CHAPTER 2: Life Cycle Assessment Methodology for Transportation Fuels

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2.1 Background

The steps used in the Life Cycle Assessments (LCAs) of transportation fuels described in this report are:

- *Step 1*: Determine the goal and scope of the assessment.
- *Step 2*: Develop an inventory of the life cycle energy use, water use, air emissions, water emissions and solid wastes for the fuel systems
- *Step 3*: Assess the impacts of the emissions
- *Step 4:* Interpretation of the LCA results.

Chapter 1 defined the goal and scope of the LCAs performed in this study. This Chapter will outline the methods used to develop inventories of life cycle energy use, water use, air emissions, water emissions and solid wastes of the fuel systems.

Although the general methodologies used to develop life cycle inventories have been codified in a variety of publications (ISO 2006a; ISO 2006b; Consoli, et al. 1993; Allen, et al. 1997), in practice, variations in the assumptions, methodological choices, strategies for filling data gaps, and other factors can have a significant impact on the results of the life cycle analyses. Accepted practices can vary among life cycle assessment practitioners, and for regulatory applications, methods are still undergoing refinement. To ensure that the results of this study are as widely accepted as possible, the study team helped organize, then participated in, a work group that developed a framework and guidance document for performing life cycle assessments of liquid transportation fuels. The work group included representatives from federal agencies, universities, consultancies and the private sector. A list of the participants is provided in Table 2.1. The work group produced a document that provided detailed guidance on methodologies, data documentation and reporting. While the report focused on estimating life cycle greenhouse gas emissions, the framework and guidance can also be applied to other life cycle inventory data, and it is this framework that will be used in this report. The remainder of this Chapter highlights key features of the framework and guidance and how they are applied in this report. Details of the framework and guidance are available in the Appendix.

Table 2.1. Participants in Working Group on Life Cycle Assessments of Transportation Fuels

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Joyce Cooper	University of Washington
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Laura Drauker	Science Applications International Corporation
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Jeffrey Gillen	U.S. Air Force Fellow at Argonne National Laboratory
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William Harrison III	US Air Force Research Laboratory
James Hileman	Massachusetts Institute of Technology
John Ingham	URS Corporation
Fred Kimler III	US Air Force Research Laboratory
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Cynthia Murphy	University of Texas at Austin
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Philip Taylor	University of Dayton Research Institute
Valerie Thomas	Georgia Institute of Technology
Michael Wang	Argonne National Laboratory
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Thomas Zidow	URS Corporation

2.2 Types of LCAs

As described in the Framework and Guidance document (Allen, et al., 2009), life cycle assessments can be done on an average or marginal basis, and can be attributional or consequential.

An LCA that considers the energy and material flows over a broad enough spatial or temporal range so that conditions are generally representative would be considered an “average” LCA. For example, this study will report an average LCA for gasoline consumed in the United States in the year 2005. This spatial scale (the United States) and time frame (the calendar year 2005) represent a relatively broad range of conditions, including the use of crude oil derived from multiple countries and the operation of refineries during both peak gasoline production (summer) and peak heating oil production (winter).

In contrast, a marginal LCA considers product produced at the margin, generally under very specific conditions. For example, this study considers the production of fuels produced from algae. Algae growth for fuel production is just beginning and the data available are for very specific algae strains under very specific growth conditions. Further, the LCAs on algae fuel processes are based on a set of technologies that are just beginning to be applied at a commercial scale, as opposed to conventional fuel technologies, which have been evolving and maturing at commercial scales for decades.

Thus, this study will report both marginal and average LCA data, and it is important to distinguish between these types of LCA data. As is described in this report, the marginal and average LCA inventory data for petroleum based fuels are quite different, and comparisons between marginal LCAs of emerging biofuels and petroleum based fuels may lead to different conclusions depending on whether a marginal or average LCA is employed for the comparison.

LCAs are also categorized as to whether they are attributional or consequential. Attributional LCAs examine a single product system and determine the material and energy flows that are attributed to that product. In contrast, consequential LCAs examine systems of products and services. In the context of the LCAs examined in this work, a consequential LCA would examine fuel systems, including both petroleum and bio-fuels. In such a consequential LCA, increased biofuel use would impact the demand for, and consequent impacts of, petroleum fuels. In addition, a consequential LCA for some types of biofuels would examine the food-fuel system, since the growth of a crop such as corn or soybeans for fuel use impacts the use of those crops for food.

For transportation biofuels, the analyses that presented in this report will be attributional, rather than consequential. There is, however, one component of the life cycles of biofuels, that is increasingly being reported, that is consequential in nature. That life cycle element is indirect land use. Indirect land use refers to the increased use of land that is required to maintain food crop production when fuel crops are added to agricultural operations. As has been reported in a number of recent publications (Fargione, et al., 2008; Searchinger, et al., 2008), the changes in carbon stored in soils can change dramatically when lands are converted to agricultural operations. Thus, including indirect land use in greenhouse gas emission estimates for biofuels has a significant impact on overall life cycle greenhouse gas emissions, and recent reports from the EPA on estimating greenhouse gas emissions for biofuels have included indirect land use (US EPA, 2009a,b). Because of these precedents, readers should be aware of the issue of indirect land use, however, attributional LCA data are the main topic of the report.

2.3 Life-Cycle Stages

Five life cycle stages are used in reporting of life cycle inventory and assessment results. The definitions and boundaries for these life cycle stages are:

- Raw Material Acquisition: Including land-use changes, the extraction of raw feedstocks from the earth
- Raw Material (particularly biomass) processing: Partial processing of raw materials (e.g., oil seed harvesting and processing, and upgrading
- Raw Material Transport and Storage (particularly biomass): Transport from the end of extraction/growing/initial processing of the raw materials to initial separation, storage and processing facilities.
- Transport to Refinery
- Liquid Fuels Production: Starts with the receipt of refinery inputs at the entrance of the refinery facility and ends at the point of liquid fuel input to the product transport system.
- Product Transport and Refueling: Starts at the gate of the petroleum refinery with liquid fuel already loaded into the product transport system and ends with dispensing the fuel into the tank of the vehicle. This includes the operation of the bulk fuel storage depot, transport of fuel from storage tanks to the pumps, and vehicle fueling."
- Vehicle Operation: Starts at the fuel tank and ends with the combustion of the fuel.

The End of Life stage encountered in my life cycles is not included in this report since the product is consumed in the vehicle operation stage. The stages are described in more detail later in the report.

2.4 System Boundary

A comprehensive LCA accounts for all process related material and energy flows, from both primary and secondary processes. For transportation LCAs, the primary process is the production and use of the fuel, while an example of a secondary process would be the production of fertilizers used as an input in the production of biofuels. The secondary processes also have inputs (which in this report will also be referred to as secondary processes) which should be accounted for. For example the production processes for nitrogen fertilizers use ammonia as an input, and the ammonia production process has energy and material flows that need to be accounted for in the life cycle assessment. The ammonia production process, in turn, requires hydrogen and the production of hydrogen involves material and energy flows that need to be accounted for in the LCA.

In principle, a life cycle assessment includes the primary and all of the secondary flows of materials, but in practice, some secondary flows are difficult to quantify and may not be significant in estimating life cycle impacts. For example, while for many biofuels fertilizer inputs will be significant, it is not necessarily clear whether inputs, such as the steel required to build the production facility, need to be accounted for. Generally, some material and energy flows are categorically excluded from consideration. In this report, flows that will be categorically excluded (based on the guidance outlined in the Appendix) are low frequency, non-predictable catastrophic events, such as large spills, and human activities that are relatively independent of the specific production or use of the product (e.g. the housing for workers in agricultural operations). Beyond categorically excluded flows, the methods for determining whether a material or energy flow should be included in an LCA have generally been left to the expert judgment of the LCA practitioner. However, in the recent guidance document provided in the Appendix (Allen, et al., 2009), this process has been systematized. To the extent practicable, this report will follow the system outlined in the decision tree shown as Figure 2.1 (Figure 3-1 in the Framework and Guidance document provided in the Appendix).

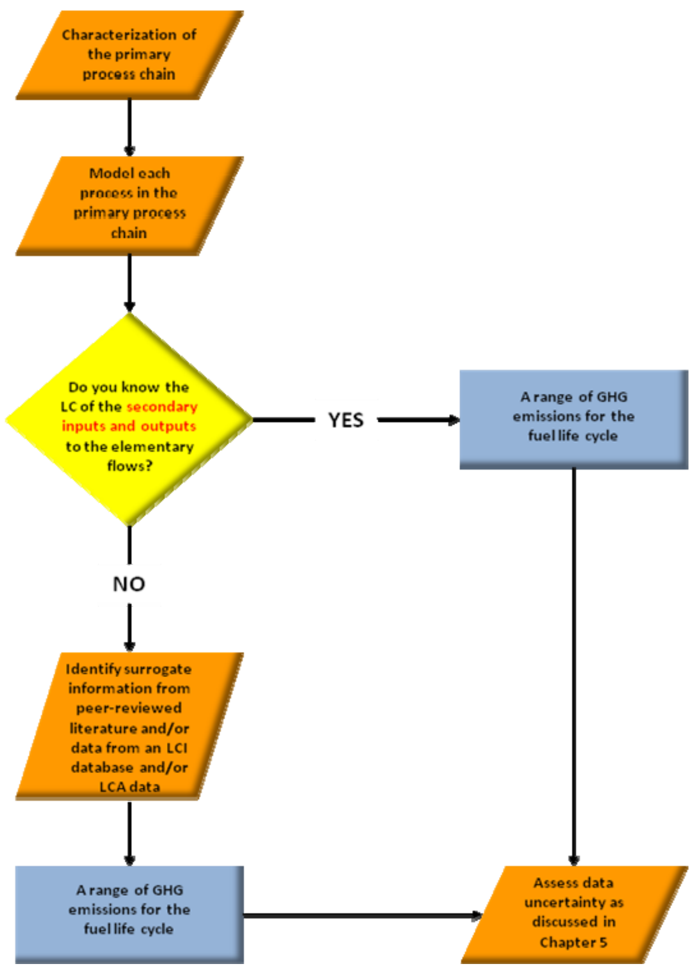

Figure 2.1. System boundary decision flow (Allen, et al., 2009).

The decision tree in Figure 2.1 contains a series of steps. The first of these steps is to characterize the primary process chain. A previous section briefly outlined the life cycle stages to be considered in characterizing the primary process chain. The methods used to characterize the primary processes (second step in the decision tree) are described in detail in subsequent chapters. The next step in the decision tree is to determine whether the life cycles of secondary material and energy flows are known. For flows that are not known, the guidance suggests methods for developing surrogates for the unknown information.

Specifically, two sources of surrogate data are recommended. These are:

- "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" (Allen, et al, 2009).
- "EIOLCA data for the life cycle of the sector in which the higher order flow is produced" (Allen, et al., 2009). The EIOLCA method is a systems level model of material and energy flows in regional or national economies (www.eiolca.net). It can provide data on average material and energy flows in broad sectors of the economy (e.g., the flows associated with the construction and operation of industrial buildings are averaged in a sector named "manufacturing and industrial buildings"). As described in the guidance, the EIOLCA model can be applied, and an uncertainty range can be assigned to those data.

Life cycle information from these two types of datasets are used to create bounds for the contribution of less well defined secondary flows, and the resulting uncertainties are reported, as outlined in later sections of this chapter. An example of the process is provided in the Guidance document provided in the Appendix.

2.5 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 among different co-products in a way that reflects the underlying physical relationships (e.g., mass, volume, energy content) among them

4. **Allocation by other relationships:** when physical relationship alone cannot be established, inputs and outputs are partitioned among 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 allocated, among all the products. The choice of allocation approach can have a significant effect on the overall results. This report clearly documents the co-product allocation approaches that are used.

2.6 Data Quality

The quality of the data used in life cycle analyses inevitably affects the results of LCAs. Recommended methods for documenting data quality and performing sensitivity/uncertainty analyses are provided by Allen, et al (2009, Chapter 5), and are summarized in the flow chart shown in Figure 2.2 (Figure 5-1 from Allen, et al, 2009). The process notes the need to characterize, data, model and scenario uncertainties. Details are provided in the Appendix.

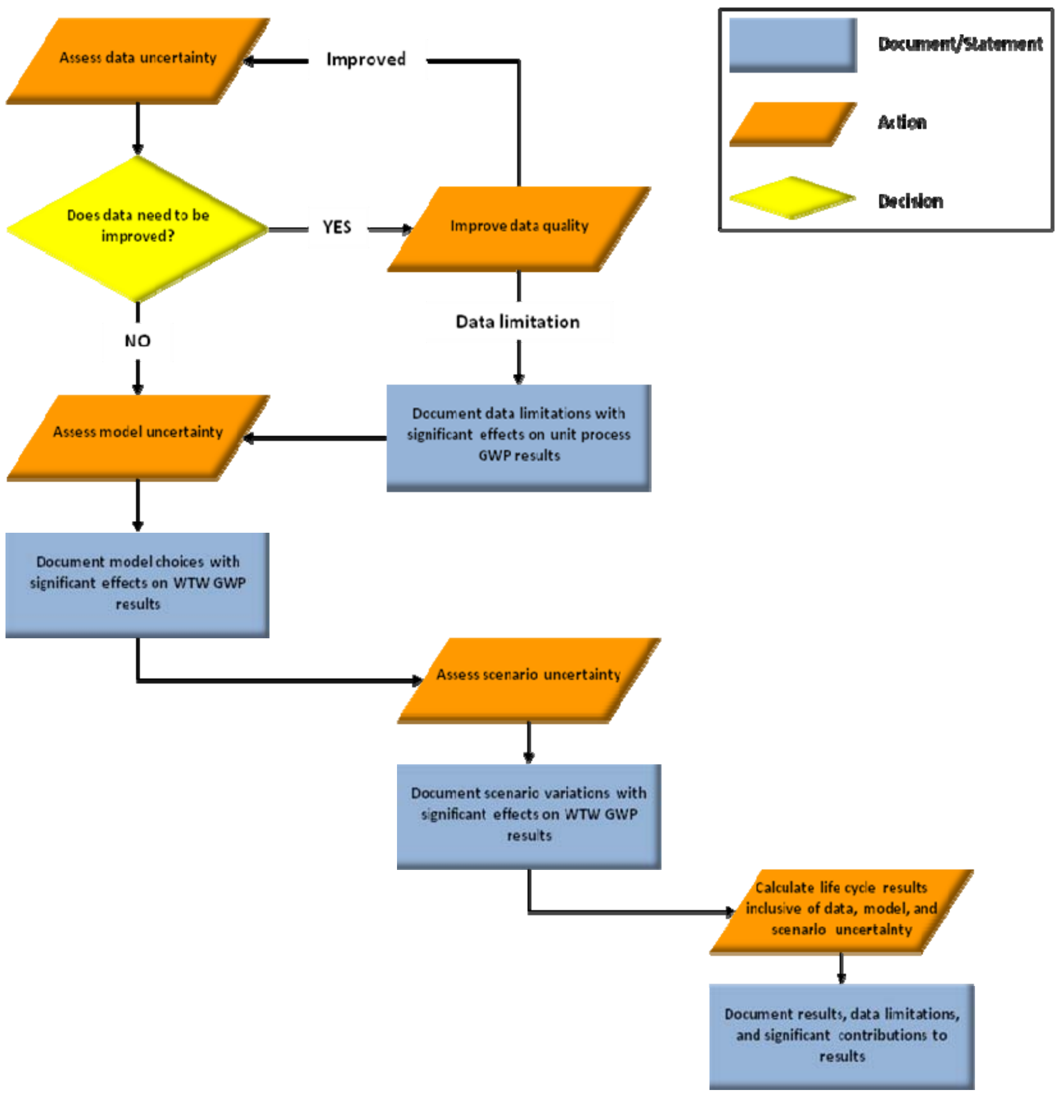

Figure 2.2. Process for assessing and documenting uncertainty in LCA.

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