values.
Representativeness	The results of this study accurately reflect the 2005 US national average GHG profile for conventional transportation fuels sold or distributed using the highest quality data publically-available.
Consistency	The study methodology and level of modeling detail were applied consistently throughout all aspects of the study. Any deviations were evaluated through sensitivity analysis and determined to have minor impact to the final results.
Reproducibility	The results of this study are 100% reproducible. Proprietary purchased data from PE International were not reported but these data are publically-available and calculated results in terms of CO_2E using the PE International data are fully reported. All documentation for PE International data sets used in this study is included as an attachment for full transparency.
Sources of Data	Industry average data were used as the primary data source. Industry specific data and engineering estimates were used when industry average data were not available. The sources of all data are clearly documented in the report for each unit process modeled.

Table 20. Example of Completed Data Quality Assessment of Study Methodology and Results *(Cont'd)*

Quality Metric	Qualitative Assessment
Uncertainty of the Information	Uncertainty is an inherent aspect of performing life cycle based studies. Probability estimates were not determined for each data point used in this study. Key parameters were assessed through sensitivity analysis in place of uncertainty analysis. This analysis has a variance of less than +/- 4% for the well-to-tank results on any single sensitivity parameter. Use phase results are static (+/- 0%) based on a fixed modeling assumption to manage the variance in the study results. The variance in the life cycle total (well-to-wheels/wake) then equates to less than +/- 1% on any single sensitivity parameter.
Study Quality/Applicable Uses	This study reflects the highest quality of life cycle (GHG) analysis based on the study goal and scope. Use of the study results is applicable for all decision types (internal, public, policy, etc.) when used in the appropriate context.

7.0 CONCLUSIONS

As described in this guidance document, the methodologies and data for estimating life cycle greenhouse gas emissions for aviation fuels are beginning to be used in regulatory and procurement decision-making. As with other complex models used in environmental decisions, a rigorous and transparent model development, documentation, and evaluation processes can improve the regulatory process. This report represents a first step in that direction. As noted in Section 2.0, for complex models used in environmental regulatory decision-making, the National Research Council (2004) made a number of recommendations regarding the use of models in environmental decision-making. The NRC recommendations, and the role of this guidance document in responding to those recommendations, are summarized below:

- ***NRC recommendation***: *Provide model documentation throughout the development and use of the model.* The working group that produced this guidance document anticipates that this report can serve as a starting point for the documentation of modeling procedures for the life cycle greenhouse gas emissions associated with aviation fuels, as these procedures evolve.
- ***NRC recommendation***: *Peer review models.* The NRC report recommends that models and modeling applications be reviewed. For life cycle studies done for the purpose of initial EISA Section 526 compliance assessments for aviation fuels, reviews may be independent peer reviews of life cycle studies done for fuels being considered for procurement, or reviews done by the procuring entity. In either case, the working group anticipates that, for the purposes of initial EISA Section 526 compliance assessments for aviation fuels, this report can serve as guidance for peer reviewers of alternative fuel assessments.
- ***NRC recommendation***: *Communicate model uncertainty.* This document provides guidance on methods for characterizing, quantifying and reporting uncertainty in the life cycle greenhouse gas emissions of aviation fuels.
- ***NRC recommendation***: *Integrate models and measurements.* This document also describes methods for combining various types of data and model estimates and describes methods for reporting these procedures
- ***NRC recommendation***: *Perform retrospective analyses of models.* Use of life cycle greenhouse gas emission estimates in federal aviation fuel procurement is just beginning. This document, which was developed with the sponsorship of the Air Force, represents a starting point for model documentation. By continuing to providing on-going updates to this document, as data and procedures evolve, the Air Force and other groups with interests in life cycle greenhouse emissions of aviation fuels, can lay the ground-work for retrospective analyses
- ***NRC recommendation***: *Assess the balance between the level of detail incorporated into models and the ability to evaluate the performance of these model features (model parsimony).* The system boundary guidance developed in this document describes methods for identifying processes that contribute significantly to model estimates, and describes methods for documenting which processes can be assumed to be negligible.

- ***NRC recommendation**: Establish procedures for overall model management.* By sponsoring the development of this document, the Air Force has initiated a process of active model management; the working group recommends that this process continue.

APPENDIX A

List of Attendees

Name	Organization
David T. Allen	University of Texas at Austin
Charles Allport	Universal Technology Corporation
Kristopher Atkins	The Boeing Company
Joyce S. Cooper	University of Washington
Robert M. Dilmore	National Energy Technology Laboratory
Laura C. Draucker	Science Applications International Corporation
Kenneth E. Eickmann	University of Texas at Austin
Jeffrey C. Gillen	U.S. Air Force Fellow at Argonne National Laboratory
Warren Gillette	Federal Aviation Administration
W. Michael Griffin	Carnegie Mellon University
William E. Harrison III	US Air Force Research Laboratory
James I. Hileman	Massachusetts Institute of Technology
John R. Ingham	URS Corporation
Fred A. Kimler III	US Air Force Research Laboratory
Aaron Levy	Environmental Protection Agency
Cynthia F. Murphy	University of Texas at Austin
Michael J. O'Donnell	University of Texas at Austin
David Pamplin	Defense Logistics Agency
Greg Schivley	Franklin Associates, A Division of ERG
Timothy J. Skone	National Energy Technology Laboratory
Shannon M. Strank	University of Texas at Austin
Russell W. Stratton	Massachusetts Institute of Technology
Phillip H. Taylor	University of Dayton Research Institute
Valerie M. Thomas	Georgia Institute of Technology
Michael Q. Wang	Argonne National Laboratory
Michael E. Webber	University of Texas at Austin
Thomas Zidow	URS Corporation

APPENDIX B

IPCC Global Warming Potentials[18]

Industrial Designation or Common Name (years)	Chemical Formula	Lifetime (years)	Radiative Efficiency (W m^{-2} ppb^{-1})	Global Warming Potential for Given Time Horizon			
				SAR (100-yr)	20-yr	100-yr	500-yr
Carbon dioxide	CO_2	See below[a]	[b]$1.4x10^{-5}$	1	1	1	1
Methane[c]	CH_4	12[c]	$3.7x10^{-4}$	21	72	75	7.6
Nitrous oxide	N_2O	114	$3.03x10^{-3}$	310	289	298	153
Substances controlled by the Montreal Protocol							
CFC-11	CCl_3F	45	0.25	3,800	6,730	4,750	1,620
CFC-12	CCl_2F_2	100	0.32	8,100	11,000	10,900	5,200
CFC-13	$CClF_3$	640	0.25		10,800	14,400	16,400
CFC-113	CCl_2FCClF_2	85	0.3	4,800	6,540	6,130	2,700
CFC-114	$CClF_2CClF_2$	300	0.31		8,040	10,000	8,730
CFC-115	$CClF_2CF_3$	1,700	0.18		5,310	7,370	9,990
Halon-1301	$CBrF_3$	65	0.32	5,400	8,480	7,140	2,760
Halon-1211	$CBrClF_2$	16	0.3		4,750	1,890	575
Halon-2402	$CBrF_2CBrF_2$	20	0.33		3,680	1,640	503
Carbon tetrachloride	CCl_4	26	0.13	1,400	2,700	1,400	435
Methyl bromide	CH_3Br	0.7	0.01		17	5	1
Methyl chloroform	CH_3CCl_3	5	0.06		506	146	45
HCFC-22	$CHClF_2$	12	0.2	1,500	5,160	1,810	549
HCFC-123	$CHCl_2CF_3$	1.3	0.14	90	273	77	24
HCFC-124	$CHClFCF_3$	5.8	0.22	470	2,070	609	185
HCFC-141b	CH_3CCl_2F	9.3	0.14		2,250	725	220
HCFC-142b	CH_3CClF_2	17.9	0.2	1,800	5,490	2,310	705
HCFC-225ca	$CHCl_2CF_2CF_3$	1.9	0.2		429	122	37
HCFC-225cb	$CHClFCF_2CClF_2$	5.8	0.32		2,030	595	181
Hydrofluorocarbons							
HFC-23	CHF_3	270	0.19	11,700	12,000	14,800	12,200
HFC-32	CH_2F_2	4.9	0.11	650	2,330	675	205
HFC-125	CHF_2CF_3	29	0.23	2,800	6,350	3,500	1,100
HFC-134a	CH_2FCF_3	14	0.16	1,300	3,830	1,430	435
HFC-143a	CH_3CF_3	52	0.13	3,800	5,890	4,470	1,590
HFC-152a	CH_3CHF_2	1	0.09	140	437	124	38
HFC-227ea	CF_3CHFCF_3	34.2	0.26	2,900	5,310	3,220	1,040
HFC-236fa	$CF_3CH_2CF_3$	240	0.28	6,300	8,100	9,810	7,660
HFC-245fa	$CHF_2CH_2CF_3$	7.6	0.28		3,380	1,030	314
HFC-365mfc	$CH_3CF_2CH_2CF_3$	8.6	0.21		2,520	794	241
HFC-43-10mee	$CF_3CHFCHFCF_2CF_3$	15.9	0.4	1,300	4,140	1,640	500

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[18] Available at http://ipcc-wg1.ucar.edu/wg1/wg1-report.html

Industrial Designation or Common Name (years)	**Chemical Formula**	**Lifetime (years)**	**Radiative Efficiency (W m^{-2} ppb^{-1})**	**Global Warming Potential for Given Time Horizon**			
				SAR (100-yr)	20-yr	100-yr	500-yr
Perfluorinated compounds							
Sulphur hexafluoride	SF_6	3,200	1	23,900	16,300	22,800	32,600
Nitrogen trifluoride	NF_3	740	0		12,300	17,200	20,700
PFC-14	CF_4	50,000	0.1	6,500	5,210	7,390	11,200
PFC-116	C_2F_6	10,000	0.26	9,200	8,630	12,200	18,200
PFC-218	C_3F_8	2,600	0	7,000	6,310	8,830	12,500
PFC-318	c-C_4F_8	3,200	0	8,700	7,310	10,300	14,700
PFC-3-1-10	C_4F_{10}	2,600	0.33	7,000	6,330	8,860	12,500
PFC-4-1-12	C_5F_{12}	4,100	0.41		6,510	9,160	13,300
PFC-5-1-14	C_6F_{14}	3,200	0.49	7,400	6,600	9,300	13,300
PFC-9-1-18	$C_{10}F_{18}$	>1,000d	0.56		>5,500	>7,500	>9,500
trifluoromethyl sulphur pentafluoride	SF_5CF_3	800	1		13,200	17,700	21,200
Fluorinated ethers							
HFE-125	CHF_2OCF_3	136	0		13,800	14,900	8,490
HFE-134	CHF_2OCHF_2	26	0		12,200	6,320	1,960
HFE-143a	CH_3OCF_3	4	0.27		2,630	756	230
HCFE-235da2	$CHF_2OCHClCF_3$	3	0.38		1,230	350	106
HFE-245cb2	$CH_3OCF_2CHF_2$	5	0.32		2,440	708	215
HFE-245fa2	$CHF_2OCH_2CF_3$	5	0.31		2,280	659	200
HFE-254cb2	$CH_3OCF_2CHF_2$	2.6	0		1,260	359	109
HFE-347mcc3	$CH_3OCF_2CF_2CF_3$	5.2	0.34		1,980	575	175
HFE-347pcf2	$CHF_2CF_2OCH_2CF_3$	7.1	0.25		1,900	580	175
HFE-356pcc3	$CH_3OCF_2CF_2CHF_2$	0.33	0.93		386	110	33
HFE-449sl (HFE-7100)	$C_4F_9OCH_3$	3.8	0.31		1,040	297	90
HFE-569sf2 (HFE-7200)	$C_4F_9OC_2H_5$	0.77	0.3		207	59	18
HFE-43-10pccc124 (H-Galden 1040x)	$CHF_2OCF_2OC_2F_4OCHF_2$	6.3	1.37		6,320	1,870	569
HFE-236ca12 (HG-10)	$CHF_2OCF_2OCHF_2$	12.1	0.66		8,000	2,800	860
HFE-338pcc13	$CHF_2OCF_2CF_2OCHF_2$	6.2	0.87		5,100	1,500	460
Perfluoropolyethers							
PFPMIE	$CF_3OCF(CF_3)CF_2OCF_2OCF_3$	800	0.65		7,620	10,300	12,400
Hydrocarbons and other compounds – Direct Effects							
Dimethylether	CH_3OCH_3	0	0		1	1	<<1
Methylene chloride	CH_2Cl_2	0	0		31	9	3
Methyl chloride	CH_3Cl	1	0		45	13	4

Industrial Designation or Common Name (years)	**Chemical Formula**	**Lifetime (years)**	**Radiative Efficiency (W m^{-2} ppb^{-1})**	**Global Warming Potential for Given Time Horizon**			
				SAR (100-yr)	20-yr	100-yr	500-yr

Notes:

a) The CO_2 response function used in this report is based on the revised version of the Bern Carbon cycle model used in Chapter 10 of this report (Bern2.5CC; Joos, et al. 2001) using a background CO_2 concentration value of 378 ppm. The decay of a pulse of CO_2 with time t is given by:

$$a_0 + \sum_{i=1}^{3} a_i \cdot e^{-t/\tau_i}$$

Where $a_o = 0.217$, $a_1 = 0.259$, $a_2 = 0.338$, $a_3 = 0.186$, $\tau_1 = 172.9$ years, $\tau_2 = 18.51$ years, and $\tau_3 = 1.186$ years.

b) The radiative efficiency of CO_2 is calculated using the IPCC (1990) simplified expression as revised in the TAR, with an updated background concentration value of 378 ppm and a perturbation of +1 ppm (see Section 2.10.2).

c) The perturbation lifetime for methane is 12 years as in the TAR (see also Section 7.4). The GWP for methane includes indirect effects from enhancements of ozone and stratospheric water vapor (see Section 2.10.3.1).

d) Shine et al. (2005c), updated by the revised AGWP for CO_2. The assumed lifetime of 1,000 years is a lower limit.

e) Hurley et al. (2005)

f) Robson et al. (2006)

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AAFEX	Alternative Aviation Fuels EXperiment
ACCRI	Aviation Climate Change Research Initiative
AGWP	Absolute Global Temperature Potentials
ARB	Air Resources Board
ASTM	American Society of Testing Materials
BTU	British Thermal Unit
CAAFI	Commercial Aviation Alternative Fuels Initiative
CARB	California Air Resources Board
CBTL	Coal/Biomass to Liquids
CLCA	Consequential Life Cycle Assessment
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e/MJ	Carbon Dioxide Equivalent per Mega-Joule
CTL	Coal-To-Liquid
DESC	Defense Energy Supply Center
DOD	Department of Defense
DOE	Department of Energy
EIOLCA	Economic Input-Output Life Cycle Assessment
EISA	Energy Independence and Security Act
EOL	End-of-Life
EPA	Environmental Protection Agency
FAPRI	Farm and Agricultural Policy Research Institute
FOSOM	Forestry and Agriculture Sector Optimization Model
F-T	Fischer-Tropsch
GHG	Greenhouse Gases
GTP	Global Temperature Potentials
GWP	Global Warming Potentials
HRJ	Hydrotreated Renewable Jet
H_2O	Water
IATA	International Air Transport Association

IO	Input - Output
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standards Organization
LC	Life Cycle
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LHV	Lower Heating Value
LTR	Linearized Temperature Response
LUC	Land Use Change
M/C	Manufacturing or Conversion
MJ	Mega-Joule
mmBTU	Million BTU
MSDS	Material Safety Data Sheet
NETL	National Energy Technology Laboratory
NO_x	Nitrogen Oxides
NPV	Net Present Value
NRC	National Research Council
PAS	Publicly Available Specification
PM	Particulate Matter
ppm	Parts Per Million
PT	Product Transport
RCRA	Resource Conservation Recovery Act
RF	Radiative Forcing
RMA	Raw Material Acquisition
RMEE	Relative Mass, Energy and Economics
RMT	Raw Material Transport and Storage
SAGE	System for assessing Aviation’s Global Emissions
SAIC	Science Applications International Corporation
SETAC	Society for Environmental Toxicology and Chemistry
SO_x	Sulfur Oxides
SPK	Synthetic Paraffinic Kerosene
TRI	Toxics Release Inventory
TTW	Tank-to-Wake

UHC	Unburned Hydrocarbons
UP	Uncertainty Principle or Unit Process
USAF	United States Air Force
WTT	Well-to-Tank
WTW	Well-to-Wake

GLOSSARY

Term	Reference[19]	Definition
Abiotic resource	F	Object that can be extracted from the environment to serve as an input for the product system and is distinguished from a biotic resource by its nonliving nature.
Accidental emission	A	An unintended environmental release.
Allocation	C	Partitioning the input or output flows of a process between the product system under study and one or more other product systems.
Alternative fuels	E	Collectively refers to natural gas (CNG, LNG, biomethane), LPG, electricity, hydrogen, an ethanol blend, a biomass-based-diesel blend, B100, and E100.
Ancillary input	F	Material input that is used by the unit process producing the product, but is not used directly as a part of the product.
Anticipated life cycle greenhouse gas emissions	B	Initial estimate of greenhouse gas (see 3.26 for a definition of greenhouse gases) emissions for a product (see 3.37 for a definition of product) that is calculated using secondary data (see 3.43 for a definition of secondary data) or a combination of primary (see 3.36 for a definition of primary activity data) and secondary data, for all processes used in the life cycle of the product.
Areas for protection	F	Broad social values with respect to the environmental policy (e.g. human health, ecological health, biodiversity, intergenerational material welfare, aesthetic values).
Attributional LCA	A	An LCA that accounts for flows/impacts of pollutants, resources, and exchanges among processes within a chosen temporal window.
B100	E	Biodiesel meeting ASTM D6751-07be1 (Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels).

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[19] This provides the source of the definition as is provided at the end of the Glossary.

Term	Reference[19]	Definition
Background data	A	The background data include energy and materials that are delivered to the foreground system as aggregated data sets in which individual plants and operations are not identified.
Biodiesel	E	A diesel fuel substitute produced from nonpetroleum renewable resources that meet the registration requirements for fuels and fuel additives established by the Environmental Protection Agency under section 211 of the Clean Air Act. It includes biodiesel meeting the following: (1) Registered as a motor vehicle fuel or fuel additive under 40 CFR part 79; (2) A mono-alkyl ester; (3) Meets ASTM D-6751-07, entitled "Standard Specification for Biodiesel Fuel Blendstock (B100) for Middle Distillate Fuels"; (4) Intended for use in engines that are designed to run on conventional diesel fuel; (5) Derived from nonpetroleum renewable resources (as defined in paragraph (m) of this section).
Biogenic	C	Derived from biomass, but not fossilized or from fossil sources.
Biomass	B	Material of biological origin, excluding material embedded in geological formations or transformed to fossil [Adapted from CEN/TR 14980:2004, 4.3].
Biomass-based diesel	E	A biodiesel (mono-alkyl ester) or a renewable biodiesel that complies with ASTM D975. This includes a renewable fuel derived from co-processing biomass with a petroleum feedstock.
Biomethane	E	Pipeline-quality gas derived from biomass as defined by the California Energy Commission (CEC), which includes any organic material not derived from fossil fuels, including agricultural crops, agricultural and forestry wastes and residues, and construction wood wastes, among others.

Term	**Reference**[19]	**Definition**
Biotic resource	F	Object that can be extracted from the environment to serve as an input for the product system, and that is distinguished from an abiotic resource by its living nature.
Blendstock	E	The blending component(s) that produce a finished fuel used in a motor vehicle. Each blendstock corresponds to a fuel chain in the ARB CA GREET. A blendstock that is used directly in a vehicle is considered a finished fuel.
Boundary	C	Set of criteria specifying which unit processes are part of a product system (life cycle).
Brines (oilfield)	A	Wastewater produced along with crude oil and natural gas from oilfield operations.
Business-to-business	B	Provision of inputs, including products, to another party that is not the end user.
Business-to-consumer	B	Provision of inputs, including products, to the end user.
By-Products	A	An incidental product deriving from a manufacturing process or chemical reaction, and not the primary product or service being produced. A by-product can be useful and marketable, or it can have negative ecological consequences.
Capital goods	B	Goods, such as machinery, equipment and buildings, used in the life cycle of products.
Carbon dioxide equivalent (CO_2e)	B	Unit for comparing the radiative forcing of a GHG to carbon dioxide [BS ISO 14064-1:2006, 2.19]. -Note 1: The carbon dioxide equivalent value is calculated by multiplying the mass of a given GHG by its global warming potential (see 3.25 for a definition of global warming potential). -Note 2: Greenhouse gases, other than CO_2, are converted to their carbon dioxide equivalent value on the basis of their per unit radiative forcing using 100-year global warming potentials defined by the Intergovernmental Panel on Climate Change (IPCC).

Term	**Reference**[19]	**Definition**
Carbon footprint	C	The level of greenhouse gas emissions produced by a particular activity or entity.
Carbon intensity	E	The amount of greenhouse gas emissions, measured on a life cycle basis, per unit of energy of fuel delivered. In this regulation, the units used are grams of carbon dioxide equivalent per megajoule (gCO_2e/MJ).
Carbon sequestration	B	Removal of carbon from the atmosphere.
Carbon storage	B	Retaining carbon of biogenic or atmospheric origin in a form other than as an atmospheric gas.
Characterization	A	Characterization is the second step of an impact assessment and characterizes the magnitude of the potential impacts of each inventory flow to its corresponding environmental impact.
Characterization factor (exposure factor, effect factor, exposure-effect actor, equivalence factor)	F	A factor which expresses the contribution of a unit environmental intervention (such as the atmospheric emission of 1 kg CFC-11) to the chosen impact categories (such as global warming and ozone depletion).
Classification	A	Classification is the first step of an impact assessment and is the process of assigning inventory outputs into specific environmental impact categories.
Combined heat and power (CHP)	B	Simultaneous generation in one process of useable thermal, electrical and/or mechanical energy.
Comparative assertion	F	Environmental claim regarding the superiority or equivalence of one product versus a competing product which performs the same function.
Competent person	B	Person with training, experience or knowledge and other qualities, and with access to the required tools, equipment and information, sufficient to enable them to carry out a defined task.
Completeness check	F	Process of verifying that information from the different phases (inventory analysis, life cycle impact assessment) is sufficient for interpretation to reach conclusions.

Term	Reference[19]	Definition
Composite Data	A	Data from multiple facilities performing the same operation that have been combined or averaged in some manner.
Conclusions and recommendations	F	Conclusions summarize the identification and evaluation of significant environmental issues. Recommendations are those features that arise directly from conclusions, given the goal of the study.
Consequential LCA	A	An LCA that attempts to account for flows/impacts that are caused beyond the immediate system in response to a change to the system.
Consistency check	F	Process of verifying that the interpretation is done in accordance with the goal and scope definition, before conclusions are reached.
Consumable	B	Ancillary input that is necessary for a process to occur but that does not form a tangible part of the product or co-products arising from the process. -Note 1: Consumables include lubricating oil, tools and other rapidly wearing inputs to a process. Consumables differ from capital goods in that they have an expected life of one year or less, or a need to replenish on a one year or less basis. -Note 2: Fuel and energy inputs to the life cycle of a product are not considered consumables.
Consumer	B	User of goods or services.
Conventional crude oil	E	A crude oil produced by a primary, secondary, or tertiary oil recovery process.
Co-products	C	Any of two or more products from the same unit process or product system [BS EN ISO 14044:2006, 3.10].

Term	**Reference**[19]	**Definition**
Credits/deficits	E	The mass of CO_2e, measured in metric tons, calculated from the difference between allowed emissions, set by either the gasoline or diesel standard, and the actual emissions generated by the use of a regulated fuel. A credit is generated when the actual emissions is less than the allowed emissions. A deficit is generated when the actual emissions is greater than the allowed emissions. In the LCFS, the total credit, calculated from the sum of credits generated under the gasoline and diesel groups, is used for the determination of compliance.
Data category	F	Classificatory division of the input and output flows from a unit process or product system.
Data quality	B	Characteristics of data that relate to their ability to satisfy stated requirements [BS EN ISO14044:2006, 3.19].
Dedicated fuel vehicle	E	A vehicle that uses a single external source of fuel for its operation. The fuel can be a pure fuel such as gasoline or a blended fuel such as E85 or B20. A dedicated fuel vehicle has one fueling port onboard the vehicle. Examples include BEV, E85 FFV, diesel running on B5 or B20, and grid independent hybrids such as a Prius.
Downstream emissions	C	GHG emissions associated with processes that occur in the life cycle of a product subsequent to the processes owned or operated by the organization in question.
E100	E	Also known as "Denatured Fuel Ethanol," a nominally anhydrous ethyl alcohol meeting ASTM D4806-08 (Standard Specification for Denatured Fuel Ethanol for Blending with Gasolines for Use as Automotive Spark-Ignition Engine Fuel).
Economic value	B	Market value of a product, co-product or waste (see 3.50 for a definition of waste) at the point of production.
Effect	F	A specific change in human health, in eco-system or the global resource situation as a consequence of a specific impact.

Term	**Reference**[19]	**Definition**
Elementary flow	F	(1) Material or energy entering the system being studied, which has been drawn from the environment without previous human transformation (2) Material or energy leaving the system being studied, which is discarded into the environment without subsequent human transformation.
Emission factor	B	Amount of greenhouse gases emitted, expressed as carbon dioxide equivalent and relative to a unit of activity. Note: For example, $kgCO_2e$ per unit input. Emission factor data would be obtained from secondary data sources.
Emissions	B	Release to air and discharges to water and land that result in GHGs entering the atmosphere.
Energy flow	F	Input flow to or output flow from a unit process or product system measured in units of energy.
Environment	F	Entire surroundings and conditions in which individuals, populations and organizations operate and interrelate. The surroundings include air, water, land, natural resources, flora, fauna and humans and extend from within an organization's location to the global system.
Environmental Aspects	A	Elements of a business' products, actions, or activities that may interact with the environment.
Environmental index	F	Resulting score representing the perceived harmfulness to the environment, obtained by quantitative weighting as a result of the valuation element.
Environmental intervention (environmental flow, environmental burden, stressor, elementary flow)	F	Exchange between the atmosphere (the "economy") and the environment including resource use, emissions to air, water, or soil.

Term	**Reference**[19]	**Definition**
Environmental issue	F	Inputs and outputs (results from the LCI) and-if additionally conducted environmental indicators (results from the LCIA), which are defined in general terms as being important in the goal and scope definition.
Environmental Loadings	A	Releases of pollutants to the environment, such as atmospheric and waterborne emissions and solid wastes.
Environmentally extended input-output (EEIO)	B	Analysis method of estimating the GHG emissions (and other environmental impacts) arising from sectors within an economy through the analysis of economic flows. Note: Alternative terms, such as economic input-output LCA (EIO-LCA), input output based LCA (IOLCA) and hybrid LCA (HLCA) refer to different approaches to implementing EEIO analysis.
Equivalency factor	A	An indicator of the potential of each chemical to impact the given environmental impact category in comparison to the reference chemical used.
Equivalent usage ratio	A	A basis for comparing two or more products that fulfill the same function. For example, comparing two containers based on a set volume of beverage to be delivered to the customer.
Evaluation	F	It is the second step within the life cycle interpretation including completeness check, sensitivity check, consistency check, as well as other checks.
Facility-specific data	A	Data from a particular operation within a given facility that are not combined in any way.
Feedstock energy	F	Gross combustion heat of raw material inputs, which are not used as an energy source, to a product system.
Final product	F	Product which requires no additional transformation prior to its use.
Finished fuel	E	A fuel that is used directly in a vehicle for transportation purposes without requiring additional chemical or physical processing.

Term	Reference[19]	Definition
Foreground data	A	Data from the foreground system that is the system of primary concern to the analyst.
Fossil	B	Derived from fossil fuel or another fossil source, including peat [Adapted from IPCC 2006 Guidelines for National Greenhouse Gas Inventories, Glossary, see Clause 2]
Fuel P&D	A	Activities involved in the processing and delivery of fuel used to run a process; also called Precombustion Energy.
Fugitive releases	F	Uncontrolled emission to air, water or land.
Functional unit	F	Quantified performance of a product system for use as a reference unit in a LCA study.
GHG emissions	B	Release of GHGs to the atmosphere.
Global warming potential (GWP)	B	Factor describing the radiative forcing impact of one mass-based unit of a given greenhouse gas relative to an equivalent unit of carbon dioxide over a given period of time [BS ISO 14064-1:2006, 2.18]. Note: Carbon dioxide is assigned a GWP of 1, while the GWP of other gases is expressed relative to the GWP of carbon dioxide from fossil carbon sources. Annex A contains global warming potentials for a 100-year time period produced by the Intergovernmental Panel on Climate Change. Carbon dioxide arising from biogenic sources of carbon is assigned a GWP of zero in specific circumstances specified in this PAS.
Goal and scope definition	F	Activity that initiates an LCA, defining its purpose, boundaries, limitations, main lines and procedures (see above).
Green technology	A	A technology that offers a more environmentally benign approach compared to an existing technology.

Term	**Reference**[19]	**Definition**
Greenhouse gases (GHGs)	C	Gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. Note: GHGs include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6).
HDV	E	Heavy Duty Vehicle. A vehicle that is rated at 14,001 or more pounds gross vehicle weight rating (GVWR).
Home fueling	E	An appliance that is located on or within a residential property with access limited to a single household.
Impact	F	The consequences for health, for the well-being of flora and fauna or for the future availability of natural resources, attributable to the input and output streams of a system.
Impact assessment	A	The assessment of the environmental consequences of energy and natural resource consumption and waste releases associated with an actual or proposed action.
Impact categories	A	Classifications of human health and environmental effects caused by a product throughout its life cycle.
Impact indicators	A	Impact indicators measure the potential for an impact to occur rather than directly quantifying the actual impact.
Impact score	F	Contribution of a product system to one impact category.
Impact score profile (environmental profile)	F	List of impact scores for all impact categories.

Term	**Reference**[19]	**Definition**
Impact vs. effect	F	Most of the environmental problems treated in present characterization methods are quantified at the level of environmental impacts (e.g., ozone formation, H+ deposition, ozone depletion, rise of radiate forcing). Environmental effects are the chosen endpoints within these impact chains (e.g., reduced human health, reduced growth of crop, dying of plants, reduced biodiversity etc.). This means that all steps in the cause-effect chain are impacts while effects are the chosen endpoints.
Indicator	F	A simplification and distillation of complex information intended as a summary description of conditions or trends to assist decisions.
Industrial system	A	A collection of operations that together perform some defined function.
Input	B	Product, material or energy flow that enters a unit process [BS EN ISO 14040:2006, 3.21]
Interested party	F	Individual or group concerned with or affected by the environmental performance of a product system, or by the results of the LCA.
Intermediate product	F	Input or output from a unit process which requires further transformation.
International Reference Life Cycle Data System (ILCD)	B	Series of technical guidance documents with quality, method, nomenclature, documentation and review requirements for quality ensured life cycle data and studies, coordinated for Europe by the European Commission's Joint Research Centre [2]
Interpretation	A	The evaluation of the results of the inventory analysis and impact assessment to reduce environmental releases and resource use with a clear understanding of the uncertainty and the assumptions used to generate the results.
Inventory analysis	A	The identification and quantification of energy, resource usage, and environmental emissions for a particular product, process, or activity.

Term	Reference[19]	Definition
Inventory table	F	List of environmental entities added to and taken from the environment (environmental interventions) through economic actions which are directly caused by processes within a product system. It is the main result of the inventory analysis.
LDV	E	Light Duty Vehicle. A vehicle that is rated at 8500 pounds or less GVWR.
Life cycle	B	Consecutive and interlinked stages of a product system, from raw material acquisition or generation of natural resources to end of life, inclusive of any recycling or recovery activity [Adapted from BS EN ISO 14040:2006, 3.1]
Life cycle assessment (LCA)	B	Compilation and evaluation of inputs, outputs and potential environmental impacts of a product system throughout its life cycle [BS EN ISO 14040:2006, 3.2]
Life cycle GHG emissions	B	Sum of greenhouse gas emissions resulting from all stages of the life cycle of a product and within the specified system boundaries of the product. Note: This includes all emissions that are released as part of the processes within the boundary of the life cycle of the product, including obtaining, creating, modifying, transporting, storing, operating, using and end of life disposal of the product.
Life cycle Greenhouse Gas Emissions	E	The aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land use changes), as determined by the Administrator, related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for their relative global warming potential. (From Section 211(o)(1) of the Clean Air Act)

Term	Reference[19]	Definition
LMV	E	Light/Medium Vehicles. A vehicle category that includes both light-duty (LDV) and medium duty vehicles (MDV).
Mass balance	C	Quantification of total materials flowing into and out of a process.
Material contribution	B	Contribution from any one source of GHG emissions of more than 1% of the anticipated life cycle GHG emissions associated with a product. Note: A materiality threshold of 1% has been established to ensure that very minor sources of life cycle GHG emissions do not require the same treatment as more significant sources.
Material P&D	A	Activities involved in the processing and delivery of materials to a process.
MDV	E	Medium Duty Vehicle. A vehicle that is rated between 8501 and 14,000 pounds GVWR.
Multi-fuel vehicle	E	A vehicle that uses two or more distinct fuels for its operation. A multi-fuel vehicle (also called a vehicle operating in blended-mode) includes a bi-fuel vehicle and can have two or more fueling ports onboard the vehicle. A fueling port can be an electrical plug or a receptacle for liquid or gaseous fuel. As an example, a plug-in hybrid hydrogen ICEV uses both electricity and hydrogen as the fuel source and can be "refueled" using two separately distinct fueling ports.
Non-conventional crude oil	E	A crude oil produced from oil sands, tarsands, oil shale, or processes such as gas-to-liquid (GTL) and coal-to liquid (CTL).
Normalization	A	Normalization is a technique for changing impact indicator values with differing units into a common, unitless format by dividing the value(s) by a selected reference quantity. This process increases the comparability of data among various impact categories.

Term	**Reference[19]**	**Definition**
Offsetting	B	Mechanism for claiming a reduction in GHG emissions associated with a process or product through the removal of, or preventing the release of, GHG emissions in a process unrelated to the life cycle of the product being assessed. Note: An example is the purchase of Certified Emission Reductions generated by Clean Development Mechanism projects under the Kyoto Protocol [3].
Output	B	Product, material or energy that leaves a unit process [Adapted from BS EN ISO 14044:2006, 3.25]. Note: Materials may include raw materials, intermediate products, co-products, products and emissions.
Precombustion energy	A	The extraction, transportation, and processing of fuels used for power generation, including adjusting for inefficiencies in power generation and transmission losses.
Primary activity data	B	Quantitative measurement of activity from a product's life cycle that, when multiplied by an emission factor, determines the GHG emissions arising from a process. -Note 1: Examples of primary activity data include the amount of energy used, material produced, service provided or area of land affected. -Note 2: Primary activity data sources are typically preferable to secondary data sources as the data will reflect the specific nature/efficiency of the process, and the GHG emissions associated with the process. -Note 3: Primary activity data does not include emission factors.
Private access	E	A fueling pump with access restricted to privately distributed electronic cards ("cardlock") or is located in a secure area not accessible to the public.

Term	**Reference**[19]	**Definition**
Product	B	Any good or service. Note: Services have tangible and intangible elements. The provision of a service can involve, for example, the following: (a) an activity performed on a consumer-supplied tangible product (e.g. automobile to be repaired); (b) an activity performed on a consumer-supplied intangible product (e.g. the income statement needed to prepare a tax return); (c) the delivery of an intangible product (e.g. the delivery of information in the context of knowledge transmission); (d) the creation of ambience for the consumer (e.g. in hotels and restaurants); (e) software consists of information and is generally intangible and can be in the form of approaches, transactions or procedures. [Adapted from BS ISO 14040:2006, 3.9]
Product category	B	Group of products that can fulfill equivalent functions [BS ISO 14025:2006, 3.12]
Product category rules (PCRs)	B	Set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories [BS ISO 14025:2006, 3.5]
Product life cycle	A	The life cycle of a product system begins with the acquisition of raw materials and includes bulk material processing, engineered materials production, manufacture and assembly, use, retirement, and disposal of residuals produced in each stage.
Product system	B	Collection of unit processes with elementary and product flows, performing one or more defined functions, that models the life cycle of a product [BS EN ISO 14040:2006, 3.28]

Term	**Reference**[19]	**Definition**
Product(s)	C	Any good(s) or service(s). Note: Services have tangible and intangible elements. Provision of a service can involve, for example, the following: an activity performed on a consumer-supplied tangible product (e.g. automobile to be repaired); an activity performed on a consumer-supplied intangible product (e.g. the income statement needed to prepare a tax return); the delivery of an intangible product (e.g. the delivery of information in the context of knowledge transmission); the creation of ambience for the consumer (e.g. in hotels and restaurants); software consists of information and is generally intangible and can be in the form of approaches, transactions or procedures.
Public access	E	A fueling pump that is accessible to the public.
Pure denatured ethanol	E	Also known as "denatured fuel ethanol," (E100) means nominally anhydrous ethyl alcohol meeting ASTM D4806-08 (Standard Specification for Denatured Fuel Ethanol for Blending with Gasoline for Use as Automotive Spark-Ignition Engine Fuel).
Racing vehicle	E	A competition vehicle not used on city streets.
Raw material	B	Primary or secondary material that is used to produce a product. Note Secondary material includes recycled material. [BS EN ISO 14040:2006, 3.15]
Raw material	C	Primary or secondary material used to produce a product.
Recycling, closed loop	F	Recovery of material on the same factory that produced the material. This kind of recovery requires a "take back" arrangement.
Regulated fuel	E	Fuel, for use in a motor vehicle, which is subject to this regulation.
Regulated party	E	A refiner, importer, producer, or provider of a transportation fuel in California subject to this regulation.

Term	**Reference**[19]	**Definition**
Renewable biomass	E	(1) Planted crops and crop residue harvested from agricultural land cleared or cultivated at any time prior to the enactment of this sentence that is either actively managed or fallow, and non-forested; (2) Planted trees and tree residue from actively managed tree plantations on nonfederal land cleared at any time prior to enactment of this sentence, including land belonging to an Indian tribe or an Indian individual, that is held in trust by the United States or subject to a restriction against alienation imposed by the United States; (3) Animal waste material and animal byproducts; (4) Slash and pre-commercial thinnings that are from non-federal forestlands, including forestlands belonging to an Indian tribe or an Indian individual, that are held in trust by the United States or subject to a restriction against alienation imposed by the United States, but not forests or forestlands that are ecological communities with a global or State ranking of critically imperiled, imperiled, or rare pursuant to a State Natural Heritage Program, old growth forest, or late successional forest; (5) Biomass obtained from the immediate vicinity of buildings and other areas regularly occupied by people, or of public infrastructure, at risk from wildfire; (vi) Algae; (6) Separated yard waste or food waste, including recycled cooking and trap grease. [Commentary. This definition comes from section 201 of Energy Independence and Security Act of 2007. ARB staff is seeking comments on the appropriateness and necessity of including this definition and how it might be used in the LCFS.]
Renewable diesel	E	A motor vehicle fuel or fuel additive which is all the following: (1) Registered as a motor vehicle fuel or fuel additive under 40 CFR Part 79; (2) Not a mono-alkyl ester; (3) Intended for use in engines that are designed to run on conventional diesel fuel; (4) Derived from nonpetroleum renewable resources.

Term	Reference[19]	Definition
Renewable energy	B	Energy from non-fossil energy sources: wind, solar, geothermal, wave, tidal, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases [Adapted from Directive 2001/77/EC, Article 2 [4]]
Routine emissions	A	Those releases that normally occur from a process, as opposed to accidental releases that proceed from abnormal process conditions.
Secondary data	B	Data obtained from sources other than direct measurement of the processes included in the life cycle of the product. Note: Secondary data are used when primary activity data are not available or it is impractical to obtain primary activity data.
Sensitivity analysis	A	A systematic evaluation process for describing the effect of variations of inputs to a system on the output.
Specific data	A	Data that are characteristic of a particular subsystem, or process.
Stressors	A	A set of conditions that may lead to an environmental impact. For example, an increase in greenhouse gases may lead to global warming.
System boundary	B	Set of criteria specifying which unit processes are part of a product system [BS EN ISO 14040:2006, 3.32]
System flow diagram	A	A depiction of the inputs and outputs of a system and how they are connected.
Transparency	F	Open, comprehensive and understandable presentation of information.

Term	**Reference**[19]	**Definition**
Transportation fuel	E	Any fuel used or intended for use as a motor vehicle fuel, other than racing fuel. In addition, "transportation fuel" includes diesel fuel used or intended for use in non-vehicular sources other than the following: (1) Locomotives, other than diesel electric intrastate locomotives as defined in title 17, California Code of Regulations, section 93117; and (2) Marine vessels, other than harbor craft as defined in title 17, California Code of Regulations, section 93117.
Uncertainty analysis	F	A systematic procedure to ascertain and quantify the uncertainty introduced in the results of a LCI due to the cumulative effects of input uncertainty and data variability. It uses either ranges or probability distributions to determine uncertainty in the results.
Unit-process	F	Smallest portion of a product system for which data are collected when performing an LCA.
Upstream emissions	B	GHG emissions associated with processes that occur in the life cycle of a product prior to the processes owned, operated or controlled by the organization implementing this PAS.
Use phase	B	That part of the life cycle of a product that occurs between the transfer of the product to the consumer and the end of life of the product. Note: For services, the use phase includes the provision of the service.
Use profile	B	Criteria against which the GHG emissions arising from the use phase are determined.
Useful energy	B	Energy that meets a demand by displacing another source of energy. Note: For example, where heat production from a CHP unit is utilized to meet a demand for heat that was previously met by another form of energy, or meets a new demand for heat that would have required additional energy input, then the heat from the CHP is providing useful energy. Had the heat from the CHP not met a demand, but instead been dissipated (e.g. vented to the atmosphere), the heat would not be considered useful energy (in which case no emissions from the CHP would be assigned to the heat production).

Term	**Reference**[19]	**Definition**
Valuation factor	F	Factor in the evaluation element transforming the impact score profile in an environmental index.
Valuation/weighting	F	Last element within impact assessment following the characterization/normalization element, in which the results of the characterization/normalization, in particular the (normalized) impact scores, are weighted against each other in a quantitative and/or qualitative way in order to be able to make the impact information more decision-friendly. This is an element which necessarily involves qualitative or quantitative valuations which are not only based on natural sciences. For instance, political and/or ethical values can be used in this element. The valuation can result in an environmental index.
Waste	F	Any output from the product system which is disposed of.
Weighting	A	The act of assigning subjective, value-based weighting factors to the different impact categories based on their perceived importance or relevance.