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The primary aim of this study is to help aviation jet fuel purchasers (primarily commercial airlines and the U.S. military) to understand the sustainability implications of their jet fuel purchases and provide guidelines for procuring sustainable fuels. This study reviews literature on life cycle analysis and sustainability and identifies the regulatory requirements and third party standards for sustainable fuel use in different regions of the world. It also provides guidance in understanding the life cycle GHG emissions impacts of jet fuels, and defining guidelines for estimating the sustainability implications of criteria other than life cycle GHG emissions such as water use, land use, criteria pollutants, air toxics, biodiversity and a number of other issues as noted throughout this report.

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Review of Jet Fuel Life Cycle Assessment Methods and Sustainability Metrics

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Terms and Abbreviations

Terms

Term	Definition
Carbon Stock	Any source which may contain a large storage of carbon, such as a forest, soil carbon, or other vegetation
Cradle-to-Grave	The life cycle of a good from raw materials to finished product and disposal. Referred to as full life cycle or fuel cycle.
Environmental Criterion	The affected object, entity, or idea due to environmental impacts. Criteria include greenhouse gases, water, biodiversity, energy, etc.
Feedstock	The biomass that is used to produce a product such as transportation fuel. Traditional feedstocks include corn, wheat, algae, etc.
FT Pathways	The Fischer-Tropsch (FT) process utilizes carbon monoxide and hydrogen gas to produce longer chain hydrocarbons. Some of these longer chain hydrocarbons can be used to produce jet fuel. An FT pathway uses the FT process to produce jet fuel.
LUC and ILUC	Land use change (LUC) occurs when land is converted to have another purpose, e.g. pasture is converted to cropland. Indirect land use change (ILUC) occurs when land elsewhere is converted to make up for the change in agricultural activity, e.g. Argentinian pasture converted to soy when corn soy rotation in U.S. is converted to corn. Also referred to as land use conversion.
Process Step	A section of the production's value chain, e.g. farming, feedstock transport, fuel refining.
Renewable Jet Fuel	Jet fuel produced from renewable sources, such as plants, as opposed to fossil sources, such as coal or petroleum.
Sustainability Impacts	These include environmental, social, and economic impacts. Only environmental impacts are considered in this report. Impacts categories are a term used in life cycle analysis.
Sustainability Metric	The measurement that is used to analyze the environmental impacts of a project.
Value Chain	A collection of all the process steps for a project. Referred to as supply chain.

Abbreviations

AB	California Assembly Bill
AFIT	Air Force Institute of Technology
AFRL	Air Force Research Laboratory
ALCA	Attributional Life Cycle Analysis
ANL	Argonne National Laboratory
ARB	California Air Resources Board
CA	California
ATJ	Alcohol to Jet
CA-GREET	The standard GREET model modified for use in CA LCFS
CH4	Methane
CI	Carbon intensity
CLCA	Consequential Life Cycle Analysis
CO	Carbon monoxide
CO2	Carbon dioxide
CSBP	Council on Sustainable Biomass Production
DI ICEV	Direct Injection Internal Combustion Engine Vehicle
DOE	U.S. Department of Energy
DOT	Department of Transportation
EERE	DOE's Office of Energy Efficiency and Renewable Energy
EISA	The Energy Independence and Security Act
EMFAC	EPA's Emission Factors Model
EPA	U.S. Environmental Protection Agency
EPD	Environmental Product Declaration
ETS	European Emission Trading Scheme
EU	European Union
FAA	Federal Aviation Administration
FAPRI	The Food and Agricultural Research Institute model; Iowa State University's Center for Agricultural and Rural Development
FAO	The Food and Agricultural Organization of the United Nations
FASOM	Forest and Agricultural Sector Optimization Model
FT	Fischer-Tropsch
FTW	Field to Wake
g CO2e	Grams of carbon dioxide equivalent
GBEP	Global Bioenergy Partnership
GHG	Greenhouse Gas
GHGenius	An LCA model based on LEM that was developed for Natural Resources Canada
GM	General Motors
GREET	The Greenhouse gas, Regulated Emissions, and Energy use in Transportation model
GTAP	Global Trade Analysis Project model
GWP	Global Warming Potential
HC	Hydrocarbon
HEFA	Hydro-processed Esters and Fatty Acids
HVO	Hydro-processed Vegetable Oil
IFEU	Institute for Energy and Environmental Research in Heidelberg, Germany

ILUC	Indirect Land Use Change
IPCC	Intergovernmental Panel on Climate Change
ISCC	International Sustainability and Carbon Certification Association
JEC	Joint Research Centre, JRC/EUCAR/CONCAWE
ISO	International Standards Organization
JRC	Joint Research Centre
LBST	Ludwig Bölkow Systemtechnik; an independent environmental consulting firm
LCA	Life Cycle Analysis or Life Cycle Assessment
LCFS	Low Carbon Fuel Standard
LEM	Lifecycle Emissions Model
LUC	Land Use Change
MOUSE	An LCA model: Matrix Organization Using Specific Energy
MIT	Massachusetts Institute of Technology
MODIS	Moderate Resolution Imaging Spectroradiometer (a Satellite Tool)
MSA	Mean Species Abundance
MTU	Michigan Technology University
N2O	Nitrous oxide
NECPA	National Energy Conservation Policy Act
NETL	National Energy Technology Laboratory
NMMTC	National Metal and Materials Technology Center
NG	Natural Gas
NGO	Non-Governmental Organization
NOx	Oxides of nitrogen
NREL	National Renewable Energy Laboratory
PCR	Product Category Rules
PAS	Publicly Available Specification
PM	Particulate Matter
RED	Renewable Energy Directive
RFS2	Revised Federal Renewable Fuels Standard
RPS	Renewable Portfolio Standard
RSB	Roundtable on Sustainable Biomaterials
RSPO	Roundtable on Sustainable Palm Oil
RTFC	Renewable Transportation Fuel Credit
RTFO	Renewable Transportation Fuel Obligation
SOx	Sulfur Oxides
SPK	Synthetic Paraffinic Kerosene
TTW	Tank-To-Wake
UN	United Nations
VOC	Volatile Organic Compound
WTT	Well-To-Tank
WTW	Well-To-Wake

Executive Summary

Aircraft operators including both commercial aviation and U.S. military have an interest in expanding the use of sustainable fuels given expanding regulations on fuels and increasing consumer awareness of environmental issues. The U.S. Department of Transportation (DOT) /Volpe National Transportation Center (Volpe Center) and the Federal Aviation Administration (FAA) Continuous Lower Energy, Emissions, and Noise (CLEEN) and Commercial Alternative Aviation Fuel Initiative (CAAFI) programs, among many others, have examined alternative feedstocks and pathways to manufacture jet fuels.

Given the importance of aviation jet fuel (19.5 billion gallons of aviation jet fuel were used in 2011 in the U.S. (EIA 2011)) and the growing interest in incorporating biofuels into the jet fuel pool, evaluating the sustainability of the production, distribution, and use of renewable jet fuel on a life cycle basis has become an important topic. Understanding sustainability requirements from a fuel purchaser's perspective is challenging because of the regionally complex mix of regulations covering greenhouse gas (GHG) emissions, less detailed regulations on sustainability, and expectations about sustainability from affected groups.

Accordingly, the FAA contracted with Life Cycle Associates, LLC, to investigate the environmental sustainability of renewable jet fuel. The primary aim of this study is to help aviation jet fuel purchasers (primarily commercial airlines and the U.S. military) to understand the sustainability implications of their jet fuel purchases and provide guidelines for procuring sustainable fuels. This study reviews literature on life cycle analysis and sustainability and identifies the regulatory requirements and third party standards for sustainable fuel use in different regions of the world. It also provides guidance in understanding the life cycle GHG emissions impacts of jet fuels, and defining guidelines for estimating the sustainability implications of criteria other than life cycle GHG emissions such as water use, land use, criteria pollutants, air toxics, biodiversity and a number of other issues as noted throughout this report. The following are the principal findings of this study:

- Existing voluntary sustainability certification schemes and GHG regulations are adaptable to renewable aviation fuels.
- Sustainability certification addresses a wide range of environmental indicators at the feedstock production and facility level. Life cycle and indirect effects for criteria other than GHG emissions are not readily monitored through certification.
- A number of LCA methods used for on-road fuels are available to estimate life cycle GHG emissions for aviation fuels. The methods yield different results for some fuel pathways. The authors believe a consistent LCA approach is a priority, otherwise fuels will be sold in regions where they receive the most favorable GHG rating with no benefit to the environment for this shuffling.
- Other schemes for environmental ratings such as product category rules with environmental product declarations for each fuel producer are also an option for aviation fuels. This approach could be more streamlined than certification schemes and involve less stakeholder input.

- The characteristics of aviation result in several challenges for the use of sustainable fuels. First, the international flights may not generate all of the incentive value under the RFS2 and RED for flight segments outside of the jurisdictions of the policies, but the plane must carry fuel for the entire trip. Secondly, aviation fuels are comingled at airport fuel storage facilities, and regulators will need to develop appropriate tracking schemes for GHG incentive programs. If a requirement for aviation fuels is developed, the same tracking challenges need to be addressed.

Environmental Sustainability

A widely accepted definition of sustainability by government entities and environmentalists is: meeting the needs of the present without compromising the needs of the future (Brundtland 1987). Most organizations define sustainability as achieving resource consumption and pollutant discharge levels that allow the current populations to meet their needs without compromising the ability of future generations to meet their own needs. In practice, assessing sustainability requires criteria that are grounded in principles of environmental management. This study focuses on the risk of significant impacts, which occur primarily during feedstock and fuel production, and reviews the methods used to quantify and monitor the environmental impacts.

Such assessments need to take into account the impacts of producing and using aviation fuels, including such life cycle phases as feedstock production, fuel refining, and jet operation. Using alternative jet fuels may affect a wide array of environmental indicators. GHGs from biofuels are potentially lower than petroleum options because carbon in the feedstock has been recently removed from the atmosphere. However, fertilizer inputs, agricultural operations, fuel processing, and other steps in the life cycle result in GHG and other emissions, as well as impacts on water, soil, and biodiversity, so the environmental performance of alternative jet fuels must be carefully examined before concluding that they provide net benefits as compared to petroleum fuels. As part of this study, representative metrics are reviewed to help stakeholders conceptualize the impact and scope of sustainability impacts. The potential impacts of renewable aviation fuels fall into the same categories as those for on-road transportation fuels. However, aviation fuels may differ in terms of the feedstock to fuel yields, and additional processing steps are required for some pathways.

Energy Consumption

For most pathways under consideration, renewable jet fuels require less fossil fuel inputs than petroleum jet fuel. Key metrics are total life cycle fossil and petroleum inputs. For most fuel pathways, petroleum is primarily used for feedstock harvesting and transport of feedstock and fuel. Total energy inputs (including the biomass) are also of interest to assess the best use of the biomass feedstock.

GHG Emissions

Energy use and greenhouse gas emissions have global impacts. GHG emissions are counted on a life cycle basis since the contribution of all inputs to feedstock production, fuel processing, and jet combustion affect the well to wake (WTW) emissions. Alternative fuels tend to have much lower sulfur and aromatic content than petroleum-based fuel, and hence lower emissions of sulfur oxides and particulate matter.

The life cycle assessment (LCA) of jet fuels is very similar to assessments of liquid ground transport fuels such as gasoline and diesel, with a few key differences and added complexities due to the global scope of the fuel production pathway and complex impacts of aircraft emissions. Many liquid fuels of different carbon lengths (gasoline, diesel, naphtha, jet fuel, fuel oil, etc.) are produced in oil refineries and biorefineries (including FT synthesis, pyrolysis, and bio-oil hydrotreating). Therefore, the jet fuel pathway includes the same production steps as ground transport fuels: feedstock production, feedstock processing, and fuel production. The analyses of on-road and aviation fuels are linked because of this reliance on the same production steps and the linkages between yields for different refinement products; increasing production of one hydrocarbon fuel reduces production of other fuels. LCAs of jet fuel can follow the same approach as those for transportation fuels. However, while they have the same feedstock and conversion technology, the jet fuel LCA needs to take into account the product yield and differences in ground transport and fuel transfer logistics. In addition, aviation emissions have potentially uncertain climate change impacts due to the altitude at which they are emitted. (Grassl, 2007; Travis 2002), which are different than the uncertainties ground transportation.

The commonly used GHG models such as GREET (Wang 2011b) and Biograce (Neeft 2012) are configured with on-road diesel data and limited jet fuel pathways. While model uncertainty exists due to the treatment of co-products, uncertainties in inputs, and other factors, modifying the models for jet fuel is straightforward. Fuel sellers face a greater challenge of complying with GHG regulations that lead to financial incentives. Conflicting regulations may apply to fuel for international flights.

Land Use

Land use for crop production and other activities has several sustainability impacts. Conversion of land to biofuel crop production results in a change in net carbon and other GHG emission flux compared to the prior use of land due to the changes in crop type, tillage, and fertilizer application. Land conversion can result in an increase in CO_2 emissions when stored carbon, especially in forests, is converted to crop production. Other types of land conversion can result in a net carbon storage (for example planting deep rooted perennial grasses on degraded land). Most calculations of land use change (LUC) focus on GHG emissions. Other environmental effects such as criteria pollutants from burning, soil erosion, nutrient run off, and impacts on biodiversity may also occur. Converting land from one use to another also results in indirect LUC. For example growing rapeseed on pasture would require converting other land to pasture or increasing animal stocking rates if overall food production is to remain constant. Indirect LUC is estimated with agro-economic models that predict the changes in land cover type associated with changes in demand for agricultural commodities. Crop residues and cover crops result in no indirect LUC provided that they do not affect agricultural production.

Biodiversity

Biodiversity is a complex ecological concept because it represents the net result of a complex set of interacting ecological, evolutionary, biogeographical, and physical processes. The definition of biodiversity is variable and usually depends on the highest conservation priority (e.g. habitat health, species indices, ecosystem function, net primary productivity, etc.). Most studies of biodiversity focus on organisms within an ecosystem or ecosystem types in contrast to the approach of public policy to biodiversity, which focuses on the values and functions of ecosystems (to provide products, ecosystem services, aesthetic value, etc.). Biodiversity assessments need to examine habitat types and potential endangered species.

Water and Soil Quality

Biofuel production affects water consumption and discharges to waterways. Crop irrigation, cooling water evaporation, and water for hydrogen production are consumptive uses of water. Agricultural run-off, fuel production discharges, and fuel spillage are sources of water pollution. Feedstock production activities can also affect soil erosion.

Many different types and qualities of water supplies exist, including fresh ground water, pumped water, saline water, waste water, and many others. Water can also be classified as renewable water (aquifers that replenish on an annual basis) and non-renewable water ("fossil" water from isolated reservoirs that do not replenish. Because the different water categories have different scarcity, economic value, and other properties, the results should be considered separately for each water type.

Direct and Life Cycle Impacts

Consideration of all environmental impacts along the product chain is an essential aspect of environmental sustainability. Sustainability indicators can be assessed with different levels of aggregation and scope including life cycle or field-to-wake (FTW), facility or operator level, or at the regional scale. Each approach is applied in sustainability assessments of biofuels used today.

Several sustainability tools examine a broad range of criteria on a life cycle basis (PE 2012, GBEP 2011, Unnasch 2011), including GHG emissions, criteria pollutants, and water impacts on a life cycle basis. However, difficulties associated with data quality, project specific practices, and regional detail, make the assessment of criteria other than energy and GHG emissions more challenging. The impacts of criteria pollutant emissions and water impacts are also regionally specific. For example, criteria pollutant emissions in urban areas have a greater impact than tanker ship emissions on the ocean. In addition, modeling systems use various approaches to address co-products, regionally specific data, as well as marginal, indirect, or consequential effects and these factors results in a range of GHG emissions results. Land use and indirect land use are an important aspect of GHG analysis. The primary emphasis of life cycle analysis for biofuel sustainability assessments used in government regulations is GHG emissions.

Other impacts such as soil quality, exposure to toxic contaminants, and biodiversity are so site specific that a life cycle assessment provides too generic a treatment without significant data collection and analysis efforts. These impacts are best minimized by monitoring agricultural land and facilities with the understanding that some upstream and indirect effects will not be covered.

Facility level sustainability indicators are monitored for each step in the value chain (feedstock, fuel refiner, transport, etc). Certifications systems such as the ISCC involve on site audits based on a defined set of criteria. Such assessments typically monitor inputs, soil quality indicators, agricultural practices, compliance with emission standards, among the many parameters investigated. The criteria for facility level standards vary among the different certification standards. In many cases, an audit requires validation of compliance with regulations such as demonstrating air emission permits. Most sustainability standards also require monitoring of "continuous improvement".

Some sustainability metrics, such as the International Sustainability and Carbon Certification (ISCC) and the Roundtable on Sustainable Biomaterials (RSB), monitor criteria pollutants by reviewing emission permits. However, this approach only verifies compliance with local regulations but does not provide an estimate of actual emissions. In addition, local permits apply only to facility level emissions, and do not take into account for any upstream or downstream impacts. Also, compliance with emissions permits provides no insight into the emissions on a per MJ basis, which is a necessary input to an LCA. Some LCA models do account for criteria pollutants but the modeling systems have difficulty handling regionally specific data. Given these considerations, users of sustainability frameworks should be cautious of criteria pollutants and air toxics rating and expect considerably more effort in evaluating site specific and regional detail than with GHG emissions.

Sustainability analyses may also be performed at the regional level. For example, under the Renewable Fuel Standard (RFS2), the EPA performs an analysis of the environmental and economic impacts of the regulation for different feedstock and fuel scenarios. The standard requires that biofuels must be produced on existing cropland. The EPA has determined that total U.S. corn acreage has not increased year over year, so a country level certification applies to that feedstock (EPA, 2010).

Developing a customized framework for aviation fuels that deviates significantly from on-road fuels can result in carbon leakage or shuffling.[1] Carbon leakage is a term used to describe a situation in which businesses transfer production operations to regions with fewer constraints on GHG emissions for reasons of cost. In this case, the overall global GHG emissions are not reduced, only geographically shifted. Shuffling occurs when feedstocks are diverted from one market to another based on government regulations or other market incentives. For example, if rapeseed oil is procured from sustainable sources for biofuel production but the global market for rapeseed oil food applications is much larger than that for biofuels, market incentives may cause

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[1] For example, if LUC emissions from a feedstock are counted under the RFS2 and RED and not counted under an aviation sustainability regime, the GHG rating would be different potentially confusing to consumers. Situations where rating systems differ could affect the perception of the validity of emission reductions.

the sustainably certified feedstock to be diverted to biofuel production and the conventional feedstock to be used for other applications.

All of the above methods provide a partial assessment of the environmental impacts of alternative fuel production. Nonetheless, there are still some problems with current sustainability assessment methods**.** LCAs (especially for non GHG impacts) tend to lack regional and site specific detail. Assessments of direct emissions only, i.e. those that occur at the facility, do not include the full life cycle emissions of all the inputs, and regional certifications are also very generic. Shuffling and carbon leakage can also make the assessment of sustainability criteria challenging. Even with these limitations, monitoring and regulation of environmental impacts has still been shown to lead to improvement in environmental performance (RSB 2010). None of the issues associated with assessing sustainability impacts is unique to aviation fuels. However, verifying sustainable aviation fuels still requires some model modification as well as assessment of the synergy among different sustainability systems across different regions globally.

Alternative Fuel LCA and Sustainability Measures

Many different environmental sustainability criteria have been developed by government organizations, trade and certification organizations, and researchers to address sustainability concerns. Table S.1 summarizes the government regulations, sustainability guidelines, and environmental declarations that could potentially affect or apply to aviation fuels. To date, sustainability related requirements for aviation fuels include GHG regulations under Section 526 of the U.S. Energy Security Act (EISA) and a GHG cap under the EU Emissions Trading System (ETS). EISA Section 526 requires military fuels (and other government purchases) to result in no more GHG emissions on a life cycle basis than a petroleum baseline. ETS applies to aviation fuels, although as of 2014, international flights on non-EU carriers were temporarily exempt for one year pending significant action by ICAO on GHG emissions.

Airlines and fuel purchasers will need to understand the sustainability requirements for on-road fuels for several reasons. The RFS2 and the Renewable Energy Directive (RED), enacted in the U.S. and EU respectively, apply to on-road transportation fuels and oblige petroleum refiners to sell a set volume of renewable fuels. Some sales of aviation fuels can contribute towards meeting these obligations under the RFS2 and RED. An attractive option would be for fuels to aviation markets to qualify for both RFS2 and RED. Pathways that qualify under one rating system may not qualify under the other due to calculation methods, requirements on land use, and differences in GHG thresholds.

Fuels sold under these programs have carried significant premiums over petroleum fuels. Therefore, if fuels derived from the same feedstocks with similar processing requirements are to be sold to both the on-road and aviation markets, the aviation market must include comparable incentives. For some fuel pathways and flight routes, the generation of incentives is straightforward, while in situations with international flights, conflicting GHG ratings, and commingling of fuels at airports achieving the same level of incentives as on-road fuels appears challenging. The GHG rating under these programs will differ, primarily due to the treatment of co-products and LUC. Due to regional differences in regulations, fuel in an aircraft could potentially meet sustainability requirements at take-off and 6 hours later the fuel might not achieve thresholds for sustainability in the country where the plane lands. Fuel purchasers will need to expect different GHG ratings under different biofuel policies into the foreseeable future. Fuels with reduced GHG emissions could generate incentives in different regions in the world. The mechanisms for realizing income from the incentives as well as the calculation methods could also vary.

Table S.1. Initiatives Based on Vehicle Fuel Sustainability

Fuel Programs	Applicable Regions	Affected Parties
Government regulations		
EISA Section 526	U.S.	Federal Agency fuel procurers, including Department of Defense components
RFS2	U.S.	U.S. fuel producers
California LCFS	California	Transportation fuel providers
European ETS	EU Countries	EU GHG emitters, plans to include aviation
European RED	EU Countries	European fuel providers
Sustainability Guidelines		
RSB	Global (members)	Biofuel ∨ Biomaterial producers
ISCC	Global	Biofuel producers
CSBP	Global (members)	Biomass and biofuel producers
RTSS	Global (members)	Soy oil producers
RSPO	Global (members)	Palm oil producers
Bonsucro	Global (members)	Sugarcane producers
GBEP	Global (members)	Biofuel analysts, policy makers
ISO 14040, 14044	Global	All LCA activities
Environmental		
EPDs and PCRs	Global	Products with environmental product declaration
PAS 2050	United Kingdom	
ISO 14025	Global	

RFS2 = Renewable Fuel Standard, EISA = Energy Independence and Security Act, LCFS = Low Carbon Fuel standard, ETS = Emission Trading System, RED = Renewable Energy Directive, RSB = Roundtable on Sustainable Biomaterials, ISCC = International Sustainability and Carbon Certification Association, CSBP = Council for Sustainable Biomass Production, RTSS = Roundtable for Sustainable Soy, RSPO = Roundtable for Sustainable Palm Oil, GBEP = Global Biomass Energy Partnership, ISO = International Standards Organization, EPD = Environmental Product Declaration, PCR = Product Category Rules, PAS = Publically Available Specification

The government regulations on biofuels provide a degree of sustainability evaluation beyond GHG emissions. These regulations include different and sometimes conflicting requirements on prior land use and GHG calculations. Nonetheless, fuel producers could certify fuels under several government regulatory programs, for example for flights form the EU to the U.S.

International standards address the general requirements of sustainability assessment. These are incorporated into voluntary standards. Voluntary feedstocks and fuel certification standards provide another option for monitoring sustainable biofuels. The International Sustainability & Carbon Certification (ISCC), Roundtable on Sustainable Biomaterials (RSB), and the Council for Sustainable Biomass Production (CSBP) provide a set of certification guidelines and standards for biomass feedstocks to fuels. These standards are focused on biofuels and do not cover all of the feedstocks and fuel pathway configurations that could be expected with aviation fuels. In addition the requirements on land use, calculation of GHG emissions, data and reporting requirements, and other aspects of sustainability verification differ considerably. Nonetheless, these existing certification systems provide a framework that is adaptable to renewable aviation fuels.

Sustainability standards can also be developed through Environmental Product Declarations (EPDs) or Product Category Rules (PCRs). Such efforts would potentially involve different stakeholder groups than government regulations and sustainability guidelines.

Procuring Sustainable Biofuels

Several options are available for ensuring aviation fuel sustainability as shown in Table S.2. Note that the thresholds for achieving GHG reduction requirements as well as the analysis methods differ for each option. These include requiring the renewable portion of aviation fuels to comply with on-road transportation requirements, certification through existing sustainability standards, or developing new standards, potentially through industry led environmental product declarations. The next step in developing a sustainability framework for jet fuel would be to select among the options for monitoring and verifying sustainable fuel production. Fuel procurers may want to opt for a uniform set of approaches or use a variety of approaches. For example, fuel purchasers could require the renewable portion of fuels to comply with prevailing regional GHG standards and also specify a GHG reduction for the blended aviation fuel product based on an agreed upon procedure. Many of the regulations for biofuels could be applied to jet fuel in their current form; although, details associated with aviation applications, comingled fuel storage and international flights need to be addressed. The thresholds for GHG regulations vary globally and the overlap among policy initiatives will need to be managed to comply with the requirements of these programs. Fuel purchasers will need to determine if the fuel sellers will retain the environmental attribute (such as a RIN) or if the credit is transferred to the fuel user.

Table S.2. Initiatives Based on Vehicle Fuel Sustainability

Sustainability Option	Feedstock Assessment	Fuel Facility Assessment	GHG Model	Example Qualifying Pathways
EU RED	Facility and Farming Certification		Biograce + LUC	Rapeseed HEFA
EPA RFS2	EPA Evaluation	Engineering Review	GREET + LUC	Camelina HEFA Switchgrass FT Jet
Certification Standards	Fuel, Biomass Standards + Audit		Various	Rapeseed HEFA
Environmental Declarations based On PRC	New standard + Audit		TBD	TBD

Existing biofuel GHG regulations involve a degree of sustainability verification either through auditing of feedstock production and fuel processing or government review of feedstock categories. The EPA RFS2 and the EU RED both provide methods for calculating GHG emissions for transportation fuels and these methods can be readily adapted for aviation pathways. The comparative GHG performance will be different for each method. So, aviation fuel procurers could opt to require compliance with the renewable portion of aviation fuels. If aviation fuels qualify for the thresholds, fuel producers will benefit from the sale of renewable fuel credits, which would contribute towards the economic viability of alternative aviation fuel production.

Fuel purchasers could also opt to use existing biofuel certification standards such as the ISCC, RSB and CSBP. This approach would require audit of agricultural practices and fuel production systems and the level of review is considered more thorough at the national aggregate classification provided under the RFS2. Fuel purchasers could specify a level of GHG reductions in combination with a protocol for GHG reductions or require achieving thresholds for government regulations for the renewable portion of fuels.

Biofuel production could be certified to these standards separately or in addition to RFS2 and RED certification. The choice to comply with RFS2 and RED could also be left to the fuel producers. However, not all feedstock and fuel combinations would meet the thresholds of the programs identified here. The requirements for land use may further limit the feedstocks and fuel combinations that would be rated in multiple jurisdictions because of conflicting requirements.

The conflict among policies may lead jet fuel purchasers to develop a set of standards that provide a more consistent basis for sustainability determination. Stakeholder led environmental product declarations (EPD) could provide another option for monitoring the sustainability of renewable jet fuels. The standards for the EPD would need to be defined in a manner similar to biofuel certification standards like the RSB or CSBP, which have broad participation of feedstock and fuel producers, government agencies, and environmental groups. The differences between an EPD and existing certification standards could involve many different details. EPDs for jet fuel could include a more limited participation of environmental groups. The aviation industry could determine procedures for sustainability and then request input from environmental groups. This organizational structure might be viewed as less rigorous than the structure for sustainability certification organizations. Feedstocks that are not addressed under RED or RFS2 or existing biofuel standards could be addressed with EPDs.

Figure S.1 shows how a sustainable aviation fuel pathway could be implemented from the fuel purchaser's point of view. The steps below assume that the fuel purchaser will perform due diligence on the fuel and also place requirements on the fuel provider to assure sustainable production. The obstacles along the way are identified in comment boxes.

First, a fuel purchaser would request a certain volume of fuel meeting a GHG reduction target and a sustainability specification. The fuel producer would need to assess the GHG intensity of fuel production process and feedstocks. From the fuel producer's point of view, the fuel would need to generate low carbon credits under all of the fuel programs that are available for on-road transportation, or the producer would be inclined to sell into on-road markets. Fuel purchases may choose to set a GHG threshold. This threshold could be an aviation specific calculation or it could be based on existing calculation methods or a combination of both.

The sustainable aviation fuel must be tracked once it is delivered. Fuel may be comingled in shared tank facilities and the fuel may be used in several jurisdictions. These boundary and comingling issues need to be addressed with regulators.

Sustainable fuel procurement would involve a sustainability assessment, either through a government reviewed program and/or an audited sustainability framework. Achieving sustainability goals will require verification of compliance with local regulations. Such compliance may not assure superior performance to baseline petroleum fuels unless these are addressed in sustainability standards. Finally, sustainable production could require the implementation of best management practices.

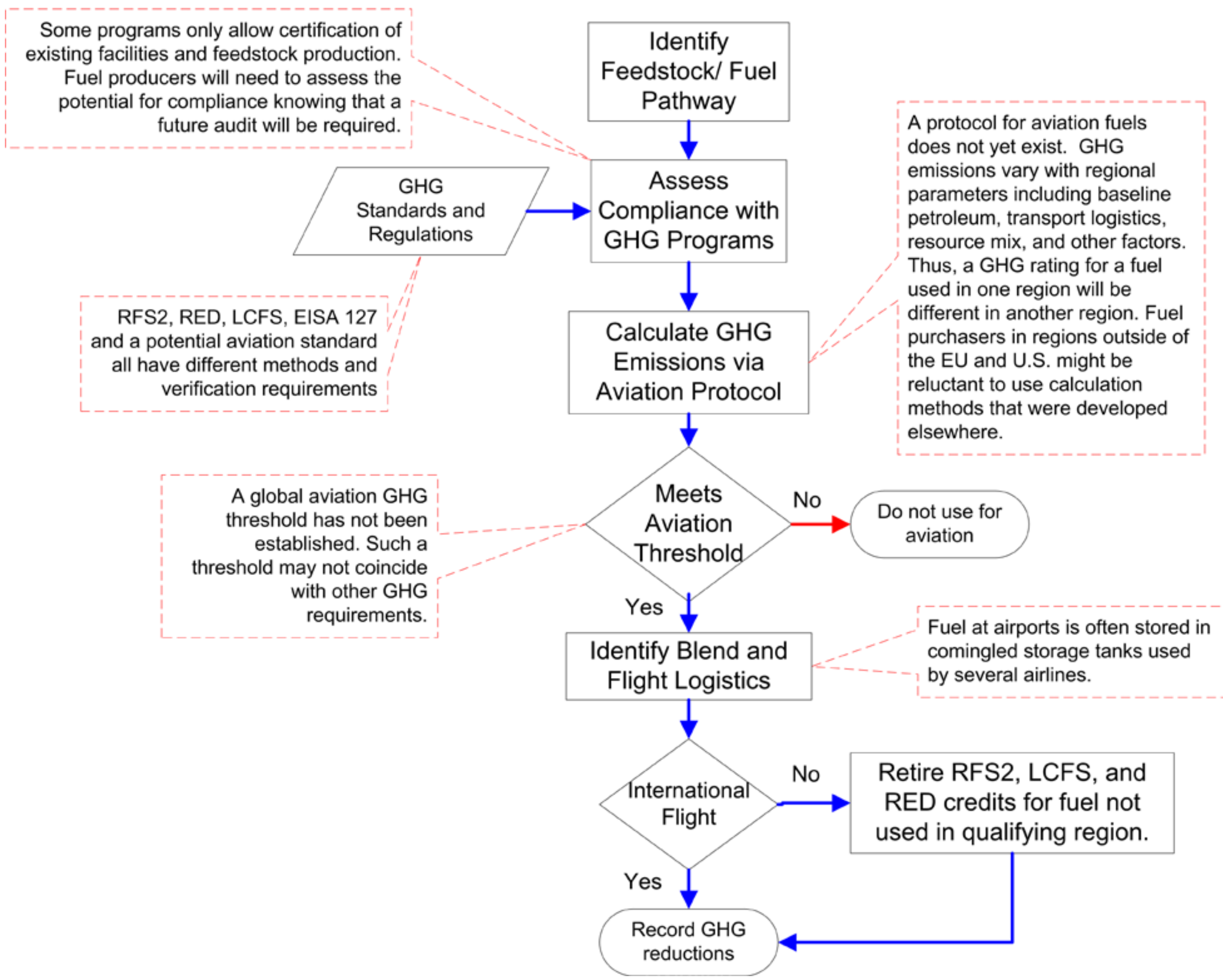

Figure S.1. Steps Involved With Using A Sustainable Biofuel for Aviation.

Recommendations

Quantifying sustainability remains a challenge due to the variety of feedstocks, fuel production processes, and stakeholder expectations. The aviation community, as a consumer of jet fuel, seeks the supply security, price stability, and improved environmental performance that biofuels may offer. As such, the aviation community should consider the sustainability of their fuel sources by considering the following for developing LCA options and sustainability verification.

- Recognize that jet fuels are similar to other transportation fuels in their life cycle and sustainability impacts.
    - Align jet fuel sustainability requirements with those for surface transportation fuels in order to avoid fuels being sold into the market where the pathway receives the most favorable sustainability treatment.
    - Adopt existing frameworks for the regulation of transportation fuel pathways for aviation fuel calculations.
        - EPA and EU analyses of herbaceous biomass, crop residue, and vegetable oil to diesel are easily modified for jet fuels.
    - Adopt biogenic carbon accounting methods that are consistent with on-road fuel LCA.
        - Treat biogenic carbon emissions from fuel facilities and fuel use as neutral
        - Adjust net biogenic carbon emissions with land use adder.
    - Recognize the different treatment of fuel pathways under international GHG regulations.
        - Presently, fuel pathways may be deemed sustainable and low GHG in one jurisdiction while not meeting requirements in another.
- Develop an LCA tool that enables consistent calculation of GHG emissions.
    - Follow both RFS2 and RED approach and show both results with one set of inputs.
    - Add regional detail, flexible LCI data, and other features to calculate emissions for major GHG initiatives.
    - Use RFS2 and RED analyses to calculate indirect land use emissions and credits for feedstocks to enable the calculation of LUC for jet fuels.
    - Include regional criteria pollutants, water impacts, and land use change as a proxy for biodiversity impacts.
- Consider the adoption of uniform sustainability guidelines for aviation fuels.
    - Provide for use of existing fuel policies and sustainability standards to rate renewable portion of aviation fuel.
    - Develop procedures to categorize marginal land and categorize second crops or cover crops with claims of zero LUC.
    - Assure compliance with regulations governing jet fuels
    - Identify methods to minimize carbon leakage.
- Develop methods to address the unique attributes of aviation fuels.
    - Work with regulators to develop a method for accounting for comingled fuels and fuel that is used in international travel.
    - Assess impact of pollutants and high altitudes and develop an aviation specific global warming potential for minor species pollutants, if appropriate.

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1. Introduction

1.1. Background

The environmental sustainability of aviation fuels has grown in importance with expanding regulations on fuels and consumer awareness of environmental issues. Research in alternative commercial aircraft fuels is often focused on blends of Hydroprocessed Esters and Fatty Acids (HEFA) (aka hydrotreated renewable jet fuel (HRJ)) with conventional petroleum derived jet fuel, because alternative jet fuels have only been approved for use in aircraft in up to 50% blends. The U.S. Department of Transportation (DOT) Volpe National Transportation Center (Volpe Center) and the Federal Aviation Administration (FAA) Continuous Lower Energy, Emissions, and Noise (CLEEN) and Commercial Alternative Aviation Fuel Initiative (CAAFI) programs have examined these and other types of alternative jet fuels. Feedstocks for these fuels can include energy crops, biomass residue, and vegetable oils from many sources. Various pathways can potentially convert these feedstocks to jet fuel. (See Section 1.3)

In the interest of reducing the climate change impacts of transportation fuel use, a number of U.S. and European governmental agencies have established regulations aimed at reducing the greenhouse gas (GHG) emissions of transportation fuels. GHG emissions have been the primary criteria that have driven policy and incentives. However, quantifying sustainability for other impact categories (i.e., criteria pollutant and air toxics emissions, water discharges, biodiversity, and others) are more challenging. The emission rates and impacts may vary regionally and may also be subject to various regional regulations. A key challenge to date has been on reaching agreement between various stakeholders on the selection of sustainability criteria that provide optimal environmental performance, while providing sufficient volumes of fuel to meet targets for transportation use.

Furthermore, well-accepted trade and certification organizations have established guidelines and standards aimed at reducing the sustainability impacts of biofuel and bioenergy development. These initiatives have led to an increase in the use of sustainably certified biofuels for on-road transportation, although transportation fuels remain a relatively small portion of the overall use of feedstocks such as rapeseed oil, soy oil, corn, and sugarcane. Most of the uses of these feedstocks are not for fuel but the demand for sustainable certification is also growing in non-fuel markets. Existing sustainability guidelines could be expanded to include jet fuel feedstocks and production processes.

Identifying metrics for ecological impacts such as biodiversity is one of the most challenging aspects of sustainability depending upon the feedstock. Crop based feedstocks will affect land use directly or indirectly. The identification of affected species varies with State and Federal regulations and with changes in land cover type. Biofuel initiatives including ISCC, RSB, RFS2, and RED have requirements on the conversion of land to biofuel production. These requirements are conflicting and do not cover all potential biomass feedstocks.

Given the importance of aviation jet fuel (19.5 billion gallons of aviation jet fuel were used in 2011in the U.S. (EIA 2011)) and the growing interest in incorporating biofuels into the jet fuel pool, evaluating the sustainability of the production, distribution, and use of renewable jet fuel on a life cycle basis has become an important topic. Accordingly, the DOT/ Volpe National Transportation Systems Center, and the FAA have contracted Life Cycle Associates, LLC, to investigate the sustainability of renewable jet fuel.

1.1.1. Sustainability Defined

Sustainability is a broad concept used to describe how processes, projects, methods, or developments can occur for an indefinite period of time without causing negative environmental, social, or economic impacts. A widely accepted definition of sustainability by government entities and environmentalists was first given during a United Nations conference on the environment and development. The definition is: sustainability means meeting the needs of the present without compromising the needs of the future (Brundtland 1987). An alternative definition by the U.S. Environmental Protection Agency (EPA) is, "sustainability creates and maintains the conditions under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic and other requirements of present and future generations" (EPA 2012). While sustainability is typically categorized into three overlapping areas, as illustrated in Figure 1.1, social, economic, and environmental, the scope of this report only discusses environmental sustainability.

Assuring that sustainability metrics can be applied to practical applications requires a consistent set of metrics and rules that are measureable and verifiable in all components of the value chain. These broad and idealistic sustainability definitions need to have solid, tangible, and sensible metrics to be meaningful and applicable. Metrics that meet these criteria have been described by the Roundtable on Sustainable Biomatierals (RSB 2010).

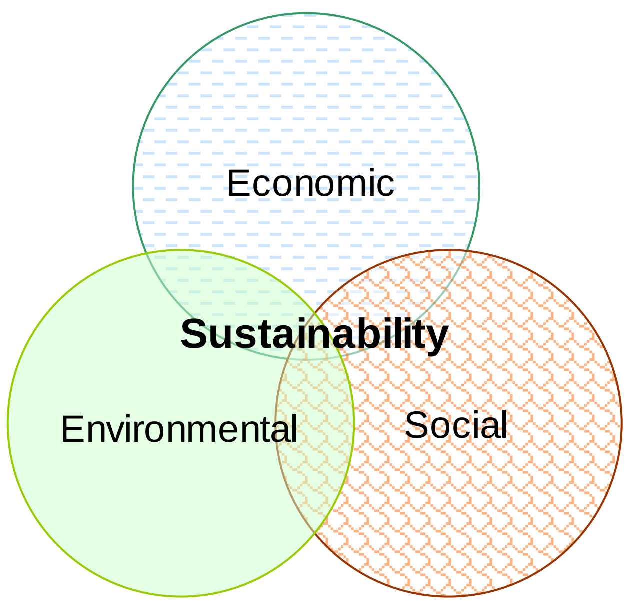

Figure 1.1. The Three Pillars of Sustainability.

Most regulatory initiatives aimed at biofuels have focused on greenhouse gas (GHG) emissions. The U.S. government and EU have responded to the concept of sustainability by creating climate change legislation to reduce GHG emissions. However, while GHG emissions reduction has become a major focus of sustainability policy, GHG impacts are only a small portion of what environmental sustainability encompasses. For a comprehensive approach to sustainability, environmental criteria such as energy use, water discharges, criteria air pollutant emissions, soil quality effects, and biodiversity impacts must be considered along with GHG emissions.

The biofuel/bioenergy industry stakeholders are keenly interested in establishing that biofuels used in transportation are sustainable in the context of current definitions of sustainability. The transportation fuels considered by stakeholders in this industry are primarily for ground transport, with a focused set of jet fuel end users that have become cognizant of their eventual responsibilities.

1.1.2. Sustainability Policies and Frameworks

This report evaluates several governmental policies that address the sustainability of transportation fuel feedstock production, fuel production and distribution, and vehicle fuel use. All government drivers are aimed at GHG emissions. Most include a sustainability element, primarily involving requirements on land conversion for different classes of feedstocks.

These include the U.S. Revised Renewable Fuel Standard (RFS2), Section 526 of the U.S. Energy Independence and Security Act (EISA), the California Low Carbon Fuel Standard (LCFS) and the EU Renewable Energy Directive (RED). These government fuel programs, listed in Table 1.1, address life cycle GHG emissions and energy use, but they do not consider other environmental criteria. These programs utilize different life cycle models and accounting rules to compare the life cycle GHG emissions of renewable fuels to petroleum fuel baselines. GHG emissions, energy use, and other environmental criteria are calculated using a life cycle assessment (LCA) model.

In June of 2015, the EPA issued a proposed finding that the GHGs from airplanes endanger human health by contributing to climate change. This would allow them to regulate GHG emissions from planes under section 231 of the Clean Air Act (CAA). This finding would apply to U.S. subsonic jet aircraft with a maximum takeoff mass (MTOM) greater than 5,700 kilograms and in subsonic propeller driven (e.g., turboprop) aircraft with a MTOM greater than 8,618 kilograms (EPA, 2015).

At that time EPA also issued an Advance Notice of Proposed Rulemaking that provides information on the process for setting an international CO_2 emissions standard for aircraft at the International Civil Aviation Organization (ICAO) of the United Nations. EPA intends to wait until ICAO has issued a coordinated, international GHG emissions standard for aircraft. EPA would then use section 231 of the Clean Air Act to adopt and implement the corresponding international aircraft engine GHG emissions standard domestically. The ICAO standard is expected to be complete in 2016 (EPA, 2015).

Table 1.1. Initiatives Based on Vehicle Fuel Sustainability

Fuel Programs	Applicable Regions	Affected Parties
Government regulations		
EISA Section 526	U.S.	Federal Agency fuel procurers, including Department of Defense components
RFS2	U.S.	U.S. fuel producers
California LCFS	California	Transportation fuel providers
European ETS	EU Countries	EU GHG emitters, plans to include aviation
European RED	EU Countries	European fuel providers
Sustainability Guidelines		
RSB	Global (members)	Biofuel/biomaterial producers
ISCC	Global	Biofuel producers
CSBP	Global (members)	Biomass and biofuel producers
RTSS	Global (members)	Soy oil producers
RSPO	Global (members)	Palm oil producers
Bonsucro	Global (members)	Sugarcane producers
GBEP	Global (members)	Bioenergy producers
ISO 14040, 14044	Global	All LCA activities
Environmental		
EPDs and PCRs	Global	Products with environmental product declaration
PAS 2050	United Kingdom	
ISO 14025	Global	

RFS2 = Renewable Fuel Standard, EISA = Energy Independence and Security Act, LCFS = Low Carbon Fuel standard, ETS = Emission Trading System, RED = Renewable Energy Directive, RSB = Roundtable for Sustainable Biofuels, ISCC = International Sustainability and Carbon Certification Association, CSBP = Council for Sustainable Biomass Production, RTSS = Roundtable for Sustainable Soy, RSPO = Roundtable for Sustainable Palm Oil, GBEP = Global Biomass Energy Partnership, ISO = International Standards Organization, EPD = Environmental Product Declaration, PCR = Product Category Rules, PAS = Publically Available Specification

LCA is a technique for quantifying and calculating the environmental impacts associated with a project on a life cycle basis. This involves defining boundaries of the system (project) and analyzing all of the inputs and material flows. The scope of the life cycle varies with GHG fuel policy and sustainability guidelines. Components of the life cycle typically include:

- Feedstock production
- Field emissions
- Residue burning
- Feedstock transport
- Biorefinery operation
- Co-product credit or allocation of co-products
- Fuel transport
- Vehicle or jet operation

Other components in the life cycle included in some regimes include:

- Land conversion
- Field establishment
- Indirect land use
- Farm equipment, biorefinery equipment, and jet equipment production
- Farm equipment, biorefinery equipment, and jet recycling

LCAs can be performed over a range of activities and environmental impacts. A full life cycle is called cradle-to-grave, and it includes all of the environmental impacts associated with the production of a good from raw materials to disposal. A field-to-wake life cycle is from the field in which a crop was grown, to the combustion of the fuel (the wake of the jet). Life cycles can also be broken up into distinct processes, such as cradle-to-gate, which does not include combustion and disposal. A discussion of LCA is found in Section 3.2, and a comparison of LCA models is found in Section 3.3.

Table 1.1 includes GHG regulations as well as several sustainability certification programs that affect biofuels. GHG regulations include extensive support documents and modeling tools for calculating GHG emissions. Sustainability guidelines establish standards for the sustainable production of feedstocks and fuels. The table contains both requirements for transportation fuels and voluntary initiatives related to the production, distribution and procurement of sustainable fuels. These sustainability standards and guidelines utilize a combined approach of sustainability best management practices and life cycle assessment (LCA) for certification. Environmental product declarations (EPDs) are similar to sustainability standards. The scope of the EPD is agreed upon by a stakeholder group. The EPD specifies the procedure for defining the environmental attributes of a product. ISO standards cover LCA and EPDs.

The first part of this study focused on describing the governmental regulatory actions and several trade and sustainability certification organizations' initiatives aimed at reducing the environmental impacts of biofuels.

1.1.3. Sustainability Metrics and Environmental Criteria

Sustainability metrics are the measurements used to analyze the environmental impacts of a project. Environmental impacts are calculated in a LCA using sustainability metrics when sufficient process and life cycle inventory (LCI) data are available. Sustainability metrics apply to the entire biofuel supply chain, from agricultural biomass feedstock production (farming) to the subsequent production and combustion of biofuels from this biomass. The feedstocks used for biofuel production include corn, sugarcane, switch grass, algae, and many other biomass crops. The greatest environmental impacts occur during biomass feedstock production (farming) and biofuel production. Other process steps include feedstock transportation and processing, as well as fuel blending and distribution. Common environmental criteria that may be considered as sustainability metrics are shown in Figure 1.2.

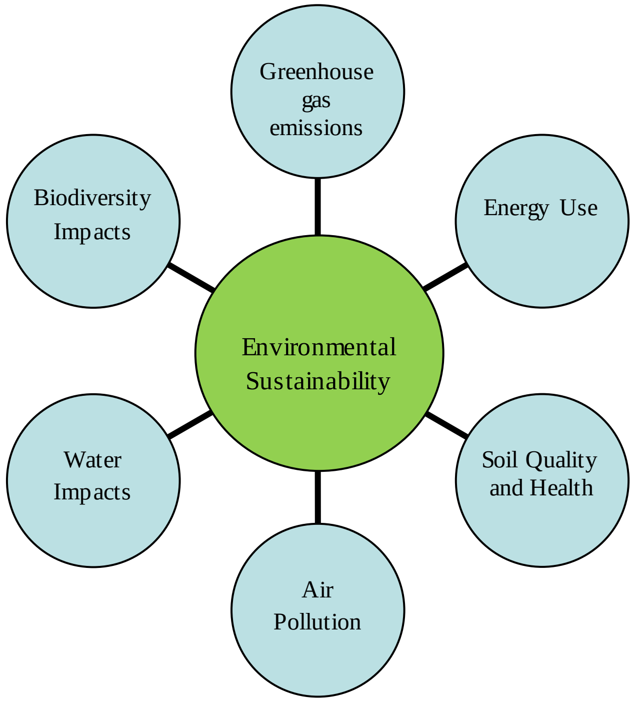

Figure 1.2. Commonly Considered Criteria for Environmental Sustainability

The above environmental criteria are considered by voluntary fuel program organizations including the Roundtable on Sustainable Biomaterials (RSB), Roundtable on Sustainable Palm Oil (RSPO), Council on Sustainable Biomass Production (CSBP), and the Global Bioenergy Partnership (GBEP). Additional sustainability metrics that are important to certification are good record keeping, transparency, and continuous improvement.

The most commonly reported sustainability metric is the life cycle greenhouse gas (GHG) emissions. Standards for GHG emissions are defined in great detail with rules that show how to account for the entire supply chain as well as upstream inputs. A product's cradle-to-grave GHG emissions per MJ of fuel produced are called its carbon intensity (CI). The most important GHGs produced by the biofuel industry are CO_2, CH_4, and N_2O.

Other sustainability metrics require monitoring at the facility level to comply with sustainability standards. The facility level is the specific facility in which a process step occurs, as opposed to using an average of feedstock production and process LCI data for an entire region or product. For the biofuel industry, this level of specificity would be at the individual farm producing the feedstock or the biofuel production plant that converts the feedstock products to transportation fuel. Metrics are not routinely specified for determining both facility specific direct and indirect effects on water, soil, and biodiversity. In the case of these criteria, the sustainability standard will likely require the implementation of best management practices, record keeping, and implementation plans.

Ultimately, the validation of sustainable practices will require auditing against a standard, recommended or best practice, or other guideline. Fuel producers and/or their auditors can use these types of resources to ensure that feedstock producers and fuel production facilities comply with these sustainability concepts; however they must be well defined so that performance can be measured.

1.2. Jet Fuel Market

Jet fuel accounts for approximately 19.5 billion gallons of liquid fuel consumed in the U.S. per year, or about 8.8% of total U.S. fuel consumption. Figure 1.4 shows the U.S. fuel consumption by fuel type in 2011. Jet fuel is used by domestic and international civil aircraft, general aviation, and military aircraft. Domestic civil aviation uses the most jet fuel at 19.5 billion gallons of fuel per year. International civil aviation uses 9.2 billion gallons of fuel per year, general aviation uses 1.8 billion gallons of fuel per year, and the military uses 3.9 billion gallons of fuel per year. Figure 1.3 illustrates the distribution of jet fuel consumption in the U.S. by sector for 2011.

For comparison, motor gasoline transportation fuel use is 129.6 billion gallons per year, 57.1 billion gallons of distillates and kerosene are used per year, and 0.2 billion gallons of aviation gasoline[2] are used per year. Furthermore, 11.2 billion gallons of LPG and 4.9 billion gallons of residual oil are consumed per year.

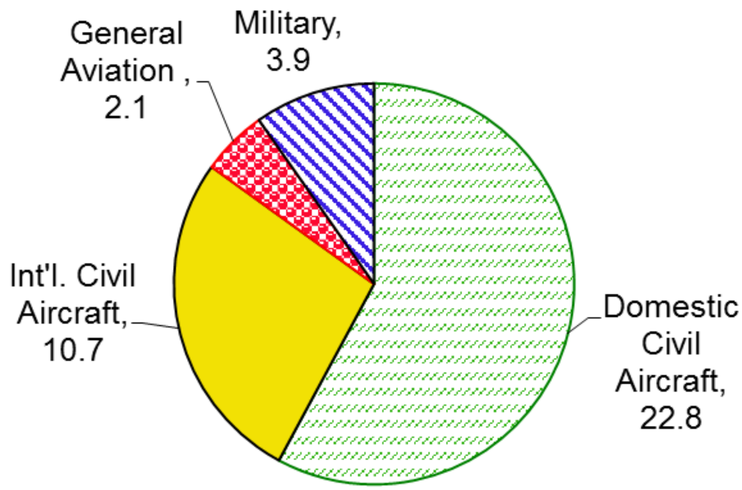

Figure 1.3. Jet Fuel Usage by Sector in Billon Gallons per Year, (FAA 2012).

[2] Aviation gasoline meets specifications of piston engine aircraft operations including high octane number.

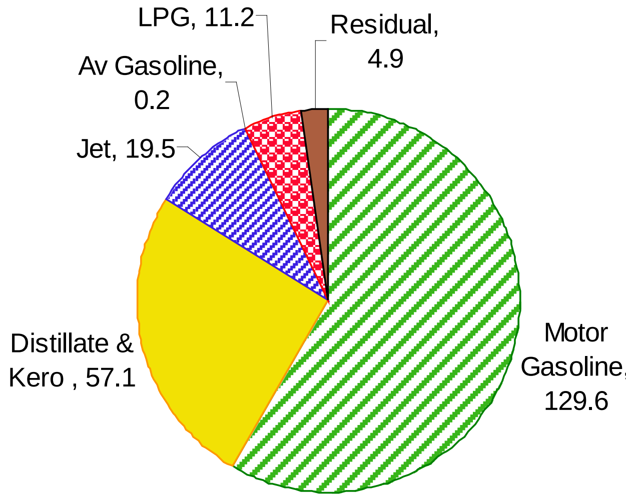

Figure 1.4. U.S. Fuel Consumption in Billion Gallons per Year, (EIA 2011).

1.3. Jet Fuel Production Options

Jet fuel is produced from the kerosene cut from petroleum refining and meets specific requirements for aviation. Kerosene is similar to diesel fuel with lighter (lower molecular weight) components and contains both paraffinic and aromatic components. Currently allowable alternative jet fuels that can be used in certified formulations are typically entirely paraffinic, the product is referred to as synthetic paraffinic kerosene (SPK), and are therefore required to be blended with petroleum-based jet fuel to ensure suitable chemical properties relating to aromatic content.

Many feedstock and fuel combinations are options for jet fuel. Feedstocks include farmed biomass, sugar crops, agricultural residue, waste material, biogas, and many others. Jet fuel specifications cover a limited set of hydrocarbons that can be met with various conversion pathways. The two currently approved pathways are hydroprocessing of esters and fatty acids (HEFA), examples include hydro-processed rapeseed, algae, and camelina oils, and fuels made via Fischer Tropsch (FT) synthesis, which involves the gasification of feedstocks such as forest material, municipal waste, or herbaceous biomass, as well as "Synthetic Iso-Paraffins" (SIP) made by a genetically modified organism from sugar feedstocks. Additional pathways are currently being evaluated for approval. This includes jet fuel made from alcohols from numerous pathways that can be oligomerized to SPK (ATJ pathway). Sugars can also be fermented to oil precursors via algae or other organisms. The pyrolysis of biomass also produced oil products that can be refined further to jet fuels.

1.3.1. Petroleum Jet Fuel

Jet fuel is currently produced from the refining of crude oil in complex oil refineries. Crude oil is separated into product streams through distillation. These streams are further refined into finished fuels as shown in Figure 1.5. Jet fuel is primarily produced from "straight run" kerosene. This kerosene is a product of the crude distillation unit, the first step in an oil refinery. Since the kerosene is one of the first products produced in the oil refinery, without secondary processing, lower energy inputs and emissions are assigned to kerosene than to diesel fuel in most studies that attribute emissions to refinery products (Wang 2004, Gerdes 2009). Diesel fuel is produced from hydrocrackers, for example, which result in additional emissions in their operation. Most diesel fuel also requires hydrotreating to meet sulfur specifications. Producing other refined products is considered more energy and emissions intense because the refinery streams are processed in subsequent units such as hydrocracking, hydrotreating (HT), fluid catalytic cracking (FCC), and other operations.

Assessing the sustainability impacts of kerosene requires attributing crude oil production, transport, and refinery emissions to all petroleum products. Several approaches are described in Section 3.

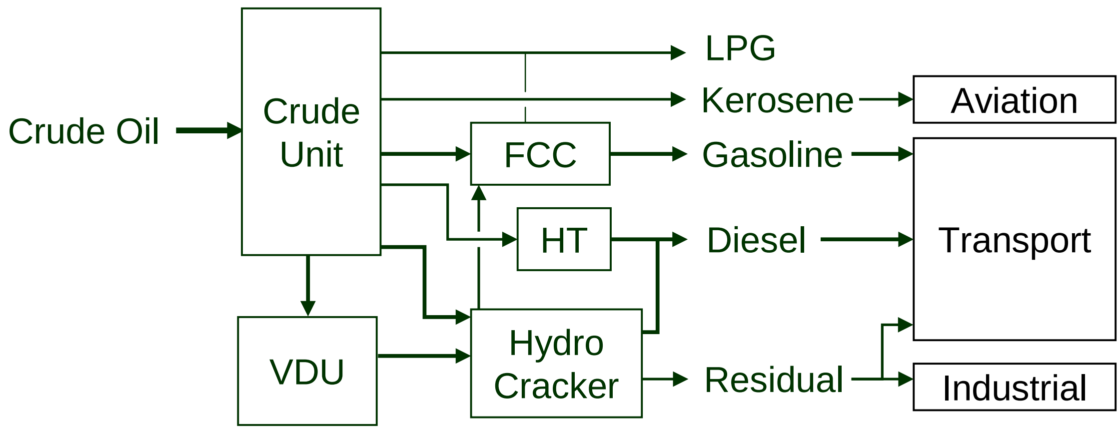

Figure 1.5. Simplified Petroleum Refinery Configuration[3].

1.3.2. Renewable Jet Fuel

CAAFI has worked with the ASTM to develop a specification for Fischer Tropsch (FT) synthetic fuels blends and Hydroprocessed Esters and Fatty Acids (HEFA) based SPK biofuels using up to 50% blends of the alternative fuels to conventional petroleum based fuels, and for SIP Fuels up to 10% blends. All three fuels are specified in MIL-DTL-83133H and under ASTM D-7566. Renewable jet fuels can be produced from various feedstocks and processes. Figure 1.6 shows the HEFA route. SPK, naphtha and diesel are all potential products. Many pathways for renewable jet fuel production share similarities with the petroleum pathways in terms of flexibility between diesel and jet production as well as the co-production of a naphtha stream. Naphtha can be used as a feedstock for chemical production or a low octane gasoline blending component. Yields from the processing of paraffinic naphtha are higher than those from petroleum sources, which affects its impact as a co-product.

[3] VDU = Vacuum Distillation Unit. FCC = Fluid Catalytic Cracker. HT = Hydro Treater

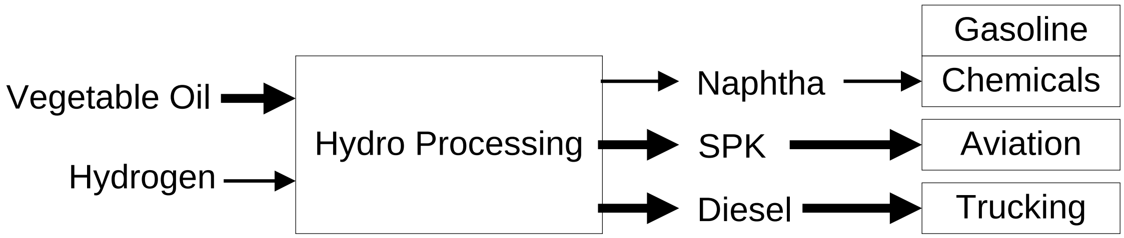

Figure 1.6. HEFA Inputs and Products.

Figure 1.7 shows potential inputs and products for an FT system. Many biomass and fossil fuel feedstocks have been considered for such systems. Some feedstocks may also be co-fed. The sustainability analysis needs to take feedstocks, treatment of co-products, and potential use of CO_2, which may be sequestered or used in other applications. The non fuel co-products of FT processing have different life cycle impacts of the petroleum substitutes, which needs to be taken into account in the environmental analysis.

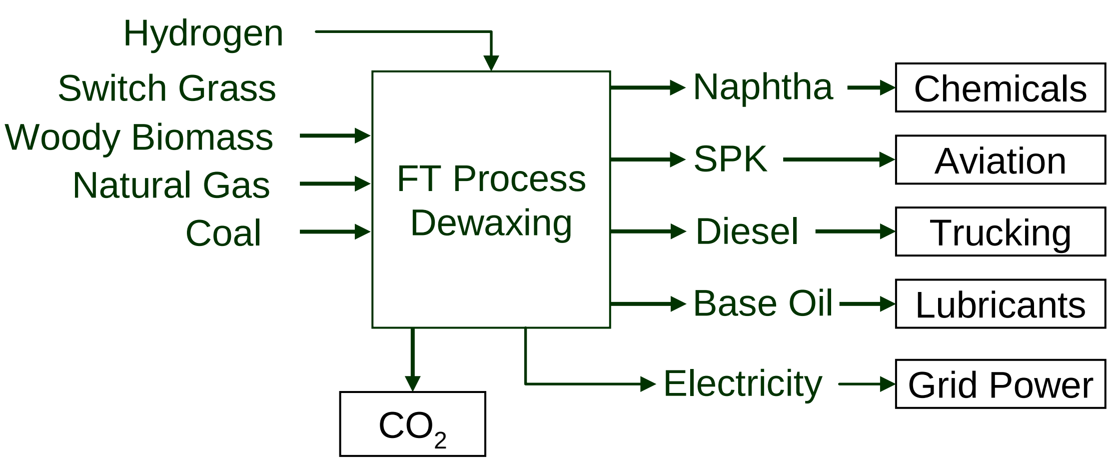

Figure 1.7. FT Jet Inputs and Products.

1.4. Objectives

The primary aim of this study is to help aviation jet fuel purchasers (the U.S. military, airlines, and aircraft and jet engine manufacturers) to understand the sustainability implications of their jet fuel purchases, and provide guidelines for procuring sustainable fuels. This includes identifying the regulatory requirements for sustainable fuel use in different regions of the world, providing guidance in calculating the life cycle GHG emissions impacts of jet fuels, and defining guidelines for estimating the sustainability implications of criteria other than life cycle GHG emissions (e.g., criteria pollutant and air toxics emissions, water discharges, and other impacts).

The objective of this report is to summarize the literature review, stakeholder research and sustainability criteria evaluation of renewable and alternative jet fuel production completed by Life Cycle Associates and to provide detailed recommendations about applying a sustainability framework to jet fuels. Life Cycle Associates has completed an assessment and comparison of existing sustainability rating systems used to analyze environmental performance to be adopted for renewable aviation fuels; a literature review of jet fuel life cycle assessments is discussed in Section 3. This report identifies current sustainability regulatory initiatives and guidelines, as well as the issues with them, and it provides recommendations that should be considered in the development of standards to guide the purchase of alternative jet fuels.

Additionally, this report seeks to enable a consistent and rational dialog about the state of development of sustainability criteria, available frameworks and the best approach for ensuring confidence in procuring sustainable jet fuel. This report focuses on the following topics:

- Renewable fuel governmental policies and initiatives
- Renewable fuel trade and voluntary sustainability certification organizations
- A review of sustainability literature
- Current LCA models and studies
- Comparison of LCA model results
- Issues with LCA models and sustainability
- Sustainability metrics
- Recommendations to purchasers of renewable jet fuel

1.5. Target Audience

The target audience for this work is purchasers of renewable jet fuel (people involved in the procurement of aviation fuels). Jet fuel procurers, including airlines, U.S. government, military and others, need a way to ensure the fuel they obtain was sustainably produced. The FAA regulates the aviation industry and needs to understand available sustainability frameworks and related issues. This project seeks to identify an appropriate rating system to quantify the emissions and environmental sustainability impacts, and thus the sustainability metrics for renewable jet fuels to inform purchasing decisions. The goal is to provide the target audience (fuel purchasers) with sufficient information to develop environmental sustainability specifications for renewable aviation fuels to foster fuel pathway sustainability.

1.6. Report Organization

The remainder of this report is organized in the following sections: Section 2 details the governmental fuel programs, and widely accepted trade and sustainability certification voluntary fuel programs. Section 3 summarizes the findings of the literature review on existing life cycle models in use today, and it highlights the biggest issues with these sustainability models, as well as additional issues with sustainability. Section 4 presents the sustainability metrics developed to assess jet fuels. Section 5 provides the key conclusions for airlines, the government, and others to consider sustainability when procuring renewable jet fuel. The Executive Summary provides a brief overview of the study and recommendations.

2. Renewable Fuel Programs: Sustainability Policies, Initiatives, and Guidelines

Policies and frameworks for the following fuel programs are intended to evaluate ground transport fuels, many or all of their features may be applied for jet fuel evaluation because of the fundamental similarities between jet fuels and ground transport fuels.

2.1. Comparison of Fuel Sustainability Initiatives

Detailed requirements of the various sustainability initiatives and government policies are shown in Table 2.1. Each of these initiatives provides a rating of fuels or consumer products based on CI. The approaches vary because different agencies developed the requirements with different stakeholder inputs and different objectives. Regional differences also affect the calculated CI of the fuel rating systems. However, the overall approach to GHG emissions differs most significantly in just a few key areas. These key areas include:

- Co-product allocation methods or selection of displacement value
- Double crediting of co-products (with impacts in other programs)
- Inclusion of land-use change impacts (direct and indirect)
- Calculation of land-area change and associated emissions
- Choice of consequential vs. attributional LCA
- Regional specific data (i.e. what region was used to generate the LCI data)
- Selection of default values for regulatory ratings

Differences in LCA approaches in these areas can lead to substantially different CI ratings among the different government initiatives identified below. A case where electricity is co-produced during a biomass to liquid fuel process illustrates many of the differences among GHG calculation methods:

- Under the RFS2, fuel pathways with export power received an emission credit based on displacing U.S. average electricity.
- Under the LCFS, a co-product electricity credit based on regional resource mix is used in many fuel pathways. ARB limits the electricity credit based on precedent established with prior pathways.
- Under the RED the displacement credit for biomass power is based on displacement of existing biomass power (which effectively yields a very small credit compared to the displacement of average grid or natural gas power).
- The procedures under EISA Section 526 are less clearly specified than the RFS2 or LCFS. A framework study by AFRL (Allen 2009) provides guidance for LCA in support of military applications, and identifies all of the issues in LCA. However, key decisions on allocation for different pathways remain open to interpretation. Government agencies use analysis from DOE to guide compliance with Section 526 and the results are not as available as EPA's documents.

Table 2.1. Comparison of Transportation Fuel Programs

Fuel Program:	Renewable Fuel Standard (RFS2)	Energy Independence and Security Act (EISA)	Low Carbon Fuel Standard (LCFS)	Roundtable on Sustainable Biofuels (RSB)	International Sustainability and Carbon Certification (ISCC)	Renewable Transport Fuel Obligation (RTFO)	Renewable Energy Directive (RED)
Region	United States	United States	California	Global	Global	United Kingdom	Europe
Agency	EPA	Federal Government	Air Resources Board	RSB Board	ISCC association	DFT	Renewable Fuels Agency
Obligated Party	Fuel producer	Fuel producer and federal purchasers	Fuel producer	All parties in value chain	All parties in value chain up to fuel producer	Fuel producer	•Bledner •Only obligates producers of 450,000 L or more
Goal	• Reduce U.S. dependence on petroleum • 36 billion gallons of renewable fuel by 2022	• Reduce U.S. government dependence on petroleum	• Reduce GHG emissions from transportation fuel use by 10% in 2020	• Provide voluntary sustainability certification program	• Provide voluntary sustainability certification program • Reduce greenhouse gas emissions by 35% from 2011	• Ensure that 5% of transport fuel is derived from renewable sources by 2010 • Reduce carbon emissions	• Reduce greenhouse gas emissions by 35% from 2011
Approach	Meet fuel category reduction threshold	Determine CI for fuel pathway using any approach	• Look-up Table CI • Method 2a application • Method 2b application	Determine CI for each part of value chain	Determine CI for each part of value chain	• Obligated fuel suppliers receive one RTFC per L of fuel • Obligated suppliers may trade RTFCs • Obligated suppliers must meet obligation each year by redeeming RTFC	Determine CI for fuel pathway using standard values or documented data
Allocation Approach	Partial-Consequential LCA, primarily substitution	Attributional LCA, LUC TBD	Attributional LCA, primarily substitution	Attributional LCA, economic allocation	Attributional LCA, energy allocation	Attributional LCA	Attributional LCA, energy allocation
Carbon Intensity Categories	60% Reduction 50% Reduction 20% Reduction	> 0% Reduction	• Look-up Table CI • Apply for unique CI	Apply for CI using online calculation modules	35% Reduction	Baseline fuel pathway CI's established	35% Reduction
Calculation Tool(s)	• GREET1.8c.0 • FASOM, FAPRI	• Unspecified • GREET	• CA-GREET • GTAP	• RSB Greenhouse Gas Tool	• ISCC GHG Emission Calculation	• Default values determined by government	• BioGrace
Modeler	EPA	Fuel producer/consultant	Fuel producer/consultant	Fuel producer/consultant	Fuel producer/ consultant	Fuel producer/consultant	Fuel producer/ consultant
Auditor	EPA engineering review	Unspecified	Air Resources Board	Certified Auditor	ISCC recognized Certification Body	ISAE 3000 verifier	ISCC certified auditor

Table 2.1. Comparison of Transportation Fuel Programs (Continued)

Fuel Program:	Renewable Fuel Standard (RFS2)	Energy Independence and Security Act (EISA)	Low Carbon Fuel Standard (LCFS)	Roundtable on Sustainable Biofuels (RSB)	International Sustainability and Carbon Certification (ISCC)	Renewable Transport Fuel Obligation (RTFO)	Renewable Energy Directive (RED)
Feedstock Producer[4]	• Renewable biomass certification • Land documentation • Monthly farming data	Unspecified	• Sustainability Requirements under development • Default data from GREET model	• Life cycle input parameters • Farming data • Regional climate data	• Life cycle input parameters • Farming data • Regional farming data	• Life cycle input parameters • Regional farming data	• Life cycle input parameters • Regional farming data
Feedstock Processor[4]	• Life cycle input parameters • Monthly process data	Unspecified	• Life cycle input parameters • Monthly process data	• Life cycle input parameters • Monthly process data	• Life cycle input parameters • Annual process data	• Life cycle input parameters • Annual process data	• Life cycle input parameters • Monthly process data
Biofuel Producer[Error! Bookmark not defined.]	• Life cycle input parameters • Engineering Review		• Life cycle input parameters • Monthly process data	• Life cycle input parameters • Monthly process data	• Life cycle input parameters • Annual process data	• Life cycle input parameters • Monthly process data	• Life cycle input parameters • Monthly process data
Biofuel Blender/Distributor[Error! Bookmark not defined.]	Average transportation modes	Unspecified	• Transport modes • Transport distances	• Transport modes • Transport distances	• Transport modes • Transport distances	• Transport modes • Transport distances	• Transport modes • Transport distances
Required Documents	• Petition application • Fuel plant registration	Depends on specific procurement	• Application • Fuel pathway document • List of equipment • Result spreadsheet • Configured CA-GREET	• Calculation modules • Greenhouse gas results • Principles and criteria • Risk assessment • Cover letter	• Documented inputs • Model or calculations • Fuel pathway report • Result spreadsheet	• Annual report • Documented inputs • Model or calculations • Result spreadsheet	• Documented inputs • Model or calculations • Fuel pathway report • Result spreadsheet
GHG Scope	WTW processing, indirect Ag, and LUC	Flexible. Farm to wake, plus materials	WTW processing, Ag, and LUC	WTW processing, Ag, LUC is TBD	WTW processing, Ag, LUC is TBD	WTW processing, Ag, and LUC	WTW processing, Ag, LUC

TBD = To be determined by governing agency

[4] Data Required

Another key difference is in the treatment of land use for crop production as well as LUC. The RFS2 requires land be in agricultural service since the data the rule was approved in 2007 while the RED requires that agricultural land not be converted to biofuel production. According to the communication documents of the EU RED (2010/C160/02) LUC that is not covered by the sustainability article (addressing highly biodiversity areas etc. where a land use change is prohibited), "still has to be taken into account in the calculation of the greenhouse gas impact". The EU also has guidelines for the calculation of land carbon stocks (2010/335/EU). These limitations appear contradictory. However, crops from one farm can be sold to meet the requirements of both policies under the appropriate circumstances.

LUC greenhouse gas emissions are counted under the RFS2, LCFS, and RED. Each program uses different modeling systems as well as different inputs to the analysis (Edwards 2011). In many instances the magnitude of predicted LUC emissions are in the same range, however, the details of the analysis vary significantly.

Note that the obligated parties differ under the various regulations. Under Section 526, the military must purchase fuels with life cycle GHG emissions no higher than a petroleum baseline. The government agencies provide spreadsheets as part of their procurement process with input from DOE. This analysis approach is not necessarily the same as that under the RFS2, which creates a situation where fuels can have different GHG ratings under different policy regimes. Adding to the complexity, aviation fuels can generate renewable identification numbers (RINs) under the RFS2 if they comply with the RFS2 reduction requirements and are used in compliance with the rule. The generation of RINs can help the economics of alternative renewable jet fuel, so the potential ratings under the RFS2 are also important.

Airlines are not obligated to comply with Section 526. Their fuel providers must meet volumetric requirements under the RFS2 primarily with on-road fuels, although aviation fuel provides another market to help with RFS2 compliance. However, HEFA diesel could just as easily be sold into the on-road transportation pool, and HEFA pathways generally generate higher diesel than jet yields, which may dampen the incentive to produce jet fuel.

2.2. Government Fuel Programs

Table 2.1 summarizes six government fuel programs that were compared for this report. These fuel programs include governmental policies and initiatives designed to ensure the sustainability of the biofuel industry. The fuel programs/frameworks include the RFS2, the U.S. Energy Independence and Security Act (EISA), the California Low LCFS, RED, and the United Kingdom Renewable Transport Fuel Obligation (RTFO). The ISCC and the Roundtable on Sustainable Biofuels (RSB) has a well-established GHG component and many of the details for the RSB certification in Table 2.1 fall into the same categories as the government programs in Table 2.1. Other than the RSB, all the other programs in Table 2.1 are mandated governmental regulatory programs.

EISA Section 526 requires GHG emissions for fuels procured by federal agencies to be no higher than a petroleum baseline. Aviation fuels are subject to cap and trade requirements in Europe.

Additionally, fuel producers may strive to take advantage of selling the fuels under the EPA RFS2, California LCFS, or EU RED in order to improve the economics of fuel production.

Government agencies have developed renewable fuel policies that address climate change; the sustainability verification in these programs are less detailed than biofuel sustainability standards. In addition, the RFS2 and RED use a threshold approach, where fuel producers must demonstrate a CI result less than or equal to an established threshold; these programs encourage fuel producers to just meet the performance threshold and provide no incentive to reduce emissions further. By contrast, the California LCFS assigns a unique CI score to each fuel pathway, which provides an incentive to reduce emissions further with the expectation that lower CI fuels would achieve a higher value in the marketplace.

2.2.1. U.S. EPA Renewable Fuel Standard 2 (RFS2)

The RFS2 was authorized in the U.S. by EPA under the Energy Independence and Security Act of 2007 (EISA). This legislation requires that 36 billion gallons of renewable transportation fuels be used annually in the U.S. by 2022. The RFS2 establishes mandatory CI emission thresholds for renewable fuel categories, categories based on percent reductions from established 2005 petroleum baseline fuel CI results. The EPA used a partial-consequential life cycle analysis approach for the RFS2, including a traditional attributional life cycle analysis of the fuel plant and feedstock/fuel transport based on the GREET (Greenhouse gas, Regulated Emissions, and Energy Use in Transportation) model (version 1.8c.0) and agro-economic modeling of feedstock production and use. The suite of models and data sources EPA used other than GREET include FASOM (Forestry and Agricultural Sector Optimization Model), FAPRI (Food and Agriculture Policy Research Institute), MODIS (Moderate Resolution Imaging Spectroradiometer) satellite data, and Winrock and GREET emission factors.

Fuel producers may submit fuel production life cycle results and inputs to EPA via the petition process to certify that their fuel falls into a specific renewable fuel category. EPA determines the fuel pathway CI based on the fuel provider's fuel plant inputs and the EPA calculated results for all other fuel pathway steps. In addition to submitting a petition application, fuel providers must register with the EPA and demonstrate that their biofuel uses renewable biomass (if they are submitting a renewable biomass pathway). The goal of submitting a petition is to demonstrate compliance with the emission reduction threshold; there is no additional value for fuel pathways with CIs lower than the threshold. If a renewable fuel is certified under the RFS2, it can be used to fulfill the federal EISA mandate.

The RFS2 places restrictions on the type of land used to grow feedstocks. Feedstock from crops must be grown on land in agricultural use prior to December 19, 2007. EPA provides national level certifications of prior land use. For example, EPA monitors the total U.S. crop land used for corn. As long as the total land in corn cultivation does not exceed a baseline, the feedstock can qualify as a renewable fuel without verification of the prior land use. Fuel production facilities are audited as part of an engineering review that is required by EPA.

2.2.2. U.S. Energy Independence and Security Act (EISA), Section 526

The 2007 EISA established energy management goals and requirements for the federal government and amended portions of the National Energy Conservation Policy Act (NECPA). Section 526, titled "Procurement and Acquisition of Alternative Fuels". The EISA requirements prohibit federal agencies from procuring alternative or synthetic transport fuels unless the fuel contract indicates a CI score less than or equal to the carbon intensity associated with a petroleum baseline fuel. In other words, the section states that alternative and synthetic fuels used by the government for transport must achieve a CI score better than or equal to the CI of a baseline petroleum fuel. Fuels research and testing are exempted from the rule.

The rule is intended to ensure that the federal government reduces its carbon footprint over time. However, the rule provides no clear guidelines, standards, or framework for assessing the CI of an alternative fuel or choosing a petroleum baseline. Therefore, the rule cannot ensure consistency among the CIs of fuels available to the government. The most frequently used model for calculating CIs is the GREET model (discussed in Section 0), which calculates life cycle results for U.S. average fuels.

2.2.3. California Low Carbon Fuel Standard (LCFS)

The California Low Carbon Fuel Standard (LCFS) was first mandated in 2007 by Governor Schwarzenegger under Executive Order S-1-07. Specific eligibility criteria were defined in 2009 by the California Air Resources Board (ARB), the agency responsible for implementing the legislation. The first monitoring year for the regulation was 2010 and the obligated parties must have demonstrated compliance beginning in 2011. The LCFS requires fuel blenders to ensure that the fuel mix they sell in California meets the established targets for greenhouse gas emissions, and the emission targets decline over time. The LCFS requires reduction of at least 10 percent in the CI of California's transportation fuels by 2020. Fuel pathway CI values are the sum of the well-to-tank, tank-to-wheel and LUC emissions. Direct LUC emissions are generally grouped into the ILUC analysis.

The LCFS provides two main ways to obtain CI values: 1) fuel providers may use a CI value from the published look-up tables for the fuel pathway. Alternatively, fuel pathway CI values are based on CA-GREET (a California-specific GREET model version) for WTT emissions with data from the fuel producer. The model contains fuel property data from CA-GREET and vehicle emission factors from the EMFAC (Emission Factors) model for TTW emissions, and the GTAP (Global Trade Analysis Project) model for LUC emissions. ARB requires the use of the CA-GREET model for determining fuel pathway WTT emissions. The model uses California-specific parameters and includes regionally specific inputs. The TTW and LUC emissions are established by ARB for all fuel pathways, so fuel producers only need to determine WTT results. ARB audits the GHG analysis through the data collection requirements of its application process.

2.2.4. European Renewable Energy Directive (RED)

The Renewable Energy Directive (RED) is a European fuel program implemented by national legislation in the different member states. The European Commission has recognized 15 certification schemes, which can be used by feedstock- and biofuel producers to show compliance with the RED requirements. Examples are the RSB EU, ISCC EU, RSPO EU, RTRS EU or Bonsucro.[5]

The RED program includes direct land use change emissions occurring after January 1, 2008. ILUC emissions have been determined for grain feedstocks and oil seeds. Life cycle calculations must follow the guidance of the "GHG Emissions Calculation Methodology and GHG Audit" document provided by the ISCC. The guidelines indicate the steps in the fuel cycle and general calculation approach, but do not prescribe use of a specific model or life cycle data. Analyses may use life cycle inventory "standard values" established by the ISCC or other documented data. For example, ISCC is one of the 15 recognized certification schemes. Life cycle calculations can follow the ISCC documents, but can also follow BioGrace or a method provided by one of the other schemes. The land used for biofuel production is covered under 2009/28/EC Article 17(3) - 17(4): Important areas are protected. From January 1, 2008 they are not allowed to be converted at all. For all other areas, LUC needs to be calculated

The BioGrace project, funded by the Intelligent Energy Europe Programme, develops calculation tools based on the RED (2009/28/EC) and the EU Fuel Quality Directive (2009/30/EC) that determines fuel pathway life cycle GHG emissions for European markets. The latest publicly available tool is version 3 of the GHG calculator, which calculates fuel cycle results based on established life cycle inventory data "standard values" stored in the tool. This tool may be used to determine CI results under the RED. The project is currently working on GHG emission calculators for regional specificity at the national level.

The RED places restrictions on the land type for biofuel production. No crop land used for food production can be used for biofuel production. The program includes incentives for the use of degraded land. Compliance with the RED requires audit of the agricultural practices and the biofuel production facility.

2.2.5. Renewable Transport Fuel Obligation (RTFO)

The Renewable Transport Fuel Obligation (RTFO) establishes fuel minimum volume requirements for the use of biofuels in the UK. The RTFO is implemented by the UK Department for Transport, which aligned its sustainability criteria in December 2011 with RED. Therefore, the RTFO requires minimum greenhouse gas savings and sustainability of land use (i.e. conservation of high carbon stocks and biodiversity for feedstock producers). All fuel suppliers who provide more than 450,000 liters of fuel per year are required to provide evidence that they are incorporating renewable fuels into their supply, or they must pay a substitute fee. Renewable Transport Fuel Certificates (RTFC) are awarded to fuel providers incorporating biofuels into their fuel supply. Fuel providers may trade certificates at market value or they can

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[5] See also http://ec.europa.eu/energy/renewables/biofuels/sustainability_schemes_en.htm)

be carried over from one year to the next. The objective of the program is to ensure that 5% (by volume) of all transport fuels are produced sustainably by 2013. The RTFO provides a carbon calculator to provide greenhouse gas savings results. There are currently no other future requirements of the RTFO beyond 2013.

2.3. Voluntary Fuel Programs

Table 2.2 compares five voluntary fuel programs, followed by a subsection describing each organization's guidelines. These commonly used trade and sustainability certification fuel programs include government sustainability standards and grants, and non-governmental organization (NGO) sustainability standards and guidelines. Their sustainability standards are generally formed by stakeholders from every sector of the biofuel industry, including farmers, biofuel refineries, government agencies, banks, and labor unions. The organizations are the Roundtable on Sustainable Biofuels (RSB), the International Sustainability and Carbon Certification (ISCC), the Council on Sustainable Biomass Production (CSBP), the Roundtable on Sustainable Palm Oil (RSPO), the California Energy Commission, and the Global Bioenergy Partnership (GBEP). These organizations have developed voluntary fuel programs specifically to ensure the sustainability of the rapidly growing biofuel industry.

Among these guidelines are voluntary certification schemes which require auditors to act as third parties for certification of sustainability standards. Sustainability guidelines or requirements must be quantified or qualified to apply the rules in a standard. These organizations seek to implement the core principle of each sustainability criterion into concrete standards.

2.3.1. Sustainability Guideline Overview

Sustainability guidelines are typically developed with three levels of detail: principles, criteria, and indicators. Principles are broad statements about sustainability. Criteria are conditions that must be met for the principle to stand and indicators are specific questions that must be answered by a farm, producer, or company for a criterion to be met, (Woods 2007). Difficulties arising with monitoring and compliance to sustainability standards are discussed in Section 3.5.5.

An example of an RSB principle, criterion, and indicator is as follows: the RSB's environmental sustainability principle for conservation of soil health is, "Biofuel operations must implement practices that seek to reverse soil degradation and/or maintain soil health." The criterion is, "Operators shall implement practices to maintain or enhance soil physical, chemical, and biological conditions." Rather than calling them indicators, the RSB calls them minimum requirements and progress requirements. One of the indicators (minimum requirements) is: "Perform periodic sampling of soil on the feedstock production [to comply with the soil management plan]." RSB provides no baseline for soil sampling, but other organizations might provide a baseline (e.g., percentage of soil organic matter content), or the criteria could focus on improvement over time from a project's own baseline.

Developers of sustainability schemes assembled them with the motivation of helping the biofuel and bioenergy industry develop sustainably. The sustainability guidelines provided by these organizations are similar. All of the schemes promote sustainable biofuel development and provide sustainability standards. All of the organization's guidelines are publicly available and most are targeted towards the global biofuel and bioenergy industry, however some concentrate their work in one region, (e.g., RSPO targets Southeast Asian palm oil.) All of the organizations, have designed or designated a calculation tool for calculating sustainability; some of the calculation tools only pertain to greenhouse gas emissions, while others are more comprehensive and might require a third party for documentation of additional sustainability criteria.

All of the guidelines are highly detailed and include multiple sustainability principles, criteria, and/or indicators (discussed below). All of the guidelines, except GBEP's[6], implicitly rely on comparison of measured indicators to baseline values, but few of the schemes provide the specific baselines for comparison. Some of the baselines refer to petroleum equivalents, and some of them refer to baselines previously established by a facility through best management practices. All of the organizations have developed sustainability guidelines with respect to LUC, water, soil, and biodiversity. The certification systems examine project specific (as opposed to national average) practices over the supply chain. Each of the voluntary fuel program organizations is discussed in the following subsections.

2.3.2. Roundtable on Sustainable Biomaterials (RSB)

The European Roundtable on Sustainable Biomaterials (RSB) is a NGO with a voluntary, international program for certifying renewable biomass feedstocks and fuels. The RSB's global coalition of stakeholders is coordinated and hosted by the École Polytechnique Fédérale de Lausanne (EPFL) Energy Center in Switzerland and includes more than 120 members residing in more than 30 countries. The RSB has developed a global sustainability standard for biomass and biofuel produced anywhere in the world, including a field-to-wheels life cycle assessment of fuel production. The greenhouse gas tool and other certification items are located online and certification relies on third party auditing. The greenhouse gas tool may be used to calculate results under several different fuel programs, including EU RED, EPA RFS2 and California LCFS. Although certification under the RSB allows fuel providers to market fuel in Europe, just like the RED, the RSB includes a much broader scope of sustainability criteria impacts than the RED.

The RSB calculation tool is organized in seven modules, representing the fuel pathway steps in fuel production. The tool is comprehensive and requires specification of a large number of inputs, requiring more data than called for by other fuel programs. The RSB tool provides disaggregated life cycle greenhouse gas emission results which are submitted to a certified auditor for review. Under RSB, only three certification bodies are recognized: (http://rsbservices.org/certification-bodies/) the accreditation of the Federal Office for Agriculture is part of the implementation of the EU RED in German legislation (Biokraftstoffnachhaltigkeits-Verordnung). It is not RSB-specific, but applies to all schemes recognized in Germany

[6] The baseline is expected to vary somewhat by region, so it is not specified under GBEP. The baseline is specified for the RFS2, LCFS, and RED.

Table 2.2. Comparison of Sustainability Guidelines by Organization

Organization	Roundtable on Sustainable Biomaterials (RSB)	International Sustainability and Carbon Certification (ISCC)	Council on Sustainable Biomass Production (CSBP)	California Energy Commission's AB118	Roundtable on Sustainable Palm Oil (RSPO)	Global Bioenergy Partnership (GBEP)
Headquarters	Lausanne, Switzerland	Cologne, Germany	Sacramento, California	Sacramento, California	Zurich, Switzerland	Rome, Italy
Target Market	Europe, Global.	Global	United States	California	Southeast Asia, Global	Developing countries, Global
Topic	Provide sustainability requirements for biofuel production	Principles, criteria and verification guidelines for the sustainable production of biomass used in different end-markets such as biofuels.	Guidelines for sustainable biomass to bioenergy conversion (bioenergy production). Feedstock and consumer standards.	Guidelines for documenting sustainable fuel production for CA AB118 grants.	Principles and criteria for sustainable production of palm oil.	International forum for developing sustainable bioenergy policy framework.
Agenda	• Promote sustainable production of biomass with sustainability standards	• Promote sustainable production of biomass with sustainability standards	• Promote sustainable production of biomass with sustainability standards	• Diversify California's transportation fuels • Promote exemplary models of sustainability	• Promote the growth and use of palm oil with sustainability standards	• Promote sustainable production of bioenergy
Sustainability Certification	X	X	X	Grant awarded	X	N/A
Sustainability Calculation Tool	RSB calculation method	ISCC calculation method	Draft standard	CA-GREET Extensive check list	RSPO calculation method	Online GHG Tool
GHG	X	X	X	X	X	X
LUC	X	X	X	X	X (Only when primary forests are concerned)	X
Water	X	X	X	X	X	X
Soil	X	X	X	X	X	X
Biodiversity	X	X	X	X	X	X

Table 2.2. Comparison of Sustainability Guidelines by Organization (Continued)

Organization	Roundtable on Sustainable Biomaterials (RSB)	International Sustainability and Carbon Certification (ISCC)	Council on Sustainable Biomass Production (CSBP)	California Energy Commission	Roundtable on Sustainable Palm Oil (RSPO)	Global Bioenergy Partnership (GBEP)
Guideline Overview	• 12 Sustainability Principles • 1-7 Criteria Per Principle • 7 of 12 principles describe environmental sustainability • Requires measurements that are subject to baseline comparisons	• 6 Sustainability Principles •6 – 24 criteria per principle •Altogether 96 indicators •2 of 6 principles describe environmental sustainability •Requires measurements that are subject to baseline comparisons	• 9 Sustainability Principles • 1-5 Criteria per Principle • 1-8 Indicators per Criterion • 6 of 9 principles describe environmental sustainability • Requires measurements that are subject to baseline comparisons	• 3 Sustainability goals (environmental and economic) • 11 Criteria • 2 of 3 goals describe environmental sustainability • Requires measurements that are subject to baseline comparisons	• 8 Sustainability Principles • 1-8 Criteria per Principle • 1-10 Indicators per Criterion • 4 of 8 principles describe environmental sustainability • Requires measurements that are subject to baseline comparisons	• 24 Sustainability indicators (environmental, social, and economic) • 8 of 24 indicators describe environmental sustainability
Comments	• Only specific operators (facilities) in supply chain must comply with certain criterion	• Separate certification for every step of process (every facility) in supply chain.	• Certification scheme and sustainability standards still being developed.	• Incentive program that provides funding for biofuel projects • Not a certification or regulatory program	• Separate certification for every step of process (every facility) in supply chain.	• Sustainability indicators for international and national development and implementation of sustainability policy. • Not a certification or regulatory program
Motivation for Organization	• Compliance with RED. • "Ensuring that biofuels deliver on their promise of sustainability"	• Compliance with RED • "Ensuring that all feedstock is fulfilling sustainability requirements, regardless from the end-market where feedstock is used"	• Ensure that "Fledgling biofuel industry" develops in a sustainable manner	• California Health and Safety Code Section 4427 : "[Alternative fuel projects] will not adversely impact natural resources, especially state and federal lands"	• Palm oil is the vegetable oil produced in the greatest quantity(~30% of all vegetable oil) • RSPO strives to ensure that producers developed in a sustainable manner	• G8 in the 2005 adopted the Gleneagles Plan of Action "to support biomass and biofuels deployment, particularly in developing countries where biomass use is prevalent"

2.3.3. International Sustainability and Carbon Certification (ISCC)

The scheme International Sustainability and Carbon Certification is a voluntary multi-stakeholder scheme operating on a global level. Following the multi-stakeholder approach, ISCC has developed a broad standard covering environmental and social sustainability for all types of biomass. Life cycle calculations must follow the guidance of the "GHG Emissions Calculation Methodology and GHG Audit" document provided by the ISCC.

In 2011, ISCC was one of the first certification schemes approved by the European Commission and may be used to market biofuels in the EU. Even though the ISCC standard goes beyond the EU RED minimum requirements, it is one of the most commonly used schemes for biofuels. As of January 2014, more than 4,800 ISCC certificates have been issued (ISCC 2014a).

The guidelines on GHG calculation indicate the steps in the fuel cycle and general calculation approach, which are based on the methodology provided by the EU RED. Analyses include comprehensive actual input data and life cycle inventory "emission factor standard values". The ISCC methodology provides disaggregated life cycle GHG emission results, which are part of the certification audit. As of December 2014, 31 certification bodies are recognized by ISCC for the certification audit (ISCC 2014b).

2.3.4. Council on Sustainable Biomass Production (CSBP)

The Council on Sustainable Biomass Production (CSBP) is developing a similar sustainability framework to the RSB's, but CSBP focuses on biomass produced in the U.S. for biofuel and electricity production. The CSBP is a non-profit NGO based in Sacramento, California. CSBP stakeholders include farmers, environmental and social interests, forestry, and other sectors. CSBP includes 17 members and two government institutions for support. Certification will require a third party CSBP-accredited auditor to audit producers' results against their standards, but the CSBP framework is still developing. Currently, they are developing the energy and emission analysis for biomass and addressing the co-product treatment. Their latest draft of environmental principles, criteria, and indicators was published on their website in 2011.

2.3.5. Government Grants and California Energy Commission's AB 118 Programs

Government grant applications for biofuels contain sustainability provisions that require consideration of impacts beyond energy use and emissions. The provisions of the grants are generally consistent with the policy initiatives discussed in Section 2.2. However, each grant provides a separate set of guidelines. The Department of Energy (DOE), California Energy Commission, and other agencies have provided several hundred million dollars for the development of biofuels; other state agencies have similar programs with lower funding levels. Many DOE projects are administered by the Energy Efficiency and Renewable Energy (EERE) program. The California Energy Commission provides California AB 118 funds for alternative fuel projects.

The Energy Commission has developed an incentive program as required by California Assembly Bill (AB) 118 to promote the sustainable production of biofuels. Biofuel producers are required to follow the Commission's sustainability guidelines for funding. The Commission's primary purpose is to help implement the California's Health and Safety Code Chapter 44271, which requires that the Energy Commission "Establish sustainability goals to ensure that alternative and renewable fuel and vehicle deployment projects, on a full fuel-cycle assessment basis, will not adversely impact natural resources, especially state and federal lands…[and] establish a competitive process for the allocation of funds for projects funded pursuant to this chapter."

A public investment fund of $1.5 billion is allotted with a yearly budget to two different biofuel incentive programs, the Alternative & Renewable Fuel and Vehicle Technology Program, and the Enhanced Fleet Modernization and Air Quality Improvement Program. By applying for the AB 118 grant and complying with the sustainability standards provided by AB 118, a California biofuel producer can be granted funding. Current funded projects include commercial vehicle demonstrations and deployment, vehicle manufacturing, fuel production and research of innovative technologies. The AB 118 program requires GHG calculations using CA-GREET or equivalent methods. While other sustainability principles are being discussed, the Energy Commission is still determining how additional principles will be incorporated into the AB 118 program. The program provided a guidance document for addressing the sustainability of fuels (McKinney 2010). The guidance document addresses environmental and social sustainability issues. Participation in a certification program is one of the preferred methods of verifying sustainability in response to these procurements.

2.3.6. Round Table on Sustainable Palm Oil (RSPO)

The Round Table on Sustainable Palm Oil (RSPO) is a well-established voluntary global initiative similar to the RSB, but focusing only on palm oil. The RSPO was formed in response to the rapid increase in palm oil production in the previous two decades to meet the growing global demands for vegetable oil. Palm oil represents the largest portion (~30%) of any vegetable oil in the bio-oil market. The RSPO's headquarters is located in Zurich, Switzerland, though their stakeholders are mostly in Malaysia and Indonesia. The RSPO has 712 members in 52 countries. They published their first draft of sustainability guidelines in 2005 and their latest draft in 2007. The RSPO certification process relies upon an RSPO approved independent certification body to document compliance with their sustainability guidelines. The RSPO's certification is then audited by a third party according to the International Organization for Standardization (ISO) Guide 65/66 requirements for verification.

2.3.7. Global Bioenergy Partnership (GBEP)

Policy makers, scientists and the Food and Agriculture Organization (FAO) developed the Global Bioenergy Partnership (GBEP) as an international forum for developing sustainable bioenergy policy framework. GBEP's secretariat team is located is Rome, Italy, and their work focuses on sustainable development of biofuels in developing countries. GBEP provides stakeholders with a useful framework for assessing bioenergy production pathways, informing policy decisions, and monitoring the impact of the framework over time. GBEP has members from 23 countries (including the U.S.) and 13 international organizations and institutions. They have an additional 22 countries and 11 international organizations and institutions partnering as observers. GBEP offers guidance for using their sustainability indicator methods for collecting data and conducting life cycle analysis on a national scale and working with other countries to build consensus on sustainability criteria and evaluation methods. GBEP has developed 24 sustainability indicators for national-level bioenergy production, including three pillars (environmental, social and economic) of 8 criteria each. GBEP also provides detailed categories for data collection.

2.4. Other Environmental Certification Programs

The following certification programs do not give sustainability ratings or minimum thresholds for sustainability; they provide guidelines for how life cycle assessments should be completed. By using these programs, the fuel producer is certifying the life cycle assessment. Upon certification, an environmental declaration, in accordance with ISO standards, can be put on the label of the product. The advantage of using a certified method for life cycle assessment is that products' environmental impacts are more easily compared.

2.4.1. Environmental Product Declarations (EPDs) and Product Category Rules (PCRs)

An environmental product declaration (EPD) is a product label based on information about the product's life cycle assessment; it can be thought of as an ecolabel or a climate declaration to allow purchasers to understand the environmental performance of a product. An EPD is comparable to a nutritional facts label on a food product, only the "nutritional" information pertains to the environment rather than to the consumer. The purpose of EPDs is to provide a transparent, standardized framework or "language" to facilitate communication of environmental impacts associated with products. The target audience for EPDs is primarily downstream product users, converters and manufacturers, and other interested parties, such as OEMs and retailers.

An EPD usually includes multiple environmental criteria recommended by the ISO, i.e. GHG emissions, energy use, waste generation, recycled materials content, depletion of stratospheric ozone layer, use of fossil energy resources, and use of mineral resources (Schenck 2010). Any producer can obtain an EPD for its product. Currently, France is requiring EPDs on all high volume consumer products, as well as imports of high volume consumer products (Schenck 2010). EPDs allow consumers to understand the environmental performance of the products they are purchasing. The overall goal of EPDs is to "provide relevant, verified, and comparable information about the environmental impact from goods and services" (IEC 2012). The International EPD Consortium (IEC) is a global non-profit organization that is the program coordinator for the international EPD system, and they will assist in the process of product category rules (PCR) development. The process for obtaining an EPD for a product includes the following steps:

1. Locate the Product Category Rules (PCRs) on the IEC website. The PCRs define guidelines for data collection and calculations. If a PCR hasn't already been registered for

the product category, then a new one must be created. Further information on PCRs is given below.

2. Product process data are collected and calculated according to the PCR. The life cycle analysis information is compiled.
3. The EPD is verified by a third party. Both individual and certification bodies are available as verifiers. A list of verifiers can be found on the IEC website.
4. The EPD is registered with the IEC. A climate declaration is published on their website for an international audience.
5. The registration fee for the EPD is paid for in the amount of €1,000. If more than one product is registered, then a discount is provided. The IEC also has an annual fee.

The product categories from the United Nations Central Product Classification (UN CPC) system include energy, food, machinery and applications, metal, rubber, plastics, glass, chemicals, services, textiles and furniture, wood, and paper. The UN CPC system is used by the IEC to develop basic PCR modules for product categories. In other words, a basic PCR module gives guidelines for how a LCA should be performed (based on ISO guidelines).

Table 2.3 compares the two types of environmental declarations: the PAS 2050 and EPD/PCR certification program. Each product is categorized using the UN CPC system to give more specific PCR. For example, the system boundaries and the functional units used for different product types vary (e.g. crude oil vs. vegetable product), and the PCRs reflect these differences so that the LCA is product specific. PCRs and EPDs already in place can be found on the IEC website.

PCRs are defined by the IEC as "a form of guidance and rules for the collection of data and other information, how the calculations should be done to transfer the data to the climate impact and how this information should be presented." If a PCR has not already been developed for a product, then the creation of one is possible. Each product should have its own PCR, and a PCR module gives guidelines for PCR development. PCRs are created for products using relevant ISO standards. The life cycle analysis standards, which include requirements and guidance for life-cycle assessments, are ISO 14040 and 14044, and the environmental declaration standard for principles and procedures is ISO 14025. The PCR creation is an open-process in order to give all stakeholders an opportunity to comment and be involved in the PCR development.

Stakeholder led environmental product declarations (EPD) could provide a parallel option for monitoring the sustainability of renewable jet fuels. EPDs could involve a process similar to the RSB or CSBP, which have broad participation of feedstock and fuel producers, government agencies, and environmental groups. Alternatively, EPDs for jet fuel could include a more limited participation of environmental groups. The aviation industry could determine procedures for sustainability and request input from environmental groups. This organizational structure might be viewed as less rigorous than the structure for sustainability certification organizations.

Table 2.3. Features of the EPD/PCR and PAS 2050 Product Certification Programs

Rating System	EPDs and PCRs	PAS 2050
Organization	International EPD Consortium	British Standard Institution
Scope	Multiple Environmental Criteria	GHG Emissions
Product Classification	Uses UN Central Product Classification System	Uses "supplementary requirements"
Basis for Guidelines	ISO14025, ISO 14040, ISO 14044	ISO 14021, ISO 14040, IPCC
Carbon Balance	Biogenic	No carbon neutral biomass for products
Publication of Results	Required For EPD registration	Not Required
Certification	Yes	Not by BSI, available from Carbon Trust
Audience	International, any product	International, any product
Cost of Use	Free use and creation of PCRs, €1000 Fee for EPD registration	Free to use guidelines, cost probably associated with certification
Auditing Facility	More difficult to audit because PCRs are product specific and may change	Easy to audit because many companies use these guidelines
Pros:	PCRs include multiple environmental criteria; PCRs are product specific so may better reflect reality of the LCA.	Generally accepted method for life cycle analysis already in place. Comprehensive study of GHG emissions.
Cons:	May need to create PCR for product, potentially a lengthy and difficult process.	Specific to GHG emissions, so no other environmental impacts are accounted for.
Additional Comments:	EPDs and PCRs can give more in depth environmental impact results. Stakeholder participation may be less broad than biofuel certification organizations.	PAS 2050 is like a general PCR specifically for GHG emissions.

2.4.2. Publicly Available Specification 2050 (PAS 2050)

The Publicly Available Specification (PAS) 2050 was created by the British Standards Institution (BSI) to standardize the method used in LCAs. According to the BSI,

> *The PAS 2050 was developed in response to broad community and industry desire for a consistent method for assessing the life cycle GHG emissions of goods and services…The PAS 2050 offers organizations a method to deliver improved understanding of the GHG emissions arising from their supply chains, but the primary objective of this PAS is to provide a common basis for GHG emission quantification that will inform and enable meaningful GHG emission reduction programs.*

The PAS 2050 provides general LCA guidelines that give step-by-step instructions of how to calculate any product's carbon footprint. The guidelines pertain only to greenhouse gas emissions, and do not account for other environmental impacts related to product production. Any entity can use the PAS 2050 method to calculate their product's carbon footprint. The PAS 2050 also discusses treatment of emissions from LUC, and it provides supplementary requirements for product LCA specificity. The process steps for calculation of greenhouse gas emissions are outlined below (PAS 2050 Guide):

1. Scoping – Determine product boundaries and create a flow chart of product life cycle
2. Data Collection – Collect activity and emissions data
3. Footprint calculations – Compile data according to functional unit
4. Interpreting footprint results and driving reductions – Identify processes that contribute most significantly to greenhouse gas emissions and identify reduction opportunities.

The PAS 2050 is based on ISO standards and standards established by the Intergovernmental Panel on Climate Change (IPCC). ISO 14021 describes standards for environmental labels and declarations and the ISO 14044 describes standards for life cycle assessments.

2.5. Programs for Aviation Fuels

The programs for sustainable feedstock, biofuel, and product certification address all of the sustainability impacts of aviation fuels from either a life cycle or supply chain perspective[7]. LCA models for transportation fuels address all of the likely attributes of feedstock production. Any new feedstocks could be modeled within existing modeling frameworks. LCA models also address all of the likely attributes of feedstock production. Yields and process inputs may vary for jet production, but the modeling frameworks are suitable for aviation fuels. Similarly, government regulations and sustainability standards for biofuels also address the site specific issues, although some feedstocks, such as forest material, are not covered by all regulations and standards.

[7] The effect of aviation exhaust emissions at high altitude has not been addressed in impact assessments.

3. Review of Existing Sustainability Rating Systems

This section provides an introduction to the concepts and methodology of life cycle assessment, a review of specific life cycle models and studies, a review of the literature applicable to the environmental sustainability impacts associated with the production of jet fuel, a comparison of life cycle model results, and a discussion of the challenges of performing life cycle analysis and adhering to sustainability guidelines.

3.1. Approaches to Fuel Life Cycle Analysis

3.1.1. Introduction to LCA

LCA is a technique used to model the environmental impacts associated with the production of a good. The product assessed can be anything manmade, from breakfast cereals to sneakers to drop in renewable jet fuel. LCA models assess environmental impacts upon a range of categories, including energy consumption, GHG emissions, criteria air pollution, eutrophication, acidification, water use, land use, and others. This is done by taking a full inventory of all the inputs and outputs involved in a product's life cycle. Environmental impacts may be generated whenever a material flow enters or exits the product system and affects the environment.

Most LCA models used for transportation fuels are spreadsheet-based and use a life cycle inventory (LCI) database to calculate the environmental impacts associated with the material flows and inputs to a fuel value chain. Additionally, LCA can be used to support fuel regulatory and/or legislative initiatives for renewable fuel targets, such as targets for GHG emission reductions. The phases of an LCA are outlined below.

a) The goal and scope definition phase: during this phase the study objective is defined, the system boundaries are determined, and modeling approaches are decided upon.
b) The inventory analysis phase: during this phase, inventory data regarding the life cycle inputs and outputs is collected and analyzed.
c) The impact assessment phase: during this phase, life cycle inventory data and impacts results are scrutinized for further accuracy and insight. This often involves sensitivity analysis and can lead to additional data collection and inventory modeling.
d) The interpretation phase: during this phase, results are interpreted, summarized, and discussed. (ISO 14044)

The system boundary defines the approach to the analysis and it ensures a consistent treatment between the case analyzed and the reference case to. Diagrams are used to identify which inputs and material flows are included in the accounting framework and which occur outside the scope of the analysis. Figure 3.1 identifies the system boundary for the 'general' biofuel pathway.

Process flow diagrams are often used to identify which inputs and material flows are included in the accounting framework and which fall outside of the system boundary. Figure 3.1 identifies the system boundary for the 'general' biofuel pathway.

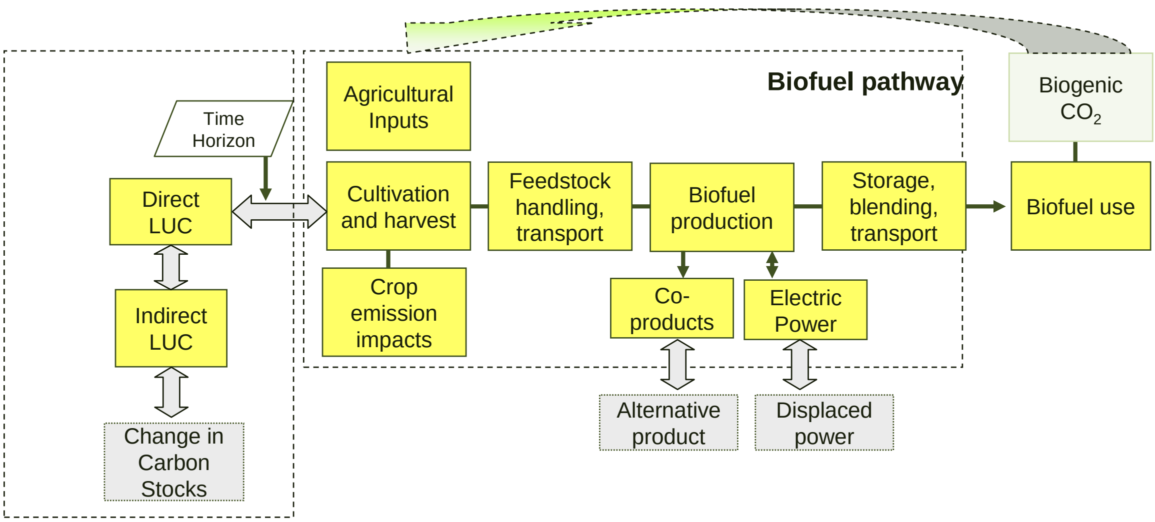

Figure 3.1. The System Boundary Diagram Identifies the Inputs and Material Flows in an LCA.

3.1.2. Carbon Footprinting

Carbon footprinting is a general term for the calculation of total GHG emissions resulting from a product's life cycle. It is essentially the performance of an LCA but with only one impact category included. Carbon footprinting has become popular in recent years as a method for demonstrating sustainability, quantification of emissions being the first step towards reduction. However, the comparison of carbon footprints between products can be misleading since different carbon footprinting methodologies may result in significant differences in emissions and/or impacts due to inconsistencies across methods.

Questions of scope are of primary importance. While in theory a carbon footprint should include all life cycle emissions, the placement of life cycle boundaries may differ between methodologies. In particular, different methods may have different views on whether to include the use stage of "active products" like cars or electronics. Cut-off criteria for upstream inputs may also differ, resulting in some analyses including more indirect emissions than others (Weidema, 2008). The time horizon for stored carbon is also a significant consideration that could affect biofuel pathways. For example, the treatment of biogenic uptake for forests converted to either stored products or fuels differs with different methods (Brandao, 2011). The question of time accounting applies to both direct conversion of biogenic carbon as well as indirect LUC (Kendall, 2009).

In considering questions of scope, it can be helpful to divide the emissions resulting from a product's life cycle into different categories. The Greenhouse Gas Protocol divides these into Scope 1, 2, and 3.

Scope 1: Direct Emissions- This refers to the emissions that occur at the production facility site from things like company vehicles, combustion sources, and fugitive emissions.
Scope 2: Energy Emissions: Scope 2 isolates all indirect emissions associated with purchased energy, such as electricity and steam.
Scope 3: Indirect Emissions from all other sources: Scope 3 encompasses all indirect emissions associated with the production of non-energy inputs, the disposal of wastes, and outsourced activities.

The carbon footprints from two studies that differ in scope will be impossible to compare. In order to qualify as a true life cycle GHG LCA according to ISO standards, it is necessary to include all up and downstream impacts. Some carbon footprints include only Scope 1 and 2 data, since the data needed to calculate scope 3 emissions are typically the most challenging to obtain. However, it has been shown that Scope 3 emissions are usually the most substantial portion of a given product's life cycle impacts. Using an economic input-output LCA modeling approach, Matthews et al. found that for the average U.S. economic sector, emissions from scopes 1 and 2 accounted for only 26% of total life cycle climate change impacts, leaving the majority unaccounted for with these boundaries.

Since greenhouse gases remain in the atmosphere for many years and continue to have a warming effect for decades or even centuries to come, questions arise about how to account for time delays in GHG impacts. Most models report impacts in terms of CO_2-equivalents over a 100 year horizon, but this minimizes or ignores longer-term impacts beyond one century (Brandau et al, 2011). IPCC publishes 500-year horizon CO_2 equivalents, but any LCA method incorporating these would find that its climate change impacts dwarf both all other impact categories and the results of other carbon footprinting methods.

Another problem is the question of how to quantify the benefits of carbon sequestration and delayed emissions over the long-term. In 2008, the British specification PAS 2050 for carbon footprinting proposed an approach for calculating short- and long-term benefits from carbon sequestration and required that credits be given for these activities BSI, 2008). The revised PAS 2050 as of 2011 requires that carbon storage benefits be given only for storage that will last over 100 years (BSI, 2911). However, the European Commission's (2010) ILCD Handbook does not award credit to the carbon balance for short-term carbon storage. Long term emissions occurring after 100 years are to be considered a separate life cycle impact category and are inventoried and reported separately from the general impact assessment results.

3.1.3. Biogenic Carbon Balance

The carbon that is removed from the air by the feedstock during its growth phase is referred to as biogenic carbon. Many models make the assumption that the amount of carbon uptake is equal to the amount emitted during the agricultural production phase of the life cycle and therefore consider feedstock production to be a carbon neutral process. The accounting method may vary.

In some models the fuel is shown as a positive emission and a credit is applied as indicated in Figure 3.1. In other approaches all biogenic carbon is treated as zero emissions. Some modeling approaches add to this the emissions from land conversion and indirect LUC.

The approach to system boundary definition varies among models and studies. For example, the ARB LCFS identifies the system boundary for each fuel case while the EPA RFS2 analysis (2010a) uses a catch-all system boundary diagram, similar to Figure 3.1 to reflect all biofuel pathways. EPA's approach falls short of clarifying the process inputs and treatment of co-products. This lack of definition is especially important since components of the fuel life cycle are based on macro-economic estimates, average values, and projections for marginal inputs.

Methods for carbon accounting differ between fuel policies, LCA models, certification standards, and other standards. Figure 3.2 illustrates different approaches for calculating the carbon balance of a fuel. The emissions from biofuel feedstock production are significant and often larger than total CO_2 emissions from fossil fuels. However, these emissions are offset by the uptake from the atmosphere. The carbon neutral plus LUC adder approach is typically adopted in fuel LCA and the reporting under the RFS2, LCFS, and RED. However, biogenic carbon still presents a reporting challenge. The GREET model, for example shows the biogenic carbon in fuel and a credit for its uptake. Researchers from the University of Michigan, argue that the full CO_2 emissions should be counted for biofuels and uptake credits should be assigned to national inventory accounting schemes (DeCicco, 2013). This approach eliminates the ILUC approach and shifts the burden of managing emissions to a national level approach.

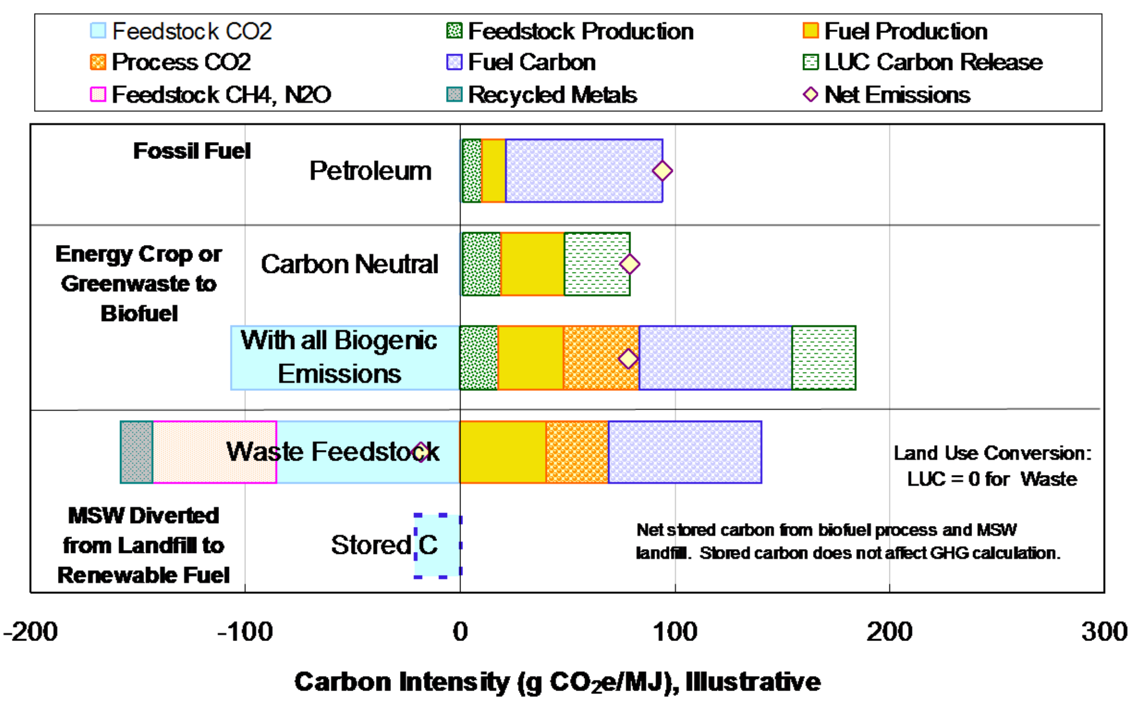

Figure 3.2. Different Carbon Accounting Approaches.

Accounting is further complicated when avoided emissions from landfills are taken into account. When feedstocks are diverted from landfills, methane and CO_2 emissions from landfills are avoided. However, some carbon is also stored in the landfill; so, the net carbon emissions may be higher when landfilled material is diverted to fuel production, but the GWP weighted emissions can be lower because methane emitted from landfills has a higher GWP than CO_2.

3.1.4. Attributional *vs.* Consequential LCA

LCAs can be broadly categorized as being attributional or consequential LCA. An attributional analysis "attributes" sustainability metrics to a fuel pathway. This type of analysis provides useful information about the total impacts of the processes used to produce a fuel, but it does not consider indirect impacts arising from production; attributional analyses only consider impacts occurring within a product's supply chain. An attributional LCA (ALCA) inventories and analyzes the direct environmental effects of some quantity of a particular product, including the direct effects of all required inputs and the direct effects of using and disposing of the product.

A consequential LCA (CLCA), in contrast, includes both direct *and* indirect effects of a production system, recognizing that all production is embedded within an economic system that adjusts in response to changes in production, and these adjustments produce additional environmental effects. Thus, consequential analysis includes both direct impacts occurring within a supply chain and indirect, market-induced changes occurring globally. CLCA is much larger in scope than ALCA and is accomplished with large uncertainty, due to the complexity of indirect impacts. The scope of CLCA includes total environmental impacts from fuel production (ALCA), plus all indirect effects that cascade over time resulting from economic effects.

3.1.5. Allocation *vs.* Substitution for Multiple Products

Properly attributing energy inputs and emissions to co-products is a significant concern for LCA because different attribution methods can lead to significantly different results for any given product or process. Handling co-products "properly", however, is challenging.

Different methods are used to attribute emissions to co-products in fuel LCA. These methods fall into two categories:

1. **Substitution (or displacement) Method**
   This approach estimates the first order market effects of producing co-products by subtracting from the LCA the impacts presumed to be avoided by substituting the co-products for other products that provide the same function.

2. **Allocation Method**
   This approach assigns a portion of the inputs and outputs within a production system among the various co-products based on either process simulations, or based on physical or economic attributes such as mass, energy content, or market value.

In general, a substitution method is preferable because it accounts for the life cycle of the fuel and the co-product, while an allocation method does not take into account the actual impact of the co-product (ISO 14040:2006). In the substitution approach, the LCA system boundaries are expanded to include the substitute product. Unfortunately, expanding the analysis can introduce additional uncertainty into the life cycle analysis of the original fuel product, and expansion may beget further expansion to address co-products of the substitute.

Using a substitution method to determine the life cycle of a fuel and co-product can yield widely differing results, especially when the amount of fuel and co-product are similar. The choice of which component is the fuel and which is the co-product drives this difference. In situations such as these, it is recommended that the allocation method be used, for consistency.

Each method encompasses benefits and weaknesses. The substitution method is considered accurate in that it calculates the environmental impact of the displaced product (Delucchi 2004, EPA 2010a,). However, the life cycle data for some products are not thoroughly examined in LCA models. Notably, the life cycle of paraffinic naphtha and lube oil base oils is treated by energy allocation in most models, even though these products have more complex life cycles (Forman 2011). The comparable treatment of N_2O emissions from U.S. crops and indirectly grown crops outside the U.S. is an issue with the EPA RFS2 approach. Determining the marginal impact of products is also an issue (Unnasch 2001). Finally, the substitution method can generate results that are dominated by co-products. This gearing effect accentuates the effect of displaced products like electric power (Larive 2008).

3.2. Literature and Model Review

Many studies examine the sustainability issues associated with fuel production and use. The studies identified and reviewed in the following sections are categorized according to the groupings indicated in Table 3.1, which provides an overview of the content of the studies. In some instances, the content of the studies is cross-cutting and the studies are identified under several categories.

Table 3.1. Categorization of Sustainability Literature

Category	Content
Life Cycle Analysis	Analysis of well to wheel energy inputs and emissions for various fuels and fuel pathways Methods for life cycle analysis including co-products and allocation procedures
Environmental Impacts	Global warming impacts, atmospheric concentrations of pollutants
Land Use Conversion, Indirect Effects	Agro-economic modeling, economic modeling, marginal effects
Carbon Stocks, Land Emissions	Carbon storage in Biosystems and soils. Emissions from land clearing and agriculture
Biodiversity and Sustainability	Categorization of biodiversity

3.2.1. Literature for Life Cycle Analysis Models, Studies, and Data

The literature on life cycle studies falls into several categories including model documentation, multi fuel studies, and single pathway studies. The objectives of the studies differ. Many of the multi fuel studies are funded to support research; others were commissioned to support fuel policy. The key difference among LCA studies is the treatment of co-products, land use conversion and to a lesser extent life cycle inventory data including methane emissions from oil and gas production

The documentation and issues with fuel LCA studies is described in a study by the Coordinating Research Council (Unnasch 2011). Each of the LCA models discussed is described by the developers as indicated in Table 3.2. Issues with co-products, system boundaries, and other factors are addressed to a limited degree in all of these studies. Unfortunately, there is no consensus on key LCA issues such as co-products, system boundaries, land use conversion, and many other parameters. Several studies from Argonne National Laboratory document the GREET model and inputs. The JRC in Europe has completed a series of studies examining fuels in the European context. The JRC study provides the basis for the BioGrace model. All of the models examine fuel pathways that are parallel to aviation pathways such as petroleum diesel, rapeseed HEFA, and biomass FT diesel. The documentation does not focus on aviation fuels but the analysis of on-road diesel is essentially the same as that of aviation fuels, with different yields and changes in energy inputs. Modifying the models for aviation pathways is straightforward assuming that data on energy inputs and yields are available.

Table 3.2. Fuel Cycle Models and Studies -Model Documentation

Primary Author	Year	Organization	Location of Use	Primary Feedstocks	Jet Type Fuels	End Use	Models
Delucchi	1998	UC Davis	US	Crude Oil Natural Gas Veg Oils Biomass	Diesel HEFA FT Diesel	DI ICEV	LEM
JRC	2011	JEC	Europe	Crude Oil Veg Oils Natural Gas Biomass	Crude Oil HEFA FT Diesel	DI ICEV	JRC/ LBST Database
Neeft	2012	Intelligent Energy Europe	Euprope	Crude Oil Veg Oils Natural Gas Biomass	HEFA FT Diesel	None	BioGrace
O'Conner	2011	(S&T)2	Canada	Crude Oil Natural Gas Veg Oils Biomass	Diesel HEFA FT Diesel	DI ICEV	GHGenius
Wang	1999	ANL	USA	Crude Oil Natural Gas Veg Oils Algae Biomass Coal	Diesel HEFA FT Diesel	DI ICEV	GREET
Wang	2011	ANL	USA				

Table 3.3 shows LCA studies covering a range of fuels. These studies support a range of policies including the RFS2. EPA documented the analysis for the RFS2 in an extensive regulatory impact analysis. Several studies support policies for California State agencies (Unnasch 2001, Pont 2007). The California ARB also documents fuel pathways for the LCFS. Studies led by MIT and by Boeing specifically examine aviation fuels using the GREET analysis framework. This study identifies the key differences in feedstock to fuel yield and other energy inputs for jet fuel compared to on-road diesel. The MIT study is based on GREET and the Boeing study relies on LCA databases. Again, the key differences in these studies are the treatment of co-products, LUC, and LCI data.

Table 3.3. Fuel Cycle Models and Studies – Pathway Comparison and Policy Support

Primary Author	Year	Organization	Location of Use	Primary Feedstocks	Jet Type Fuels	End Use	Models
ARB	2009a 2009b	ARB	CA	Crude Oil Veg Oils	Diesel HEFA	DI ICEV	CA-GREET
Brinkman	2005	GM/ANL	USA	Crude Oil	Diesel	DI ICEV	GREET
EPA	2010a	EPA	USA	Veg Oils Algae Biomass	HEFA FT Diesel	DI ICEV	GREET FASOM FAPRI
Kinder	2009	Boeing	Global	Biofuels	FT Jet HEFA Jet	Jet Aviation	Boeing Database
Pont	2007	TIAX	CA	Crude Oil Natural Gas Veg Oils Biomass	Diesel HEFA FT Diesel	DI ICEV	CA-GREET
Stratton and Hileman	2010	MIT	USA	Crude Oil Natural Gas Veg Oils Algae Biomass Coal	Jet FT Jet HEFA Jet	Jet Aviation	GREET
Unnasch	1996	Acurex	CA	Crude Oil Natural Gas	Diesel Various	DI ICEV	Database Calculation
Wallace	2001	GM/ANL	USA	Crude Oil	Diesel	DI ICEV	GREET

Table 3.4 summarized many of the LCA studies that focus on a single fuel pathway with applicability to either renewable or baseline petroleum aviation fuels. The studies include a range of feedstocks and fuel products. On-road transportation fuels are the focus of most of the studies. Nonetheless, they provide a great deal of detail on feedstock production and fuel conversion. Again the co-product methods and sources of LCI data are key differences among the studies. Some studies are based on process simulations or projections for future fuel production facilities. ARB requires fuel producers to publish their pathway documents to determine the CI und the LCFS. However, fuel producers normally do not show confidential data, including yields, power and process heat consumption. The results of LCA studies are summarized in Section 3.4.

Table 3.4. Fuel Cycle Models and Studies- Single Fuel Comparisons

Primary Author	Year	Organization	Location of Use	Primary Feedstocks	Jet Type Fuels	End Use	Models
Allen	2011	UT Austin	US	Algae Biomass Coal	Jet FT Jet	Jet Aviation	UT Austin Database
Clarens	2009 2113	U. Virginia	USA	Algae	HEFA	DI ICEV	SimaPro CA-GREET
Feng	2011	AFIT	USA	Crude Coal Biomass	Jet HEFA Jet	Jet Aviation	EIO LCA
Forman	2011	Sasol	CA	Natural Gas	FT Diesel	DI ICEV	GREET
Frank	2011	ANL	USA	Algae	HEFA HEFA Jet	DI ICEV Jet Aviation	GREET
Gärtner	2006	IFEU	Europe	Veg Oils	HEFA	DI ICEV	IFEU Database
Gerdes	2009	NETL	USA	Crude Oil	Diesel	DI ICEV	
Hennecke	2011	Abengoa	Europe	Biomass	Ethanol	None	Custom Tool
Huo	2008	ANL	USA	Veg Oils	HEFA	DI ICEV	GREET
Keesom	2009	Jacobs	CA	Crude Oil Bitumen	Diesel	DI ICEV	GREET Jacobs Petro Plan
Kinsel	2010	AFIT	USA	Crude Coal Biomass	Jet HEFA Jet	Jet Aviation	EIO LCA
Marano	2001	NETL	USA	Biomass Coal	FT Diesel	DI ICEV	N/A
Mungkalasiri	2012	NMMTC	Global	Algae Biomass Waste Lipids	HEFA	Jet Aviation	SimaPro
Rosenfeld	2009	TIAX MathPro	CA	Crude Oil Bitumen	Diesel	DI ICEV	GREET MathPro
Rye	2011	CSIRO	Australia	Algae	HEFA Jet	Jet Aviation	SimaPro
Sheehan	1998	NREL	USA	Soy Oil	Biodiesel	DI ICEV	NREL Database
Shonnard	2009	MTU	USA	Crude Oil Camelina	Diesel Petroleum Jet HEFA Jet	Jet Aviation	SimaPro7.1
Wang	2004	ANL	USA	Crude Oil	Diesel	DI ICEV	GREET

DI ICEV = Direct Injection Internal Combustion Engine Vehicle, FT = Fischer Tropsch, EIO LCA = Economic Input-Output Life Cycle Assessment

The approaches different among the studies in Table 3.4 both in terms of the input assumptions, LCI data, and co-product methods with notable differences in baseline petroleum pathways. Studies by Jacobs engineering (Kessom 2009, 2012) and Sasol (Forman 2015) apply a substitution analysis to co-products such as residual oil, and lubricants. The GREET model matches refinery data with process modeling (Wang 2004). MathPro uses a linear programming approach to identify the incremental impact of producing fuels. Most biofuel LCA studies allocate emissions to both diesel, jet, and naphtha used as fuels.

Table 3.5 shows studies that address LCA methods. The literature identifies the issues with co-products including details on the choices between substitution and allocation. Substitution is preferred over allocation but in instances where multiple fuel products are produced from the same process, the guidance is less clear.

Table 3.5. Life Cycle Assessment Guidance

Primary Author	Year	Organization	Topics
Allen, D.T.	2009	The Aviation Fuel Life Cycle Assessment Working Group	Framework and guidance for estimating greenhouse gas footprints of aviation fuels
Brander	2012	Econometrica	Dealing with substitution effects
Ekvaal, T.	2004	Chalmers University	System boundaries for consequential LCA
Guinee, J. B.	2009	Leiden University	Issues with system boundaries and co-products
Guinee, J.B.	2010	U. of Leiden: Institute of Environmental Science	Review of Life Cycle Assessments: Past, Present, and Future
ISO	2006a	International Standards Organization	Standards for life cycle assessment
O'Conner	2013	$(S\&T)_2$	Comparison of fuel LCA studies and uncertainty
Unnasch	2011	Life Cycle Associates	Review of LCA models, methods, and LUC.
Wang, M. Q.	2011a	ANL	Methods for treatment of co-products in LCA

3.2.2. Literature for Environmental Impacts due to Emissions and LCA Guidance

Emissions are a major focus of environmental impacts and LCAs of biofuel projects. Table 3.6 summarizes literature associated with emission impacts. These studies include results of GHG emissions from renewable fuels by Beer (2009) and Delucchi (2003), forest changes by Canadell, Crutzen, and Penman, and a review of environmental performance metrics by Schulze.

Table 3.6. Environmental Impacts: Emissions

Primary Author	Year	Organization	Topics
Beer, T.	2009	CSIRO Atmospheric Research	Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles
Canadell, J.G.	2008	Global Carbon Project	Managing forests for climate change mitigation
Crutzen, P.J.	1990	Max Plank Institute, Germany	Biomass burning in the tropics: impact on atmospheric chemistry and biogeochemical cycles
Delucchi, M.	2003	UC Davis: Institute for Transportation Studies	A Lifecycle Emissions Model (LEM): Emissions from Transportation Fuels, Motor Vehicles, Transportation Modes, Electricity Use, Heating and Cooking Fuels, and Materials
Grassl, H.	2007	Max Plank Institute	Climate forcing of aviation emissions.
Penman, J.	2003	Intergovernmental Panel on Climate Change	Definitions and methodological options to inventory emissions from direct human-induced degradation of forests and DE vegetation of other vegetation types
Schulze, P.C.	1999	National Academy of Engineering	Measures of environmental performance and ecosystem condition
Unnasch	2001	Arcadis	Toxic air contaminants, criteria pollutants
Wang	2000	ANL	Toxic air contaminants, criteria pollutants

3.2.3. Literature for Land Use Conversion: Indirect Effects

The issue of indirect LUC is still a matter of significant debate. Clearly the use of arable land makes the land unavailable for other cropping purposes. However, special situations such as marginal land, cover crops, and double cropping make the assessment of indirect LUC challenging. EPA and the California Air Resources Board (ARB) have made LUC analyses of major feedstocks such as corn, soybean oil, and sugarcane. The treatment of cover crops is less well defined under these programs. The EU incorporated indirect LUC into the RED.

The appropriate approach for modeling indirect land use conversion GHG impacts is a hotly debated topic. Direct land use change is the conversion of grass or forestland to cropland intended for the production of biofuel feedstocks. Indirect land use change occurs when grass or forestland ends up being converted to agriculture to meet constant demand for crops that are now going to biofuel production. Indirect land use change may occur anywhere on the globe. In order to estimate the GHG impacts of this effect, modeling must be performed to predict where the resulting land conversion will take place, and what quantity of land will be converted to what crop. There is great uncertainty inherent in this process, and the use of a different iLUC model, or the lack of iLUC inclusion, can result in very different life cycle carbon footprint results.

The RFS, LCFS, and RED have all developed LUC analysis which are added to the FTW results for biofuels. Some of the LUC results are similar, even though the details vary. For example, the

EU assigns 55 g CO_2e/MJ for vegetable oils (IPFRI) and the result for the LCFS for soy oil based biofuels is 62 g CO_2e/MJ (ARB 2009). These LUC results could be higher with lower feedstock to aviation fuel yields. A contrasting result is provided by EPA for diesel and aviation fuels from camelina. EPA assumes that the camelina will be grown as a cover crop and therefore the LUC will be zero. EPA would reassess the zero LUC if actual production practices differ.

The issue surrounding LUC has not settled towards consensus. Recently a working group of ISO 13065 could not find consensus on the treatment of indirect effects. The workgroup will not prescribe specific methodologies for sustainability indicators with the exception of GHG emissions (Kline 2013).

These studies apply various approaches to determine the land that is indirectly converted by the use of, primarily, food crops such as corn, soy, and canola. However, non-food crops such as switchgrass are also grown on arable land and therefore result in soil carbon storage. Cropping could take place on marginal land and not displace food crops; so, many different GHG scenarios are possible for biomass feedstocks. The indirect effect of agriculture on land clearly needs to be part of a GHG analysis if the results are to be considered meaningful and consistent with fuel policies such as the RFS2.

Table 3.7 focuses on the indirect effects associated with land use conversion. Of particular note are the modeling studies that examine LUC by Kloverpris and Tyner, and comparisons of different LUC modeling approaches by Sanchez.

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Table 3.7. Land Use Conversion and Indirect Effects

Primary Author	Year	Organization	Topics
Bauen, A.	2010	E4tech	A causal descriptive approach to modeling indirect land use change impacts of biofuels
Brander, K.M.	2007	International Council for the Exploration of the Sea	Global fish production and climate change
Broch, A.	2012	Desert Research Institute	Comparison of LUC approaches and N_2O emissions
Chalmers, J.	2011	Winrock International	Biofuels and indirect land use change: challenges and opportunities
Cornelissen, S.	2009	Ecofys	Summary of approaches to accounting for indirect impacts of biofuel production
Delucchi, M.	2004	UC Davis: Institute of Transportation Studies	Conceptual and methodological issues in lifecycle analysis of transportation fuels
Edwards, R.	2010	JRC, Italy	Comparative modeling of biofuel impacts using indirect land use modeling including GTAP, FAPRI, CAPRI, and others.
Fritsche, E.	2009	Oeko-Institut, Germany	Direct and indirect land-use competition issues for energy crops and their sustainable production- an overview
Golub, A.	2013	Purdue University	GTAP model of LUC and co-products.
Gnansounou, E.	2008	Laboratoire des systèmes énergétiques, Switzerland	Accounting for indirect land-use changes in GHG balances of biofuels.
Keeney, R.	2009	Purdue University: Dept. of Agriculture	The indirect land use impacts of United States biofuel policies: The importance of acreage, yield, and bilateral trade responses
Kloverpris	2008	Novozymes	Modeling indirect land use change with the GTAP model
Lapola, D	2010	U. of Kassel, Germany	Indirect land-use changes can overcome carbon savings from biofuels in Brazil
Liska, A.J.	2009	U. of Nebraska	Indirect land use emissions in the life cycle of biofuels: regulations versus science
Lywood, W.	2009	Ensus Ltd.	Modeling of GHG emissions from indirect land use change from increased EU demand for biofuels
Marklund, L.G.	2008	UN Food and Agriculture Organization	FAO datasets on land use, land use change, agriculture and forestry and their applicability for national greenhouse gas reporting
Marshall, E.	2011	U.S. Dept. of Agriculture	Measuring the indirect land-use change associated with increased biofuel feedstock production: a review of modeling efforts
Pearson, T.	2005	Winrock International	Sourcebook for land use, land-use change, and forestry projects

Table 3.7. Land Use Conversion and Indirect Effects (Continued)

Primary Author	Year	Organization	Topics
Plevin, R.J.	2008	UC Berkeley: Energy and Resources Group	Greenhouse gas emissions from biofuels' indirect land use change are uncertain but may be much greater than previously estimated
Post, W.M.	2000	Oak Ridge National Laboratory, TN	Soil carbon sequestration and land-use change: processes and potential
Reinhard, J.	2009	Technology and Society Lab, Switzerland	Global environmental consequences of increased biodiesel consumption in Switzerland: consequential life cycle assessment
Ros, J.P.M	2010	Netherlands Environmental Assessment Agency	Identifying the indirect effects of bio-energy production
Sanchez, S.T.	2011	Life Cycle Associates	Accounting for indirect land-use change in the life cycle assessment of biofuel supply chains
Searchinger, T.	2008	Princeton University, Woodrow Wilson School	Use of U.S. croplands for biofuels increases greenhouse gases through emission from land use change
Tipper, R.	2009	Ecometrica and Green Energy	A practical approach for policies to address GHG emissions from indirect land use change associated with biofuel
Tyner, W.	2010	Purdue University: Dept. of Agriculture	Land use changes and consequent CO_2 emissions due to U.S. corn ethanol production: a comprehensive analysis
Unnasch	2014	Life Cycle Associates	Review of economic models that predict land conversion component of LUC

3.2.4. Literature for Carbon Stocks and Land Emissions

Carbon stocks, including forest and soil carbon, are important to consider in the carbon accounting of agricultural production. Cutting down a forest and replacing it with a farm may release the carbon stored in the trees and plants into the atmosphere. Additionally, deforestation prevents the land from sequestering more CO2 from the atmosphere. While the biofuel feedstock will sequester carbon, most of that carbon is rereleased into the atmosphere when the finished biofuel products are consumed. The following studies listed in

Table 3.8 address carbon stock emissions factors, such as those from Harris and ICF. Other studies give models and estimates of carbon stocks in forests, such as those by Gibbs and Goetz. Houghton addresses the changes in the net flux of carbon due to land use change. Soil carbon stocks are addressed by Anderson-Teixeira (2009), Guo, and Schlesinger.

Table 3.8. Carbon Stock and Land Emissions Analysis

Primary Author	Year	Organization	Topics
Anderson-Teixeira, K.J.	2009	U. of Illinois: Energy Biosciences Institute	Changes in soil organic carbon under biofuel crops
Adams, D.M	1996	USDA: Forest Service	The forest and agriculture sector optimization model (FASOM): model structure and policy applications
Eggleston, S.	2006	Intergovernmental Panel on Climate Change	Guidelines for national greenhouse gas inventories
Fargione, J.	2008	The Nature Conservancy	Land clearing and the biofuel carbon debt; analysis of the greenhouse gas savings of biofuel production
Gibbs, H.K.	2007	U. of Wisconsin: Center for Sustainability and Global Environment	Monitoring and estimating tropical forest carbon stocks
Goetz, S.J.	2008	Woods Hole Research Center	Mapping and monitoring carbon stocks with satellite observations: a comparison of methods
Guo, L.B.	2002	Oak Ridge National Laboratory, TN	Soil carbon stocks and land use change: a meta-analysis
Hertel, T.	2010	Bioscience	Global Land Use and Greenhouse Gas Emissions Impacts of U.S. Maize Ethanol: Estimating Market-Mediated Responses
Harris, N.	2009	Winrock International	Land use change and emission factors: updates since the RFS proposed rule.
Houghton, R.A.	2003	Woods Hole Research Center	Revised estimates of the annual net flux of carbon to the atmosphere from changes in land use and land management 1850-2000
ICF	2009	ICF International	Emissions from land use change due to increased biofuel production: satellite imagery and emissions factor analysis
Lim, B.	1999	Winrock International	Carbon accounting for forest harvesting and wood products: a review and evaluation of different approaches
Marshall, L.	2009	World Resources Institute	Biofuels and the time value of carbon: recommendations for GHG accounting protocols
Olson, J.S.	1983	Oak Ridge National Laboratory, TN	Changes in the global carbon cycle and the biosphere
Schlesinger, W.H.	2000	Duke University	Soil respiration and the global carbon cycle

3.2.5. Literature for Biodiversity, Water, and Soil

The environmental effects that can impact biodiversity, water, and soil must be addressed for biofuel production sustainability because land use changes affect biodiversity, and biofuel projects affect water supplies and soil health. Studies on the environmental effects of biofuel production on biodiversity, water and soil are listed in Table 3.9. Biodiversity modeling and quantification, such as the use of mean species abundances (MSA), are addressed in studies by Alkemade (2009), Soulé (2006), and ten Brink (2007). Other studies discuss how biodiversity is affected by land use change and population. Water studies include those of water use calculations by Wu (2011a, 2011b) from the Argonne National Laboratory. The soil studies provide information about quantifying soil health (soil indexing) by Andrews (2001) and soil sustainability by Doran (2000) and Rigby (2001). Section 4 provides greater detail on these multimedia impacts.

Table 3.9. Water, Soil, and Biodiversity.

Primary Author	Year	Organization	Topics
Biodiversity			
Alkemade, R.	2009	Globio	Framework for modeling human impacts on biodiversity
Dale, V.H.	2010	Ecological Society of America	Biofuels: Implications for land use and biodiversity.
Soulé, M.	2006	J. of California Agriculture	Biodiversity indicators in California: taking nature's temperature.
ten Brink, B.J.E.	2003	Ministry of Transport and Public Works, The Netherlands	A quantitative method for description & assessment of ecosystems: The AMOEBA-approach
Tilman, D.	1996	U. of Minnesota	Biodiversity: population versus ecosystem stability
Zedan, H	2000	Convention on Biological Diversity	International treaty with respect to biodiversity. Strategic plan for promoting biodiversity.
Water			
Wu, M.	2011	Argonne National Laboratory	Calculating water consumption and water withdrawal for petroleum and bio-based fuels using the GREET model.
Wu, M.	2011	Argonne National Laboratory	Calculating water consumption and withdrawal for electric power generation using the GREET model
Soil Health			
Andrews, S.S.	2001	USDA	A comparison of soil quality indexing methods for vegetable production systems in Northern California.
Doran, J.W.	2000	USDA	Soil health and sustainability: managing the biotic component of soil quality
Rigby, D.	2001	U. of Manchester	Farm level indicators of sustainable agricultural practice

3.2.6. Literature for Sustainability Indicators and Certification

In order to confirm or deny the sustainability of a practice, product, or business, the indicators associated with the project must be fully understood and taken into account. Traditionally, indicators refer to measurable environmental or social aspects that specify the wellbeing of an area. Examples of indicators include cancer rates, education levels, and water quality of a specific county. Indicators even include economic interactions like stockholder profits and materials for production. Sustainability indicators, however, are much more broad. They take into account not only the specific indicators but also the way indicators affect each other and are affected by each other. For example, rather than looking at cancer rates, education levels, and water quality of a specific county individually, the focus would be on the relationship between the three indicators and how they interact with each other. Sustainability indicators reflect the truth that these seemingly unrelated indicators are in fact extremely interconnected. The multidimensional analysis of indicators and their effects has led to the implementation of standards and the creation of certifications.

Studies that incorporate indicators and/or certifications are listed in Table 3.9. Reports that focus mostly on sustainability in jet fuels include Novelli's (2013) and Futurepast's report (2012). Reports on separate topics also provide valuable definitions, explanations, and examples of sustainability indicators and certifications. The environmental indicators and effects of changes in the U.S. food system are addressed by Heller (2000). Although not about jet fuel, this report utilizes tables and literature to accurately and clearly describe sustainability indicators.

Table 3.10. Sustainability Certification and Indicators

Primary Author	Year	Organization	Topics
Indicators			
Efroymson, R.A.	2012	Environmental Management	A look at the sustainability of biofuel production and its environmental indicators
Heller, M. C.	2000	University of Michigan	The recent changes in the US Food System and the indicators resulting from these changes
Novelli, P.	2013	ICAO	Explores sustainable alternative aviation fuel and describes the definition of sustainability indicators in regards to jet fuel
UNEP	2011	UNEP	How to use a life cycle assessment to create a life cycle sustainability assessment
Zhou, Z.	2006	Elsevier	Defines indicators and breaks them down into four categories
Certification			
Futurepast	2012	Futurepast: Inc.	Evaluation and definition of sustainability in alternate aircraft fuel supply chain
Guariguata, M. R.	2011	CIFOR	An overview and critique of the governmental certification system
Sheehan, J. J.	2009	Elsevier	Connects sustainability in biofuels to social and political implications
Yeh, S.	2009	University of California, Davis	Discusses the requirements for the California Low Carbon Fuel Standard and the criteria and principles revolving around the regulation.

3.3. Life Cycle Models and Studies

Fuel LCA models facilitate comparison of the environmental impacts associated with transportation fuel production because a consistent application of assumptions for all of the inputs and processes in the fuel supply chain is used. Furthermore, fuel LCA models support developments in new transportation technologies and government fuel policies.

The life cycle models that have been used to address the CI component of sustainability are listed in Table 3.11 along with the version of the LCA model reviewed. In most cases, these are the most recent versions of the models. While the CI is the most commonly measured environmental impact for LCA, the models below also include additional environmental criteria. However, there is no consensus among model developers for the treatment of some of these additional environmental impacts, so the analysis of air pollutants, water use, soil health, and biodiversity is still a growing and advancing area of study.

Table 3.11. Versions of LCA Models Reviewed

Model/Study	Version Year
GREET_1	2012
CA-GREET 1.8b	2009
BioGrace v4 public	2012
GaBi v5	2011
LEM	2006
GHGenius 3.15	2009
MIT AFRL/ GREET	2010
LCA LCM	2012

Table 3.12 shows the model application and the region in which it was used, various modeling assumptions, and the allocation method applied to co-production of naphtha and electricity, the dominant fuel co-products from jet fuel production.

Table 3.12. Summary of Select Fuel LCA Modeling Studies.

Model/ Study	Applicable Region	Co-product Method		ILUC Modeling	Agricultural Emissions	Prior Land Use Requirements
		Naphtha	Electric Power			
EPA RFS2, GREET	U.S.	Allocation	Substitution, U.S. average	FASOM, FAPRI	FASOM plus IPCC Tier 1	No conversion of forest. Land must be in Ag use.
LCFS, CA-GREET 1.8b	California	Allocation	Substitution, CA marginal	GTAP	IPCC Tier 1	None
RED, BioGrace v3	Europe	Allocation	Substitution, Biomass power	MIRAGE (GTAP database)	Nitrogen model predictions	No conversion of crop land.
GaBi v5	Global	Variable	Substitution, variable	None	Various	None
LEM	U.S.	Allocation	Substitution, U.S. average	Internal to model	Nitrogen model	None
GHGenius 3.15	Canada and U.S.	Allocation	Substitution, variable	Internal to model	Internal to model	None
ARFL Guidance	U.S.	Evaluates allocation	both, prefers method	Describes approaches	Describes approaches	None
MIT Partner	U.S.	Evaluates both, prefers allocation by energy	Substitution, U.S. average	Direct LUC Calculation	IPCC Tier 1	None
LCA LCM	U.S., Global	Evaluates both, preference for allocation method	Substitution, variable	External Inputs	DAYCENT or IPCC Tier 1	None

RED provides credit of use of marginal land.
RED requires inclusion of direct land use conversion if it occurs.

3.3.1. Greenhouse gas, Regulated Emissions, and Energy in Transportation (GREET) Model

The Greenhouse gases, Regulated Emissions and Energy in Transportation (GREET) has become the standard for use in performing life cycle assessments of transportation fuels in the U.S. The GREET model was first developed at Argonne National Laboratory (ANL) by Michael Wang and his team, (Wang 1996). The model has been updated several times since then, and the most recent model is GREET1_2011. It is a Microsoft Excel 2003 spreadsheet with several macros that can be used directly or manipulated with a graphical user interface (GUI) packaged with the model download. The GUI is considered unhelpful by many because it obscures access to the inputs and facilitates input to only a limited set of key assumptions; the spreadsheet model itself is more useful.

GREET models emissions of the three traditional greenhouse gases (CO_2, CH_4 and N_2O) and additional criteria air pollutants such as PM 2.5, PM 10, NO_x and SO_x. Global warming potential values are used to aggregate the three GHG species emissions into a single carbon dioxide equivalent result. Volatile organic compounds (VOC) and carbon monoxide (CO) are counted as CO_2 because they are assumed to degrade in the atmosphere in less than 100 years.

The GREET model includes provision for a wide range of feedstocks, fuels, and end use applications. GREET models more than 100 fuel production pathways in on-road vehicle and aviation applications. The GREET model is available to the public, and it can be downloaded at http://greet.es.anl.gov/.

The model also generates LCI data that can be used in external analyses. The model is configured with different co-product allocation methods. Widely different co-product methods are used in studies based on GREET.

GREET simultaneously calculates the WTW emissions for numerous fuel pathways. The fuel pathways rely on the same LCI data for most energy carriers and inputs. Using the same LCI data for multiple pathways (for example fertilizer) limits the ability to apply regionally specific factors to a set of multiple fuel and feedstock scenarios. Consequently, criteria pollutant emissions in GREET represent a global average based on U.S. data rather than regionally specific factors.

3.3.2. California CA-GREET Model

The California Air Resources Board (ARB) contracted Life Cycle Associates to revise and modify the default GREET model Version 1.8b. The result was CA-GREET which is intended to be used to perform the life cycle analyses of fuels for California's LCFS. CA-GREET differs from the default GREET model by providing California specific emission factors, urban shares, and a regional lookup table that allows a user to select from eight regions in a pull-down menu. The regional inputs represent feedstock and fuel region parameters involved in the production of California fuels, rather than U.S. average parameters. More information on the CA-GREET model can be found at http://www.arb.ca.gov/fuels/lcfs/ca-greet/ca-greet.htm. The model is configured with co-product treatments that were selected by the California ARB (ARB 2009a). The updated version is CA-GREET2.0.

3.3.3. BioGrace Model

The BioGrace model developed by Intelligent Energy Europe is synchronized with the default values in a spreadsheet model for analysis under Annex V (2009/28/EC) of the EU RED. The BioGrace model regional specificity allows for general use or national (within Europe) use. For example, it is available to Spain, Holland, and Germany using regional data from those countries to calculate GHG emissions. Biograce contains parameters and functional units that are consistent with the European Commission's Joint Research Centre (JRC) analysis (JRC 2008).

BioGrace provides over 15 biofuel pathways in separate workbooks. The calculation scheme for each pathway is consistently organized to facilitate auditing. A key feature of the analysis is energy allocation for co-products. BioGrace is configured with the energy allocation approach specified under the EU Directive. Thus, the tool is not configured to provide the flexible options for examining co-products as in other fuel LCA models. Another significant feature of BioGrace is the exogenous LCI data, which are user-provided as external model inputs. Biograce can be downloaded at http://www.biograce.net/.

Biograce calculates WTT results on a single worksheet for each fuel pathway. Every pathway is a unique set of calculations but the calculations are parallel for each pathway. Fuel producers customize the pathways further for certification under the RED. The model is very easy to follow and regionally specific LCI data can be applied to each step in the fuel cycle. The model is configured to calculate GHG emissions and no other life cycle impacts.

3.3.4. GaBi Model

PE International developed GaBi LCA software for evaluating product environmental performance. GaBi is a user-friendly GUI program that focuses on modeling the environmental impacts of many types of products, ranging from grocery store goods to transportation fuels. GaBi includes social, environmental, and economic impacts in their modeling. The environmental impacts include greenhouse gases, water consumption, and regional groupings of criteria pollutants. A significant feature of GaBi is that it contains over 4,500 LCI datasets based on data collection from their previous work, which enable the user to model numerous life cycle pathways without having to collect additional LCI data from outside sources. However, the source of the LCI data is unavailable, whereas it is available in models such as GREET. GaBi can be purchased at http://www.gabi-software.com/.

GaBi is works is a database approach and is extremely flexible in terms of customizing LCI data, fuel production pathways, and life cycle impact analysis.

3.3.5. Lifecycle Emissions Model (LEM)

LEM was developed by Dr. Mark Delucchi at University of California, Davis (Delucchi 2003). It is a spreadsheet-based model that estimates energy use, criteria pollutant emissions, and CO_2-equivalent greenhouse-gas emissions from a variety of transportation fuel and electricity generation lifecycles. Moreover, LEM calculates LUC emissions; the model includes input data for up to 30 countries, for the years 1970 to 2050, and it is fully specified for the U.S. The LEM calculates lifecycle emissions for a wide variety of both light and heavy duty vehicles, including locomotives, ships, and pipelines. It includes a wide range of modes of passenger and freight transport, electricity generation, and heating. For transport modes, it represents the lifecycle of fuels, vehicles, materials, and infrastructure. The LEM is compared to the GHGenius in the following subsection.

3.3.6. GHGenius Model

The GHGenius model evaluates additional fuel pathways for Natural Resources Canada (Delucchi 1998); it is based on an early version of LEM, though it has been updated, most recently in 2010 ((S&T)[2] 2010). GHGenius is a spreadsheet-based model that, like the LEM, can calculate energy and emissions associated with conventional or alternative fuel production for the past, present, and future projections (through 2050). GHGenius includes the three traditional greenhouse gases, CO_2, CH_4 and N_2O, in addition to CFC-12 and HFC-134a. The model also includes the criteria pollutants. GHGenius uses global warming potentials (GWP) values rather than LEM CO_2 Equivalence Factors (CEFs) to aggregate greenhouse gas emissions to a total g CO_2e value, although the model allows the input of CEFs or other metrics for aggregating emissions.

LEM and GHGenius are much more complex than other LCA models and offer greater functionality. This includes representation of over 20 different geographic regions and soil types, nitrogen and sulfur tracking through Biosystems after atmospheric deposition, indirect greenhouse gas impact calculations, and dynamic representation of the atmosphere and its major constituents over time. The climate impact of greenhouse gas emissions varies over time in LEM, which yields life cycle emission results that are much more difficult to assess than the simple analyses based on the Intergovernmental Panel on Climate Change (IPCC) global warming potentials (GWPs).

The GHGenius model includes many more alternative fuel pathways and scenarios than the LEM, but only models the fuels for light-duty vehicles, class 3 to 8 heavy-duty trucks, urban buses, light-duty BEVs, and FCVs. There are currently more than 200 vehicle, fuel, and feedstock pathways represented in the GHGenius model. LEM models a wider range of vehicles, including mini-buses, mini-cars, mini-scooters, and the like, but contains fewer alternative fuel pathways. GHGenius calculates results for several different regions of interest, including three sub-regions of Canada (east, central, and west), the United States, Mexico, and India. GHGenius is available for public use and it can be downloaded at http://www.ghgenius.ca/.

3.3.7. Air Force Research Laboratory Study (AFRL)

The Aviation Fuel Life Cycle Assessment Working Group conducted a study for the Air Force Research Laboratory (Allen 2009) to develop a framework and to provide guidance for the LCA of alternative jet fuel. The document was prepared for federal agencies procuring renewable jet fuel in accordance with EISA Section 526. The scope of the AFRL study includes the LCA of aviation fuel for GHG emission results, but it does not include any other environmental criteria. Because EISA requires alternative fuels to be compared to baselines, the LCA methods described in the study can be used for both conventional jet fuel and renewable jet fuel production pathways. The AFRL study analyzes several LCA models (including GREET, CA-GREET, and

LEM) and assembles results from a number of other LCA studies that have addressed aviation jet fuels. The study compares different methods for completing the LCA of GHG emissions for aviation fuels, but does not describe a definitive model such as GREET or GHGenius. It evaluates different modeling choices for each stage of an LCA and discusses the issues and consequences of what those choices would be, i.e. using a substitution method or an allocation method for co-products analysis.

3.3.8. Massachusetts Institute of Technology Air Force Research Laboratory (MIT AFRL) Partner Project 28 Study

The Massachusetts Institute of Technology (MIT) led a research project managed by the Federal Aviation Administration, Air Force Research Laboratory (AFRL), and DLA-Energy to perform an extensive LCA of GHG emissions from renewable jet fuel pathways (Stratton 2010). The analysis is based on the GREET model with the addition of vegetable oils and algae oil pathways. The study examines LUC impacts and addresses different allocations of products considered as substitutes for petroleum distillate fuels in the boiling range between jet fuel and diesel on-road vehicle applications. The study uses the allocation method for fuels that are co-products, such as naphtha. The study also provides an extensive consideration of CLCA issues. Additionally, the uncertainty analysis comprehensively examines the range of variability in the LCA results due to co-product method.

3.3.9. LCA LCM

Life Cycle Associates developed a flexible life cycle analysis framework which can be applied to any fuel pathway using LCI data derived from any source. The Life Cycle Associates Life Cycle Module (LCA LCM) utilizes a modeling approach called matrix organization using specific energy (MOUSE) which uses matrix (linear) algebra to combine LCI data from the GREET model with input parameters to develop a customized fuel pathway analysis. The MOUSE can be updated for projects interested in multiple environmental criteria such as greenhouse gas emissions, energy use, and water use. Process inputs and environmental criteria are modeled so that each calculation corresponds to one criterion for one input; thus the LCM produces fully disaggregated results.

The MOUSE framework offers many advantages over existing life cycle models including transparency, efficiency, and flexibility. The simple calculation format and fully disaggregated results provide maximum transparency, allowing feedstock producers, fuel producers, regulators and auditors to easily understand the analysis. The framework is highly efficient because the user may specify inputs for multiple pathway scenarios simultaneously and analyze multiple scenarios quickly and efficiently. Additionally, the LCM framework facilitates uncertainty and sensitivity analyses using Crystal Ball or other statistical software packages; most life cycle models available today are not conducive to uncertainty and sensitivity assessments. The MOUSE framework is extremely flexible and can utilize LCI data from any source and track results for any environmental criteria. The tool may be applied to any production pathway in any region, including production of biochemicals and bioproducts such as jet fuel.

3.4. Comparison of Model Results

The LCA studies in the literature focus primarily on energy inputs and GHG emissions. Greenhouse gas emission results for diesel and jet fuels are presented here from a range of studies. Both the EPA and the EU studies examine several renewable diesel and FT diesel pathways. Figure 3.3 shows the greenhouse gas emissions (CI) results for several renewable diesel and jet fuel pathways.

Greenhouse gas (GHG) emissions are long lived and have an impact on a global scale. Therefore, GHG accounting must include the well to wake (WTW) emission from fuel production to jet fuel combustion on a life cycle basis. LCA of jet fuel are very similar to assessments of liquid ground transport fuels such as gasoline and diesel, with a few key differences and added complexities due to the global scope of the fuel production pathway and complex impacts of aircraft emissions. Many liquid fuels of different carbon lengths (gasoline, diesel, naphtha, jet fuel, fuel oil, etc.) are produced in oil refineries and biorefineries (including FT synthesis, pyrolysis, and bio-oil hydrotreating). Therefore, the jet fuel pathway includes the same production steps as ground transport fuels: feedstock production, feedstock processing, and fuel production. The analyses of liquid fuels are linked because of this reliance on the same production steps and the linkages between yields for different refinement products; increasing production of one hydrocarbon fuel reduces production of other fuels.

LCA's of jet fuel can follow the same approach as those for transportation fuels. For the same feedstock and conversion technology, the jet fuel LCA needs to take into account the product yield and differences in ground transport and fuel transfer logistics and fugitive emissions. Other than differences in yield and distribution logistics, the fuel production emissions per MJ of jet fuel are comparable to those for on-road diesel.

The CO_2 emissions from fuel combustion depend on the molecular composition of the fuel. CO_2 from jet and diesel are almost identical per MJ of fuel combusted. However, minor emission species may have significant GHG impacts. The impacts are associated with gases and particulates emitted at aircraft cruise altitude (approximately 30,000 ft) along with the landing and take-off phases of flight. Emission factor data have been characterized for many commercial aircraft, but military aircraft emission factors are not generally available. The secondary and higher order impacts of the aircraft emissions are complex, poorly understood, and vary with altitude and latitude. In addition to the complexity of aircraft emission impacts, the large geographical scope of airplane travel has other complicating consequences.

Figure 3.12 shows life cycle GHG results for aviation fuels and from on-road diesel produced by feedstocks and processes that could also produce jet fuel. The range in emissions illustrates some of the issues with LCA and the need to develop a harmonized approach for jet fuel. One reason for this is that the method for determining a petroleum baseline differs among LCA studies and policies. Approaches range from assigning only the refinery emissions[8] associated with crude

[8] GREET approach

distillation to jet to performing a linear programming model to determine the marginal emissions from refining and crude oil[9].

The allocation of emissions to fuels and co-products is one of the key issues in fuel LCA. The primary co-products from jet fuel production include naphtha, lubricant base oil, electric power, and other hydrocarbons. Approaches for co-product treatment include providing a displacement or substitution credit for the co-products, or allocating emissions by energy or market value. LCA results can become counter-intuitive when jet fuel is a minor product and the credit for co-products results in very low or negative GHG emissions. GREET uses a substitution credit for electric power and allocates emissions between jet and naphtha. The Biograce model uses energy allocation for all co-products except electric power. Electric power receives a credit based on the source of energy for power production.

Direct and indirect land use emissions and agricultural emissions are treated differently in various LCA models. The RFS2 provides the most detailed treatment. The land impacts of feedstocks are estimated for the agricultural land that is brought into production to make up for the land used to grow feedstock. Land use impacts for new feedstocks such as algae, camelina, jatropha, and others, which may be grown on marginal crop land or as second cover crops, are not thoroughly examined. For example, a cover crop might not be grown in the absence of a policy to convert it to aviation fuel. Alternatively, the cover crop may displace a food crop and result in indirect land use impacts. Similarly, animal feed co-products displace other crops and may result in reduced production of that crop or indirect land use change.

The inputs for the GHG results in Figure 3.12 are largely based on modeling studies. They do not include the audited energy inputs and emissions for actual fuel production processes.

Government agencies have developed GHG or sustainability policies that address climate change, but the programs primarily focus on life cycle GHG emissions and compare results to a petroleum baseline. Because airplanes fly internationally, jet fuel sustainability analysis in the U.S. must be "harmonized" with sustainability frameworks used in other countries. This includes considerations of general methods, data sourcing, treatment of co-products, scope of assessment, and baseline thresholds. This is challenging given the different priorities and resource availability of different countries and regions; for ground transport fuels, fuel programs in different countries utilize different methods, data, and co-product treatments.

The results show a wide variability in the fuel cycle CI for similar pathways. Most of the variability is due to differences in process assumptions, co-product allocation methods, and scope of the system boundary. Because this wide variability exists, and because this variability is so dependent on assumptions and co-product methods, the reader is cautioned to draw no firm conclusions about the relative performance of different fuel pathways without understanding all of the assumptions used in the life cycle analyses. Some of the key differences that affect the greenhouse gas emissions are discussed below.

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[9] Biograce/ EU approach.

Jet fuel is generally considered to have lower refining energy intensity than diesel because kerosene is often a straight run product. This assumption needs to be carefully examined from a consequential perspective since displacing petroleum jet fuel with renewable jet fuel will affect refinery operations. Both the GREET and the MTU model assign a lower refining intensity to jet fuel.

Direct and indirect LUC and agricultural emissions represent a significant portion of a fuel's life cycle emissions. EPA calculates the soil carbon storage associated with switch grass as well as the indirect effects associated with crop movement. Another significant impact is N_2O from nitrogen fixing plants such as soybeans and miscanthus. These agricultural N_2O emissions contribute a significant source of uncertainty and may produce misleading estimates of the greenhouse gas impacts from feedstocks. GREET follows the IPCC Tier 1 method and utilizes a simplistic estimate of N_2O emissions from nitrogen fixing crops. The inputs to BioGrace as well as the FASOM model reflect estimates from soil models that the emissions for nitrogen fixers are much higher than those assumed in GREET.

Assumptions on fuel product yield also affect the LCA results. Jet fuel is challenging to produce from vegetable oils because the hydrocarbon chains that make up the vegetable oil-derived triglycerides tend to have carbon numbers close to 18. This is the appropriate molecular composition for diesel fuel. However, jet fuel requires lower carbon numbers in the 12 to 14 C chain-length range. Thus when vegetable oils are converted in a hydro-cracker to hydrotreated vegetable oils (HVO), the jet fuel yield will be lower than that for the diesel yield. Naphtha and fuel gas are co-products from hydroprocessed vegetable oil feed. Unless these are processed into other higher carbon number hydrocarbons, the yield for jet fuel production will be lower than the yield for diesel production.

The life cycle GHG emissions for jet fuel show wide variability for several reasons. First, the jet fuel yields from different hydoprocessing technologies are proprietary and are not generally available to the public. Thus, the inputs to models such as GREET should be considered placeholders. Any assessment of jet fuels needs to take into account actual energy inputs and yields.

The credit for naphtha also has a significant effect on the life cycle emissions of HEFA and FT jet. The average life cycle CI for petroleum naphtha is larger than that of renewable jet fuel. The effects of using naphtha as a chemical feedstock are also significant and are not examined in the above LCA studies. Thus a credit based on substitution results in a lower GHG intensity at lower jet fuel yields. Therefore, a substitution credit for naphtha based on petroleum naphtha should only be applied in combination with a detailed consequential analysis of oil refining. The credit for co-product electric power also differs among LCA models and policies. The EPA RFS2 and GREET provide a credit based on the average electric-generating grid mix while the RED and BioGrace provide a credit based on the feedstock for the fuel production process.

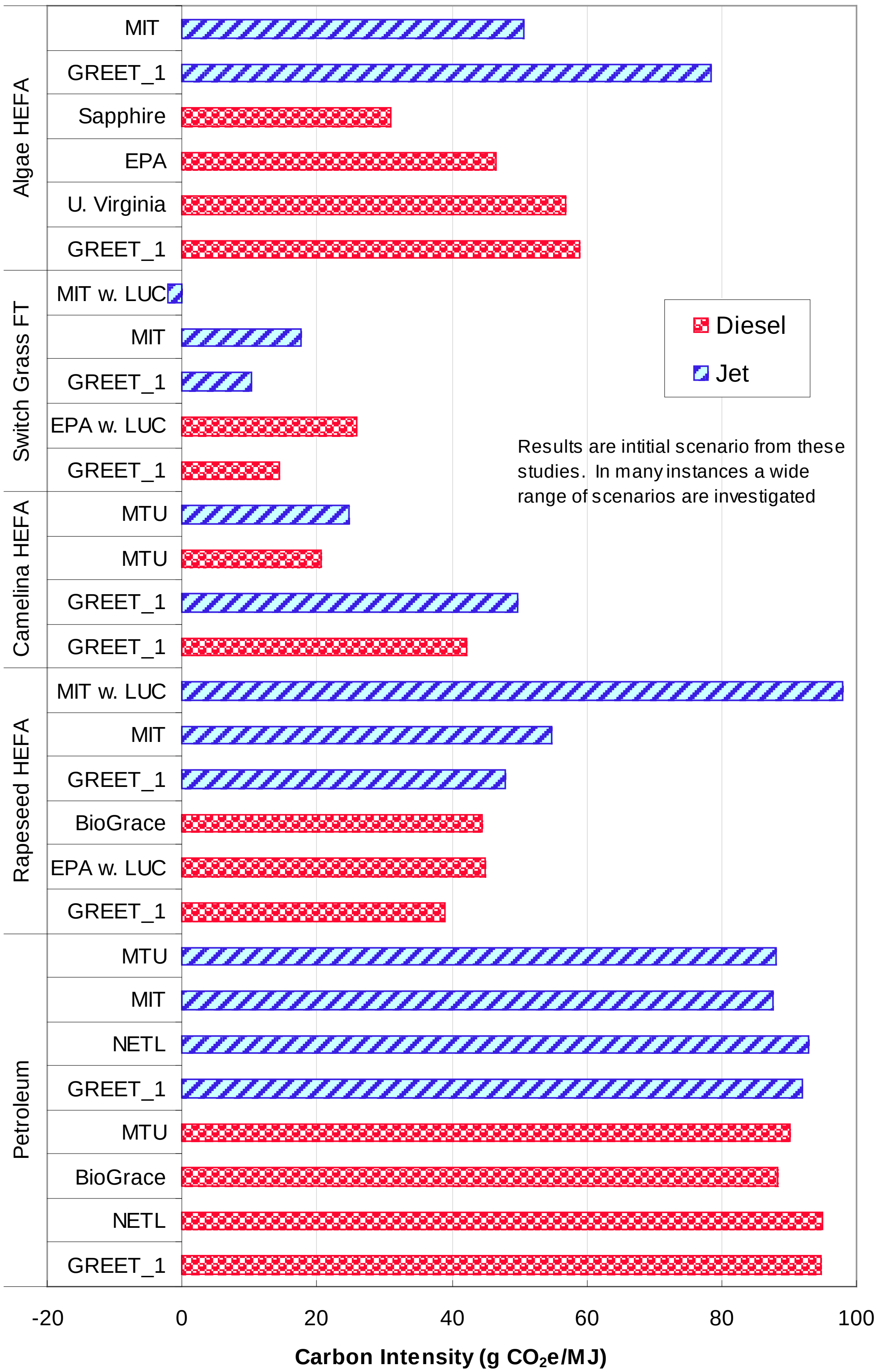

Figure 3.3. CI Comparison of Emissions from Jet and Diesel Fuel Pathways.

3.4.1. Energy Inputs

Results for energy inputs are often difficult to compare because researchers use various methods to define total energy inputs. Some researchers group all energy together while others break out energy resources by category. In the authors' opinion, total energy input from biomass pathways is a misleading indicator since the reader often does not understand the relative mix of biomass and fossil energy[10]. Most biofuel pathways use a comparatively small (less than 0.3 J/J of product) fossil energy input and even less petroleum input. Farming energy, nitrogen fertilizer, and natural gas for hydrogen are the most significant fossil fuel energy inputs for the production of renewable jet fuel. In the authors' opinion, LCA studies should identify biomass crop, biomass residue, and renewable power as separate categories. The total life cycle energy input of petroleum and fossil fuels is a more helpful indicator than net energy value.

3.5. LCA and Sustainability Issues

3.5.1. Model Treatment of Criteria Pollutants

In addition to GHG emissions, fuel LCA models such as GREET, GHGenius, LEM, GaBi, and custom data bases examine life cycle emissions of criteria pollutants (Wang 2011, Delucchi 2003, O'Conner 2011, Unnasch 1996). Some studies also examine air toxics (Wang 2003, Unnasch 2001). Assessments of criteria pollutants are very difficult to execute in a meaningful manner because these emissions depend upon local pollution regulations and offset requirements. The regional distribution of emissions is also important since much farming activity occurs in rural areas and therefore has lower impacts on the human population. For example, marine tankers used to transport crude oil and fertilizer result in a large fraction of the particulate matter (PM) emissions from some fuel pathways, but the emissions occur in the open ocean and are therefore less likely to impact humans.

GREET and several studies for California state agencies attempt to deal with the regional distribution of criteria pollutants. GREET provides an urban shares input. The urban shares input in GREET often combines emissions sources. A more granular analysis is needed to provide an accurate assessment of criteria pollutants. Studies for the California Energy Commission (Pont 2007) and California Air Resources Board (Unnasch 2001) examine the urban emissions in greater detail for a single region and also take into account air pollution offset requirements.

Another issue with criteria pollutants regards the treatment of co-products. Beneficial LCA results are often achieved for some criteria pollutants due to co-product credits. The same detail must be applied to co-product credits in terms of regional details, permit levels, and offsets.

[10] The energy return on investment calculation is a derivative of total energy and does not represent fossil fuel displacement.

3.5.2. Co-product Allocation Methods

The allocation of life cycle impacts to co-products remains one of the key uncertainties in assessing the environmental sustainability impacts of fuels. ISO standards for LCA (ISO 14040 series) provide guidance on the treatment of co-products. The displacement method is preferred, and it is recommended that you perform an alternatives analysis using the allocation method. The ISO standards also call for an uncertainty analysis in cases where the allocation procedure has a significant effect on the outcome.

The approaches to evaluating the primary co-products associated with jet fuel pathways, as well as the treatment of similar co-products for other fuels are listed in Table 3.13. Each co-product presents several challenges due to the difficulties in identifying an appropriate displacement credit that reflects both the marginal impact of the co-product as well as CLCA considerations.

Several divergent approaches to co-products analyses result in wide differences in life cycle GHG emissions results. The LCA of biomass-derived jet fuel based on gasification with FT synthesis and hydro-processing illustrates many of these issues. In GREET, for example, diesel, jet fuel, and naphtha are treated as primary fuel products and electric power is a co-product of some FT process configurations. In other modeling approaches, naphtha is treated as a co-product (Stratton, Forman 2011).

Typically, unconverted synthesis gas is burned to generate power. Lower fuel conversion yields (of CO to higher C chains) correspond to higher levels of power generated, thus displacing grid electricity. These electrical power inputs are reflected in the GREET model scenarios in which the default co-product credit is based on grid power. This treatment causes several issues to arise: first, the power credit is greater for lower yields, so the life cycle GHG emission can actually be negative when the gallons of FT fuel per ton of biomass are low (30 gal per ton) and the co-produced power is high (10 kWh/gal). The problem then is that fuel producers using FT process configurations may be acting more like power plants than like fuel producers to obtain a lower CI rating for their FT fuel.

Another issue concerns the treatment of the export electric power as a credit against grid power, (an example is given in Section 2.1). Sales of biomass derived electric power will likely be used to meet a renewable portfolio standard (RPS). The purchasers of the renewable power would have the expectation that the power carries a low carbon intensity. However, if a co-product credit is assigned in a program such as the LCFS, where the GHG emissions are weighted, a double credit will result. The EU has a different approach. The credit for electric power is based on displacing biomass derived power. The credit is much smaller and does not generate a double credit.

Yet another issue with FT pathways is the co-production of several fuel products, typically jet fuel and naphtha. The energy inputs and emissions can be distributed to both energy products, which is the approach in the GREET model for renewable diesel and renewable jet fuel, and implicitly for the FT pathways (where the entire product is treated as transportation fuel).

Table 3.13. Different Approaches to Co-products in Fuel LCA

Co-product	Pathways	Approaches
Electric power	FT Jet, SPK, Biomass Cellulosic Ethanol	a. Credit for electric power based on average or marginal power (EPA 2010). b. Alternative approach is credit based on biomass power (Larivé).
Seed Meal	HR Jet, Oil Seeds Soy Renewable Diesel	c. Credit for meal based on displacement method (EPA 2010, LCFS). d. Hybrid allocation between meal and energy products (ANL GREET). e. Alternative approach is energy allocation (RED).
Naphtha	FT Jet, SPK, Biomass FT Diesel, Biomass FT Diesel, NG	f. Allocation energy inputs, emissions, and co-products (EPA, GREET, RED, Stratton 2010, Shonnard 2010). g. Provide substitute credit based on naphtha for steam cracker feed (Forman 2011).
Petroleum Refinery Products	Diesel Kerosene Jet	h. Allocate emissions to refinery product based on process level energy intensity (Wang 2004). i. Estimate marginal refinery emissions based on LP model (JEC, Rosenfeld 2009). j. Allocate emissions to refinery products and provide displacement credit for non-transport products – coke, sulfur, and residual oil (Keesom 2009)

FT = Fischer Tropsch, SPK = Synthetic Paraffin Kerosene, HR = Hydrotreated renewable

Econometrica points out the issues with substitution analysis (Brander, 2012). The value of the credit for naphtha is much higher with this approach. However, this approach has several problems when viewed in the context of a consequential LCA. The life cycle of naphtha can be readily determined from an energy allocation approach to petroleum naphtha and bio-naphtha. Since naphtha is used to produce many products (gasoline, chemicals, etc.), and is not usually used directly as a process fuel or transport fuel, determining a substitute product for co-product naphtha is difficult. Providing a substitution credit for naphtha does not give a symmetrical result when naphtha is treated as a transportation fuel.

Another issue is the LCI data of jet fuel used in some studies (Shonnard 2009). The LCI data used in an LCA calculation tool would give different results depending on what the LCI accounts for. For example, a significant quantity of kerosene is a straight run product from oil refineries. However, displacing petroleum jet fuel with renewable jet fuel would affect how oil refineries are configured. Therefore, the petroleum jet fuel baseline that uses straight run kerosene is an oversimplification that does not take into account CLCA considerations.

3.5.3. Time Horizon

Most LCA's treat all emissions as occurring at the same time and do not consider the effect of emission timing. Different emission time profiles for feedstock and biofuel production affects the comparison of emission results across different studies. Land clearing and other start-up activities represent an up-front cost and initial emissions to biofuel production that is different in nature from the ongoing emissions from the biofuel production cycle. LCA calculations require allocation of the ongoing emissions to the functional unit (e.g. 1 MJ of biofuel).

The simplest approach to converting initial emissions to a per-MJ flow is to distribute the emissions over a quantity of biofuels associated with the project life time (usually 20-30 years). No clear objective scientific method provides a basis for choosing this value; EPA RFS2 and the ARB analysis of LUC emissions chose to assume 30 years of fuel production at current yields. Time horizons of 100 years were also examined. Both approaches present challenges. A long time horizon may capture the ongoing emissions from biofuels, but presents the problem of shifting environmental burdens to future generations. Also, accounting for the GWP weighted emissions of initial emissions does not necessarily reflect the environmental impacts or cost of global warming.

The use of a 30-year time horizon is arbitrary. Some biofuel projects may fail and revert to other land uses more quickly. Other biofuel projects can persist for many decades. Additionally, accounting for the long-term uptake of CO_2 at the farm-level presents challenges. Two recent approaches that address time accounting are O'Hare, et al. 2009 and Kendall, 2009.

In a study by UC Davis (Kendall, 2009), a time factor approach applies to biofuel timing as a one-time shock value rather than an amortized value, therefore the burden of project set-up emissions does not span over several successions of biofuel crops. This value is generally higher than the effect from amortized values.

3.5.4. Water Impacts

Water impacts are a difficult topic in the LCA of biofuels. Quantifying water consumption in a meaningful way is challenging due to the many types of water and significant differences in water stress indices across different regions. A water stress index gives a rating as to how stressed, or how secure, a water resource is. Life cycle analysis accounts for the criteria of interest at all stages of the production pathway expressed per "functional unit" of analysis, which represents the value of product (such as energy content, fresh water use, etc.). Fuel life cycle analysis determines the total impacts (emissions, energy use, water use) per megajoule (MJ) of fuel or per mile driven. However, water consumption is not easily amenable to this sort of characterization. Consumption of water from different resources (e.g. groundwater, surface flows, rainwater, saline aquifers), at different locations, and at different points in time, can have vastly different implications, and impacts are difficult to quantify and compare meaningfully. Section 4 further discusses the treatment of water impacts.

3.5.5. Other Sustainability Issues

Other sustainability issues not specifically discussed in the above subsections deserve mention. The following subsections describe issues pertaining to sustainability rating systems. These sustainability issues are the sustainability scope, the treatment of marginal land and cover crops, the quantification of non-air pollution environmental criteria on a life cycle basis, and the principle of continuous improvement.

3.5.5.1. Sustainability Rating Systems

Sustainability guidelines and certification schemes have developed as a response to the growing need to ensure that biofuels are as sustainable as they claim to be. The more established trade and sustainability certification organizations, discussed in Section 2.3, attempt to provide balanced standards with the feedback from numerous stakeholders. The balanced standards aim to be not so rigorous and detailed that they are impossible to meet, but not so easily met they have no impact. However, finding the right balance of sustainability rigor and feasibility is easier said than done.

3.5.5.2. Sustainability Scope

Environmental sustainability has many definitions, and determining what is sustainable and what is not sustainable is a controversial topic. A significant issue with measuring environmental sustainability is what the scope of the sustainability assessment is and how deep the assessment should go. The more specific sustainability assessments are, the more difficult or impossible compliance with the standards becomes. For example, ensuring the sustainability of a fuel over the value chain where metrics are examined for the feedstock and fuel production facility provides the greatest level of detail and certainty. However, data availability at the facility level is a significant challenge. Component suppliers may guard proprietary information, lack ideal record keeping, or they are indifferent to meeting reporting requirements.

The sustainability guidelines developed by the organizations in Section 2.3 have three layers of depth: sustainability principles, criteria, and indicators. Principles are broad statements, criteria describe what needs to be accomplished for the principle to be met, and the indicators are the specifics of how the criteria are fulfilled. The more criteria and indicators a principle has, and the more specific they are, the more difficult the sustainability assessment. However, many indicators describe best management practices and compliance with the law. Thus, for many sustainability principles to be met by biofuel developers, following best management practices and abiding by the law is enough for certification under most certification systems. Whether following best management practice and abiding by the law is sufficient to assure a truly sustainable system may remain controversial in the opinion of some stakeholders.

3.5.5.3. Best Management Practices

Best Management Practices (BMP) prevent adverse environmental impacts from agricultural operations. Agricultural BMPs are management, agronomic, land use, and other practices that permit economic and viable production while achieving the least possible adverse impact on the environment. BMPs also minimize possible adverse impacts on ecosystems and human health. With BMPs, farming can continue to be viable within the needs of the farm, surrounding area and watershed.

Fertilizer and pesticide run off can be controlled so that pollution of surface and ground water does not occur. The use of drinking water, and impacts on aquatic life and recreation are considered in BMPs. The depletion of soil carbon, emissions from farming operations, and other effects can also be minimized by adequate BMPs.

3.5.5.4. Marginal Land and Cover Crops

Many crops are often treated as marginal crops in that they do not require the conversion of land or diversion of food crops. Examples include winter cover crops, crop residues, and crops grown on marginal or contaminated land. Determining the marginality of crops is a significant issue because biofuel producers have an incentive to grow crops on the highest yielding land.

3.5.5.5. Non-Air Pollution Criteria

Non-air pollution criteria are difficult to quantify on a life cycle basis. Criteria such as water use, biodiversity, soil quality, water discharges, and others all have indirect effects, as discussed in the jet fuel context in Section 4.2. At present, all non-air emission sustainability certifications are focused on direct effects that can be audited at the facility level. However, the use of resources such as water and land result in indirect effects. The inability to address indirect effects is a shortcoming of facility level sustainability assessments.

3.5.5.6. Continuous Improvement

Sustainability strives for continuous improvement. Improvement can include reduced fertilizer, land, electric power, diesel fuel, and other process inputs. Improvement can also encompass better record keeping in order to support the assessment of sustainable production and processing. Requiring improvement presents an additional constraint on fuel developers and feedstock suppliers who may be under the impression that they simply need to comply with the law and achieve best management practices.

3.5.6. Jet Fuel Compared to On-Road Diesel Fuel

Fuel LCA models and studies (GREET, BioGrace, EPA Database Calculations) examine pathways for on-road diesel that are similar to jet fuel pathways. The studies and policy initiatives that do not specifically include jet fuel provide helpful insight in the LCA of jet type fuels and the treatment of their environmental impacts. The key differences between jet and diesel fuels include:

- The upstream fuel cycle and feedstocks sustainability issues are identical for transportation fuels and jet fuel on a per unit of feedstock basis.

- The total greenhouse gas emissions from combustion are almost identical for diesel and jet fuel because the carbon per MJ is comparable, and the contribution of CH_4 and N_2O

emissions is small. The variability is about 2 g CO_2e/MJ difference between diesel and jet fuel.

- For pathways such as crude oil refining, hydrotreated vegetable oil (HEFA), and FT fuels, the yields differ significantly between jet fuel and diesel. In the case of most vegetable oil hydroprocessing to jet fuel, the results are such that a lower jet fuel yield and higher naphtha yield occur compared to vegetable oil hydroprocessing for diesel. The co-product treatment of naphtha becomes important (Section 7.7.1.2). For petroleum refining, straight run kerosene is assigned a lower CI than cracked products.

- The impact assessment for jet fuel differs from on-road fuels. Aircraft produce emissions at ground level that lead to local burdens of criteria pollutants. Emissions of black carbon at high altitudes also have climate consequences that differ from on-road fuels. Alternative fuels with the same properties as petroleum jet fuels are unlikely to change the emissions of black carbon, SPK formulations will have a higher hydrogen to carbon ratio than the petroleum fraction of jet fuel.

4. Advancing Alternative Jet Fuel Sustainability Assessments

In an effort to move forward with developing standards for sustainable alternative jet fuels, procurers of jet fuel and other stakeholders will need to identify metrics to address sustainability and life cycle assessment of jet fuels. Fuel procurers need well defined standards or rating systems that can be used in procurements in a consistent manner. Achieving a consistent sustainability assessment will require accurate and consistent reporting. Also disparities between international stakeholders and policy makers need to be understood, if not resolved. This section describes the sustainability issues that affect aviation fuels uniquely. Many sustainability indicators have been developed for renewable on-road fuels and these indicators could be applied to aviation fuels. A description of these indicators is provided in Appendix A.

The methods to assess environmental sustainability described in Section 3 include a diverse set of regulatory requirements, models, and certification schemes, with many variants around the world. The scope of sustainability regulations includes cap and trade of CO_2 emissions and life cycle GHG intensity regulations. The scope of these regulations ranges from direct facility emissions, in the case of cap and trade, to the full life cycle emissions including all direct and indirect effects. Within the scope of LCA, assessments focus on the life cycle (direct plus upstream) impacts occurring within the production chain (ALCA) or they estimate the global cascading effects with agro-economic models. Land use change has also been incorporated into traditional ALCA by treating estimates of the indirect emissions as an incremental addition to the conventional direct well-to-wake (WTW) results.

Regulations on criteria pollutants, water quality, soil impacts, and other environmental sustainability effects are not regulated on a fuel output basis. These impacts are covered to some extent under U.S. and EU GHG regulations. The environmental effects of the additional sustainability indicators have been incorporated into biofuel sustainability initiatives and standards primarily through site specific certification of agricultural practices.

The following section discusses the factors in sustainability assessment that are unique to jet fuel, followed by a brief discussion of each sustainability criterion. Each subsection discusses the general approach for incorporating sustainability indicators into a GREET-type life cycle analysis for criteria conducive to life cycle accounting. Water consumption and pollutant discharge impacts may be modeled with life cycle assessment, but the results have limited use unless considered in the context of local resource availability. For water consumption, the resource availability is defined by the annual replenishment of each water type (fresh, saline, waste, etc.); resource availability for water pollutant discharges is defined as the capacity for waterways to disperse and decompose pollutants. Soil impacts cannot be modeled on a life cycle basis easily, therefore assuring ongoing soil health relies on farmers adhering to "best practices". Biodiversity impacts cannot be assessed on a life cycle basis and must be handled using regional biodiversity indicators. Exposure to toxins and hazard management cannot be modeled on a life cycle basis and rely on site specific certification and adherence to "best practices" and avoiding banned chemicals.

4.1. Sustainability in the Jet Fuel Context

Life cycle analysis and sustainability assessments of jet fuel are very similar to assessments of liquid ground transport fuels such as gasoline and diesel, with a few key differences and added complexities due to the global scope of the fuel production pathway and complex impacts of aircraft emissions. Many liquid fuels (gasoline, diesel, LPG, jet fuel, fuel oil, etc.) are produced in oil refineries and biorefineries (including from processes such as FT synthesis, pyrolysis, and bio-oil hydrotreating). Jet fuel pathway includes the same production steps as ground transport fuels: feedstock production, feedstock processing, and fuel production.

The analysis steps for on-road diesel and jet fuel produced from the same feedstocks and processes are almost identical. Analysis of each fuel can be accomplished by allocating the energy use and emissions for each of these steps among the fuels produced based on the energy content of each (energy allocation) or by performing a substitution analysis with a credit for co-products. Jet fuel procurers should provide a comparable treatment of alternative jet fuel and on-road diesel fuel. An inconsistent treatment of jet fuel would result in a distortion in the fuel market where fuels that appear to have low impacts under rules adopted for jet would flow to the aviation market, while fuels that perform well under transportation rules would flow to those markets.

Important differences between jet fuel and ground transport fuel assessments include the fugitive emissions occurring during fuel transport and transfers, the aircraft fuel combustion emissions per MJ of fuel use, and the impact of gases and particulates emitted at aircraft cruise altitude (approximately 30,000 ft) and emitted along the landing and take-off phases of flight. Emission factor data have been characterized for many commercial aircraft, but military aircraft emission factors are not generally available (IPCC 2000). The secondary and higher order impacts of the aircraft emissions are complex, poorly understood, and vary with altitude and latitude. In addition to the complexity of aircraft emission impacts, the large geographical scope of airplane travel has other complicating consequences.

Because fuels are traded internationally, airplanes fly internationally, and GHG emissions have long lasting global emissions, jet fuel sustainability analysis needs to have a consistent framework for sustainability reporting and GHG calculations. Otherwise, inconsistent metrics will lead to fuels being sold in markets that provide the most favorable ratings without benefit to the environment.

A jet fuel sustainability assessment would also include an analysis under the EPA RFS2 method as well as the RED Biograce method in order to provide full transparency. This is challenging given the different priorities and resource availability of different countries and regions; for ground transport fuels, fuel programs in different countries utilize different methods, data, and co-product treatments.

4.2. Sustainability Criteria

Appendix A summarizes the environmental sustainability criteria (impacts) that have been identified through review of the existing fuel programs, rating systems, and criteria. These criteria are applicable to both on-road and aviation fuels. The results of this review were characterized by the CAAFI team and summarized in working documents. Several useful tables were developed that summarize sustainability criteria in the context of the fuel pathway chain, feedstock production, fuel production, and the progression of steps feedstock and fuel producers need to take to ensure smooth fuel commercialization and sales (CAAFI 2013).

4.3. Baseline Considerations

The baseline considerations differ for many of the sustainability indicators and programs under consideration by this report. These factors include baseline petroleum emissions, baseline agricultural and alternative fuel activity, which affect consequential and indirect effects such as land use change, and other system boundary considerations. The baseline considerations are presented in Table 4.1.

4.3.1. Petroleum Baseline

The petroleum baseline differs for each policy initiative based on factors that involve the regional resource mix, mix of extracted oil and thermally produced petroleum, transport distances, allocation procedures, and the modeling approach. Regional differences in refinery configuration, fuel specifications, and diesel to gasoline output also affect refinery energy requirements and emissions.

Table 4.1. Baseline Considerations for the Jet Fuel LCA

Initiative	Petroleum Baseline	Agricultural Baseline	Indirect Effects
EPA RFS2	U.S. 2005 baseline with GREET resource mix: 93 g CO_2e/MJ Diesel 89 g CO_2e/MJ Jet	Land must previously be used for agriculture	Indirect LUC from FASOM and FAPRI. Limited consequential LCA for energy inputs
California LCFS	California average based on resource mix in CA GREET: 101.3 g CO_2e/MJ Diesel	No requirement	Indirect LUC effects calculation in GTAP
EU Directive	EU mix. Based on marginal refinery analysis: 87.6 g CO_2e/MJ Diesel	Land must not be previously used for agriculture	LUC under investigation. No other indirect effects.

4.3.2. Agricultural Systems Baseline

Different policy initiatives attempt to control land conversion, although the approaches are sometimes in opposition. Under the RFS2, land must be in agricultural service and LUC emissions are counted as part of the LCA. Under the RED, land may not be diverted from food production. These conflicting requirements still appear to allow fuel producers to sell into both markets.

4.4. Direct Impacts, Indirect Impacts, and CLCA

Most LCA models such as GREET only address the WTW direct effects of transportation fuel production and use. The direct effects are those specifically associated with the actual greenhouse gas emissions (and other impacts as noted in Section 4.1), and are incorporated into an ALCA. However, there are additional impacts not directly attributable to the greenhouse gas emissions (for example) from elements of a fuel pathway. These are induced or indirect effects of the fuel pathway process emissions. These indirect effects are usually the indirect impact of LUC or ILUC. The analysis of ILUC and other indirect fuel cycle inputs and effects is grouped into a category termed consequential LCA (CLCA). The EPA's RFS2 analysis is identified as a CLCA. The CLCA aims to identify the inputs on the margin of production such as the land required to grow crops that replace any crops used for biofuel production, or the fertilizer required to grow new crops. Ideally, CLCA takes into account the global agricultural, food, economic, and energy system.

4.5. Environmental Criteria Issues

Several approaches to assigning sustainability impacts are options for jet fuel pathways. The site specific certification where only activity and impacts from the facility are monitored is the norm for cap and trade of GHG emissions as well as certification of feedstocks under frameworks such as the RSB, CSBP, RSPO, and others.

Thus, jet fuel producers are left with the option of using LCA models to estimate energy inputs, GHG emissions, and global criteria pollutant emissions. Other sustainability criteria will require site specific sustainability certifications.

The environmental criteria most often considered for environmental sustainability impacts are energy use, greenhouse gas emissions, air pollution, water impacts, soil health, and biodiversity. Life Cycle Associates developed detailed recommendations for feedstock and fuel production for each sustainability impact and several other issues related to life cycle assessment and sustainability.

Appendix A identifies key environmental criteria and reviews the treatment of indicators in different sustainability frameworks. However, developing a sustainability requirement for fuel procurement will involve additional work to determine which sustainability standards address the environmental principles outlined in this study. Certification standards such as RSB and CSBP involve a great deal of detail to provide sustainability criteria that are auditable. Such a "benchmarking" exercise would identify what indicators are included in each standard and to what degree of rigor they are measured and reported.

4.6. Land Use Change and Food vs. Fuel

A significant concern with the growing biofuel production industry is that land once devoted to food crops is being converted to land for biofuel feedstocks. This displacement of cropland has the effect of increasing the cost of food. It should be noted that the magnitude of the increase is difficult, if not impossible, to ascertain in a manner agreed upon by all stakeholders. This displacement is the source of the food vs. fuel controversy and has led many feedstock producers to seek feedstocks or land types that avoid this controversy. Strategies to avoid this controversy impacts include cultivation of cover crops or rotating crops and cultivation on marginal or abandoned land.

Many biofuel options such as using feedstock camelina have been identified as cover crops or second crops for the production of jet fuels. These crops could also provide feedstocks for HEFA fuels. The assessment of land use conversion and the incremental nature of crop types should be as rigorous for jet fuel feedstocks as it is for on-road fuels. Classes of crops cannot reasonably be judged to have no land impacts when used for renewable jet fuel feedstocks while land impacts are counted under the RFS2.

Procurers of aviation fuels will need to address land use issues. Several options are used in existing biofuel certification systems. Several feedstocks, such as camelina and other rotation crops, crop residues, and crops grown on marginal lands have been identified as options with no impact on food crops. Methods for assessing the food crop impact will need to be part of a sustainability assessment.

4.7. Sustainability Verification

Users of alternative jet fuels may wish to market the sustainability of their operations. Sustainable jet fuel could eventually lead to more complex financial transactions as both the fuel and environmental attributes have value.

Fuel procurers will need to develop specifications to ensure the sustainable production of aviation fuels. The specifications at a minimum should include:

- Requirements for a LCA or LCA tool to quantify global energy inputs and GHG emissions
    - Energy use and GHG emissions have global impacts. The use of resources is tightly linked to upstream activities, so emissions must be measured on a life cycle basis. Additionally, GHG emissions are well mixed and long-lived. Local scale accounting of GHG emissions such as emissions from jets, fuel processing, or other steps in the life cycle are not as meaningful as the well to wake analysis, which represents the global GHG impact.
- Sustainability certification requirements for other indicators
    - Procurement specification could require implementing best practices and management plans, and adhering to permitted resources use and pollutant levels.

> Life cycle assessments are ideal for characterizing energy use and greenhouse gas emissions, while limitations and qualifiers for criteria pollutants and water impacts must be well understood before these impacts can be incorporated into sustainability requirements on a life cycle basis. Other impacts such as soil quality, exposure to toxic contaminants, and biodiversity are so site specific that a life cycle assessment provides too generic a treatment of the effects. These impacts are best minimized by monitoring agricultural land and facilities with the understanding that some upstream and indirect effects will not be covered.

Many sustainability definitions include the need for continual improvement over time and this report also recommends continuous improvement effected through evolving baselines. Continual improvement is motivated by the expected improvements in feedstock and fuel production over time as producers learn to operate more efficiently in addition to adopting technological advances. Additionally, the sustainability criteria metrics and quality of collected process data should be refined over time as scientific understanding improves and data collection becomes standardized and common practice.

5. Recommendations for Sustainability Assessment of Jet Fuels

5.1. Consistent Treatment of Jet Fuel and on-Road Fuels

The impacts of GHG emissions are global in nature. In order to reduce the climate changing impacts of these gases, reductions must be made on an aggregate global level. The international nature of air travel presents several problems for the purchasers of jet fuel with regard to GHG accounting. For one thing, there is a cost associated with compliance with many different standards. For another, the achievement of global targets requires consistency and comparability of emissions calculations. As described in section 2.3, different sustainability metrics employ methodologies that may differ in scope, allocation method, or data sourcing. These inconsistencies make it meaningless to compare results across models. In order to measure progress towards a goal, it must be possible to calculate the change in emissions from a given baseline. This requires consistency in GHG accounting methods in order to avoid shuffling of fuels with no environmental benefit. For example, if rapeseed based HEFA were sold for aviation purposes without including LUC emissions and LUC emissions were included for on-road applications, the aviation market could be more attractive. Claims about GHG reductions would be suspect if fuels from the same feedstock receive widely different GHG ratings.

In order to avoid shuffling of fuels to markets that provide favorable ratings, renewable jet fuel analysis needs to be consistent with analysis of ground transport and aviation fuels analyses in other countries. Jet fuel should be treated consistently with ground transport fuels because the production of renewable jet fuel requires the same process steps as the production of other renewable transportation fuels: feedstock production, feedstock processing, and fuel production. In fact, jet fuel emissions have a much greater impact on secondary and higher order greenhouse gases and pollutants than ground transport emissions due to the additional warming effect of sulfur emissions at the altitude of aircraft.

The differences between jet and other fuels fall into several well defined categories. Jet fuel yields will likely be lower than diesel yields from many classes of vegetable oils. Therefore, for many hydroprocessing technologies, more feedstock will be required to make a MJ of jet fuel than a MJ of diesel. Life cycle results may be clouded by co-product credits, but the impact on ecosystems is the same for jet and diesel except for differences due to yield. Thus, the life cycle greenhouse gas impacts for renewable on-road diesel and renewable jet fuel should closely align. Fuel procurement requirements should take into account the treatment of comparable feedstocks and fuel pathways in order to avoid shuffling of high impact fuel production pathways into less regulated markets.

5.2. Sustainability Verification

The next step in developing a sustainability framework for jet fuel would be to select among the options for monitoring and verifying sustainable fuel production. Several options are available for evaluating aviation fuel sustainability. These include: requiring aviation fuels to comply with on-road transportation requirements; certification through existing sustainability standards; or developing new standards, potentially through industry led environmental product declarations. Fuel procurers may want to opt for a uniform set of approaches or use a variety of approaches. The different possible approaches to renewable certification of jet fuels is the following:

- Use existing transportation fuel regulations and certification thresholds
    - RFS2 and RED provide a basis for GHG calculation with limited sustainability assessment
    - Analysis of aviation fuels requires adjustment to GHG calculations
    - DOE provides guidance for EISA Section 526 GHG analysis without detailed sustainability assessment
    - Note synergies between on-road policies and aviation
        - RFS2 and RED are not a requirement for aviation fuels
        - RFS2 and RED certification provide a financial incentive to fuel producers
- Certify fuel under existing certification standards
    - Operator level certification provides more detailed sustainability evaluation
    - GHG calculation methods may deviate from RFS2 and RED approaches
    - Not all feedstocks are covered by certification standards
- Develop new certification standards and protocols
    - Need to develop requirements, stakeholder feedback, certification procedures
    - Sustainability metrics and stakeholder groups may differ from existing standards

Differences in sustainability requirements among sustainability standards leads to carbon leakage

Many of the sustainability metrics in place today could be applied to jet fuel without any modification. These programs either focus on the life cycle impacts occurring within the production chain or they estimate the global cascading effects with agro-economic models (see Appendix A). Land use change has also been incorporated into traditional analyses by treating estimates of the indirect emissions as an increment to the conventional direct well-to-wake (WTW) results. Verification of sustainable feedstock and fuel production practices are accomplished through the approaches described in Section 3.

Most existing government-based biofuel GHG standards involve sustainability verification through either auditing of feedstock production and fuel processing or government review of feedstock categories. Because of this, the EPA RFS2 and the EU RED both provide methods for calculating GHG emissions for transportation fuels. These methods can be readily adapted for aviation pathways. The comparative GHG performance will be different for each method, and purchasers of aviation fuels will need to either set GHG targets or use the threshold levels set by fuel policies. If aviation fuels qualify for the thresholds, fuel producers will benefit from the sale of renewable fuel credits, which would contribute towards the economic viability of alternative aviation fuel production. Fuel producers may also want to achieve sustainability targets as a matter of corporate social responsibility or national governance. Additionally, fuel producers may strive to take advantage of selling the fuels under the EPA RFS2, California LCFS, or EU RED in order to improve the economics of fuel production.

However, it is important to remember that compliance with regulatory emissions limits does not necessarily ensure a reduction in GHGs relative to baseline petroleum fuels unless a meaningful reduction target is set. GHG emissions are governed under EISA Section 526 for the procurement of fuels by federal agencies. Aviation fuels are subject to cap and trade requirements in Europe.

Government agencies have developed renewable fuel policies that address climate change, but the programs primarily focus on life cycle greenhouse gas emissions and compare results to a petroleum baseline. The RFS2 and RED use a threshold approach, where fuel producers must demonstrate a CI result less than or equal to an established threshold; these programs encourage fuel producers to just meet the performance threshold and provide no incentive to reduce emissions further. By contrast, the California LCFS assigns a unique CI score to each fuel pathway, which provides an incentive to reduce emissions further with the expectation that lower CI fuels would achieve a higher value in the marketplace.

Fuel purchasers could also opt to use third party biofuel certification standards such as the RSB and CSBP. This approach would require an audit of agricultural practices and fuel production systems, and the level of review is considered more thorough at the agricultural facility level than that provided by RED or RFS2 certification. Fuel purchasers could specify a level of GHG reductions aimed for and achieved. These standards could be used alone or in addition to RFS2 and RED certification.

Stakeholder led environmental product declarations (EPDs) could provide another option for monitoring the sustainability of renewable jet fuels. The standards for the EPD would need to be defined in a manner similar to biofuel certification standards like the RSB or CSBP, which have the broad participation of feedstock and fuel producers, government agencies, and environmental groups. However, EPDs for jet fuel could include a more limited participation of environmental groups. The aviation industry could determine procedures for sustainability and then request input from environmental groups. This organizational structure might be viewed as less rigorous than that of sustainability certification organizations. If this is a concern, EPDs could serve as a useful tool for addressing biofuels not currently accepted by RED, RFS2, or existing biofuel certification standards. Again, fuel producers could certify fuels under RED and RFS2 in addition to an EPD if the fuels meet the requirements of the fuel policies.

Table 5.2 summarizes the various approaches for verifying the sustainability of renewable fuels. The RED approach involves certification and auditing of the feedstock and fuel production. In RED, GHG emissions are calculated using BioGrace. An aviation pathway could be certified within the existing protocols and with simple modifications of BioGrace to account for the jet fuel production pathway. Aviation fuels are also accommodated within the RFS2 framework. Under RFS2, the EPA reviews the land conversion requirements and verifies GHG reductions. Fuel production facilities are reviewed through an independent engineering assessment. Fuels that result in GHG emissions that do not achieve the RFS2 or RED thresholds could be rated using a % reduction from petroleum basis, as has been done by the EPA already regarding camelina-based jet fuel (EPA 2013).

Table 5.1. Regulations and Certification Standards Renewable Fuels

Sustainability Option	Feedstock Assessment	Fuel Facility Assessment	GHG Model	Example Qualifying Pathways
EU RED	ISCC or RSB	standard + Audit	Biograce + LUC	Rapeseed HEFA
EPA RFS2	EPA Evaluation	Engineering Review	GREET + LUC	Camelina HEFA Switchgrass FT Jet
Certification Standards	Fuel, Standards	Biomass + Audit	Various	Rapeseed HEFA
Environmental Declarations	New standard	+ Audit	TBD	TBD

In conclusion, the development of a sustainability framework for jet fuels should involve developing or implementing a reliable and valid sustainability assessment tool. This could be done either through a government reviewed program and/or a neutral third party sustainability organization. Achieving sustainability goals will require verification of compliance with local regulations or sustainability measurements.

5.3. Selection of Life Cycle Assessment Model

GREET provides a good framework and good LCI data for life cycle assessments. However, the spreadsheet model has limited capacity for expansion and is inflexible for regional assessments. In the view of the Authors, GREET is difficult to modify for new fuel pathways and the results are aggregated and difficult to understand and audit by non-experts.

On the other hand, developing an LCA model for certification based on GREET and the EPA RFS2 would be relatively straightforward. The model could include GREET life cycle data and RFS2 FASOM and FAPRI results (see Appendix A). The model could be customized for a set of jet pathways and feature agreed upon co-product allocation schemes. The same model could also generate the same results as the Biograce model to provide a reference point for how the fuel would be rated under the RED.

For example, the LCA LCM model (Unnasch 2013) is a flexible life cycle analysis framework which can be applied to jet fuel production using LCI data derived from any source. The model is a transparent model, with efficient coding providing stability and flexibility when creating new fuel life cycle pathways. The fully disaggregated results allow feedstock producers, fuel producers, regulators and auditors to easily understand the analysis. GaBi and SimaPro provide disaggregated results for a wide range of environmental criteria, but the LCI data and calculations contained in these models are not publicly available or verifiable.

5.4. Conclusions

Quantifying sustainability remains a challenge due to the variety of feedstocks, fuel production processes, and stakeholder expectations. The aviation community, as a consumer of jet fuel, seeks the supply security, price stability, and improved environmental performance that biofuels may offer. In order to quantify these benefits, they also seek a method for measuring and reporting on the sustainability of aviation biofuels.

Life cycle assessments are ideal for characterizing energy use and greenhouse gas emissions, while limitations and qualifiers for criteria pollutants and water impacts must be well understood before these impacts can be incorporated into sustainability requirements on a life cycle basis. Other impacts such as soil quality, exposure to toxic contaminants, and biodiversity are so site specific that a life cycle assessment provides too generic a treatment of the effects. These impacts are best minimized by monitoring agricultural land and facilities with the understanding that some upstream and indirect effects will not be covered. The project team developed information on metrics used for environmental indicators to help stakeholders conceptualize the impact and scope of sustainability impacts. This information could frame the development of sustainability standards or procedures and prioritize impact categories.

While all of the environmental sustainability guidelines differ in their exact content, the principles that are most commonly used for developing standards include:

1. Use of best resource management practices
2. Conservation of large above or below ground carbon stocks (e.g. forests)
3. Conservation of biodiversity
4. Conservation of soil health
5. Conservation of water resources
6. Minimization of pollution and harmful effects to air quality (including GHGs)
7. Transparency of biofuel or bioenergy production processes
8. Continuous environmental improvement

We recommend that the aviation community keep in mind the recommendations presented in the executive summary when determining a course of action regarding the sustainability of their fuel sources.

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7. Appendix A – Summary of Life Cycle and Sustainability Criteria

7.1. Energy Use

Energy inputs include fuel and electricity consumed throughout the fuel pathway. These include the upstream fuel cycle energy inputs for the production of energy carriers, such as diesel fuel and electric power, as well as chemicals and fertilizers. Energy inputs are grouped according to the type of resource. The categories in this study include fossil, petroleum, natural gas, coal, and "other" including biomass and other renewable sources. Fossil fuel energy use (non-renewable fuel use) is a more meaningful and useful metric than total life cycle energy use because many biorefineries use biomass energy to cogenerate electricity that is then used for fuel production. Use of the biomass for steam generation to meet process heat requirements and produce electricity has a different value and availability than fossil energy sources. Considering the different fossil energy results separately can provide greater nuance into energy use if different impact values for the different energy types can be established.

The relative energy metric is joules of energy consumed per megajoule of fuel delivered. The absolute energy metric would be joules of energy consumed per joule of energy consumption deemed to be the "fair share" energy consumption allotment for a specific producer.

Energy use is required for the production of all feedstocks and fuels and comes in many different forms, including renewable and non-renewable energy sources. Since different renewable and non-renewable forms of energy have significantly different regional scarcities, costs, carbon intensities, and other environmental impacts, life cycle energy use results should be evaluated on a disaggregated basis. Most fuel producers know their monthly energy use because of monthly utility bills, and feedstock producers typically know the quantity of fuel they consume each year. This data should be maintained and organized by energy type and date, which will allow producers and fuel procurers to monitor the energy balance of producers over time.

7.2. Greenhouse Gas Emissions

Greenhouse gas emissions affect the global climate by absorbing and retaining radiation, and are a key sustainability indicator. Growth in greenhouse gas emissions is likely to accelerate global climate change through the warming of the atmosphere. Although climate change is a global phenomenon, regional weather events including flooding, droughts, fires, mudslides, and powerful storms and tornadoes will become more severe with uneven geographical distribution of GHG emissions.

Greenhouse gas assessments build upon life cycle energy analysis by applying life cycle emission factors and fuel combustion emission factors to the energy use results. Therefore, the quality of a life cycle greenhouse gas assessment depends on the quality of the input data, fuel property data, LCI data, and emission factors.

Greenhouse gas emissions include direct and indirect emission species. Direct greenhouse gas emissions include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), carbon monoxide (CO), and volatile organic compounds (VOC). The CO and VOC are quickly converted to carbon dioxide in the atmosphere, and thus have a GWP of 1 when expressed as carbon dioxide (fully oxidized form). Carbon dioxide, methane and nitrous oxide are long-lived and well mixed in the atmosphere and cause warming by absorbing infrared radiation reflected up from the earth's surface. Ozone (O_3) is also a direct greenhouse gas, but is classified as a secondary or higher order pollutant and is not typically directly emitted.

Indirect greenhouse gas species are short-lived and heterogeneously distributed in the atmosphere and impact climate by affecting the levels of direct greenhouse gases. These include CO, VOC, oxides of nitrogen (NO_x)**,** oxides of sulfur (SO_x), aerosols (black carbon, organic carbon, sulfates and mineral dust), hydrogen (H_2), CFC-12, and HCFC-134a, and can be grouped in three categories: reactive gases, aerosols, and refrigerants (chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC)).

Reactive gases include nitrogen oxides, volatile organic compounds, and carbon monoxide, which participate in complex radical chemistry that effect hydroxyl radical (OH·) levels and perturb methane and ozone levels.

Aerosols include nitrates, sulfates, and particulate matter (PM). The net climate impact of aerosols is extremely complex and involves many mechanisms. Most of the black carbon forms a condensation nucleus for aerosol formation, and the aerosol eventually contains many constituents. Climate models estimate a large positive forcing for black carbon that functions as condensation nuclei. Organic carbon, by contrast, has a significant negative greenhouse gas impact due to efficient ultra violet radiation absorption. The uncertainty of the net climate impact of aerosols remains high.

CFCs and HCFCs released into the atmosphere from air conditioning systems are long lived with a high radiative forcing value, meaning they trap a relatively large amount of heat in the atmosphere compared to other GHGs. But they also destroy stratospheric ozone, offsetting a small portion of the positive forcing, albeit with other negative effects.

Along with energy use, direct greenhouse gas emissions are the most well defined of the sustainability impacts to calculate because the net impact is mostly insensitive to emission timing and location. Greenhouse gas assessments build upon the life cycle energy analysis by applying life cycle emission factors (also known as LCI data) and fuel combustion emission factors to the energy use results. Therefore, the quality of a life cycle greenhouse gas assessment depends on the quality of the input data, fuel property data, LCI data, and emission factors. Most fuel pathway analyses focus on direct GHG emissions and calculate total life cycle greenhouse gas emissions, or carbon intensity (CI), based on the IPCC GWP values (2007) for a 100-year time horizon. Most analyses exclude the climate impact of secondary and higher order atmospheric species.

The relative GHG sustainability metric is grams of carbon dioxide equivalent emissions (g CO_2e) per MJ of fuel produced. The absolute sustainability metric is more difficult to conceptualize because it relies on the "fair share" assessment of a project's greenhouse gas emissions. There are two obvious ways to define "fair share" for greenhouse gas emissions. The first is to determine some finite but positive greenhouse gas emission level that is deemed sustainable long-term and to allocate this among producers. In this case, absolute greenhouse gas emission sustainability may be defined as kilograms of carbon dioxide equivalent emissions (kg CO_2e) per kilogram of "fair share" carbon dioxide equivalent emissions. The second definition asserts that only carbon neutral projects are sustainable and requires projects to obtain credits or offsets for all greenhouse gas emissions. "Fair share" emission assessments are unnecessary under this definition.

Several GHG modeling systems are configured or readily adapted to examine jet fuel. EPA's RFS2 analysis provides the greatest level of detail for both the farming and refining emissions. Fuel pathways examined under the RFS2 can be scaled based on fuel conversion yield to develop jet fuel pathways. The Biograce model used for RED certification can also generate jet fuel pathway. Fuel producers should know their GHG intensities or ratings under each of these regulatory systems[11]. Many other LCA tools can also be used to calculate GHG emissions from jet fuels. These modeling systems may result in a relatively wide range in GHG emissions, depending primarily on the treatment of co-products.

In the U.S., the only GHG requirement for aviation fuels is for government purchases to comply with EISA Section 526. The methods for measuring compliance are not examined in the same detail as the EPA RFS2 method. Understanding the GHG impact under this regulation as well as under the RED will allow jet fuel suppliers the greatest flexibility in generating credits under these programs. In the authors' opinion, a set of simple tools that mimics the EPA RFS2 analysis and simultaneously provides the results for the RED would be ideal. An approach to cover crops and crops grown on marginal lands is also necessary for many new biofuel feedstocks to assure that direct and indirect land emissions and credits are consistently taken into account.

7.3. Criteria Pollutant Emissions

Criteria pollutant (CP) emissions arise from combustion, fugitive losses, and other processes that occur during feedstock and fuel production, such as microbial nitrification and denitrification of nitrogen fertilizer to nitrogen oxides during crop cultivation. These pollutants reduce air quality and can harm populations and property; the severity of impacts caused by criteria pollutants varies significantly from low impact in remote areas to significant damage in urban areas or sensitive habitats. Criteria pollutant (CP) emissions can be minimized with emission abatement technology, such as particulate filters or selective catalytic reduction, but criteria pollutant emissions cannot be completely eliminated. Producers must balance the benefits of emission abatement technology with the higher costs associated with abatement.

[11] The EPA determines if categories of fuel/ feedstock combinations (for example switch grass to FT diesel by "any process" qualifies as a cellulosic biofuel with a 60% reduction in GHG emissions.

Criteria pollutant (CP) emissions contribute to health problems, photochemical smog, and acid rain. Criteria pollutants are regulated by the U.S. National Ambient Air Quality Standards (NAAQS) and the EPA provides a daily Air Quality Index (AQI) which provides an indication of local air quality. The AQI is related to the concentrations of pollutants and EPA provides an online calculator for converting between atmospheric concentrations and the AQI.

CP emissions include VOC, NO_x, SO_x, and PM. Photochemical smog includes these primary pollutants and secondary pollutants, including ozone (O_3) and secondary PM. CP emissions are known to increase rates of respiratory problems, eye irritation, cardiac arrest, cancer, and birth defects. These pollutants also participate in a wide range of chemical reactions in the atmosphere that can influence the oxidizing power of the atmosphere.

Total life cycle criteria pollutant emissions are calculated the same way that greenhouse gas emissions are calculated in life cycle analysis. However, total criteria pollutant emissions provide little insight towards environmental sustainability because they are distributed over open oceans, the upper atmosphere, urban airports, and rural farms. Determining the portion of total emissions that negatively affect humans or property is difficult because the regional distribution affects impacts. Many models, including GREET, apply urban share factors (percentages) to each fuel pathway step which represents the portion of the criteria pollutants that are emitted in urban areas. This approach is highly simplified and makes no attempt to model the actual dispersion of criteria pollutants from stationary and mobile sources to population centers using regional airshed modeling. Regional grouping of criteria pollutants can provide a better estimate of the effect on urban areas. Regional grouping is implemented in all of the California fuel LCA studies (Unnasch 1996, Unnasch 2001, Pont 2007).

As in the case of GHG emissions, several LCA tools calculate CP and air toxic emissions. These emissions are more difficult to interpret than GHG emissions which have global rather than local impacts. The impacts of CP emissions depend on the exposure to human populations or ecosystems and the exposure level varies significantly throughout the fuel cycle. In addition, the emission rates depend on site specific details, equipment type, condition, emission standards, and many other factors.

The relative CP metric for comparing CP performance among fuel pathways is grams of pollutant per MJ of fuel produced. When regional atmospheric data are available, CP equivalency factors may be developed that allow aggregation of the different CP emission species into a single air quality indicator. In most cases, these data are unavailable and assessments must consider individual pollutants or utilize generalized equivalency factors (which contributes significant uncertainty). Like the absolute metrics for energy and greenhouse gas emissions, the absolute CP metric can be conceptualized but not easily implemented. The absolute CP metric is kilograms of CP emissions annually per kilogram of “fair share” CP emissions for a specific project. Air permits provide a mechanism for assessing the CP impact of a facility, however, developing a consistent comparison is challenging. Air permits depend on grandfathering of prior facilities, purchases of offsets, and local regulations.

Further assessments of CP impacts can be accomplished with an air shed model, which calculates the concentration of each pollutant resulting from CP emissions under different scenarios.

Unlike GHG emissions, most of other pollutant emissions are considered problematic on a local or regional basis rather than a global basis. Therefore, the relative impact of these emissions should be determined by geographic location. Because of the importance of background pollutant concentration on the impact of pollutants affecting air quality, and the possibility that the background emissions vary among the regions where the feedstock and fuel are produced and where the fuel is used, an inventory of criteria pollutants on a life cycle basis may be misleading. As such, each of the components of the fuel supply chain is likely to be examined individually as well as on a life cycle basis. Life cycle GHG tools do not handle CP emissions as well as energy or GHG emissions. The range of local emission regulations as well as the spatial distribution of emissions makes CP emissions and air toxics from LCA models aggregate estimates. An LCA tool based on GREET could handle CP emissions in regional detail. The tool could be populated with regionally specific emission factors and emissions could be grouped by region. However, implementing this feature in GREET requires considerable data and analysis.

7.4. Water Impacts

Many different types and qualities of water supplies exist, including fresh ground water, pumped water, saline water, waste water, and many others. Water can also be classified as renewable water (aquifers that replenish on an annual basis) and non-renewable water ("fossil" water from isolated reservoirs that do not replenish. Because the different water categories have different availabilities, economic value, and other properties, the results should be considered separately for each water type.

Water consumption results represent water demand by a production pathway, which is not meaningful unless compared with the regional supply and demand for water – water stress indicators measure the imbalance between water consumption and available water resources. The water stress indicator typically used is the ratio of water consumption (or withdrawal) to the regional water available. This metric is a simplification of reality because aquifers have different rates of replenishment and other characteristics, but it provides a useful context for understanding water use on a project-level basis.

The Water Global Assessment and Prognosis (WaterGAP) model, developed by the Center for Environmental Systems Research (CESR) of the University of Kassel, calculates water consumption and withdrawal results for domestic manufacturing, electricity production, irrigation, and livestock sectors, in addition to water availability on river basin scale. The stress indicator ranges from low stress (0.1 – 0.2) in parts of South America, Canada, parts of Africa, Russia, Asia, and Australia to high stress (> 0.8) in the Western United States, Saharan Africa, the Middle East, and parts of Asia and Eastern Australia. The WaterGAP model generates color-coded maps indicating the water stress index on global, national, and regional levels.

Electricity generation and certain fuel processing steps require water withdrawn from a river, lake or sea for cooling, followed by discharge back in the water body at an elevated temperature; this is known as water withdrawal, or thermal pollution. Water withdrawal requires electricity for pumping the water, which also requires a small quantity of cooling water (with an associated electricity burden). Water withdrawal may be accounted on a life cycle basis similar to water consumption.

Water discharge encompasses any discharge involved in or leading to transportation fuel production that negatively impacts a water resource. Therefore, fuel pathway discharges include water discharges from processing steps in addition to discharges that result from vehicle/jet aircraft operating practices. Pollutant discharges from agricultural processes include nutrient pollution, toxic contaminants, and suspended solids (measured as total suspended solids). Water pollution discharges from fuel plants include organic compounds (measured by biological oxygen demand (BOD) and chemical oxygen demand (COD)), oil and grease, suspended solids, acids, and bases. Water pollution discharges from a facility are regulated and the facility must adhere to permitted pollution levels.

Feedstock production as well as biorefinery operation and fuel distribution often require the consumptive use of fresh water and result in the release of pollutants to the environment. Feedstock production consumes water through evapotranspiration of irrigation or rain water in the field. Biofuel refineries consume water through several mechanisms, including evaporation, incorporation into the fuel product, and discharge as effluent. Some fuel providers produce water from geological formations or through chemical reactions during feedstock or fuel processing. Water consumption is similar to energy consumption in several key respects. Like energy use, water consumption is a regional impact that includes a wide range of water types exhibiting differences in scarcity, chemical properties, and value. Additionally, water may be classified as renewable and non-renewable water, similar to energy, because some aquifers replenish on an annual basis and others are isolated reservoirs trapped in geological formations. Many water categories have been devised but most water life cycle analyses categorize water as ground water, surface water, saline water and waste water.

Negative impacts on water can include loss of water security, eutrophication of water ways, threats to fisheries and wildlife habitat from algal blooms and pollutants, and the introduction of harmful pollutants into drinking water supplies. Note that some biofuel pathways can use substantial quantities of water and result in fertilizer run off that affects waterways.
The production of petroleum jet fuel also results in water consumption and pollutant discharges. Renewable and petroleum fuel production pathways can result in spills from marine tankers, pipelines, and other transport modes. Understanding the relative impacts between renewable jet and petroleum jet requires a life cycle analysis.

The relative water use metric is liters of water (for each type) consumed per MJ of fuel produced. The ideal absolute water use metrics would be liters of water consumed or withdrawn per liter of “fair share” water for consumption and withdrawal. The relative metric for water pollutant discharges is grams of pollutant discharged per MJ of fuel delivered. The absolute metric for water pollutant discharge is grams of pollutant per gram of “fair share” pollutant discharge for a producer. Both metrics present complications in LCAs because of the potential for trans-regional supply chains for which water scarcity varies by economic operator. Similar to other resources, the "fair share" portion would be determined by measuring the water available annually at the watershed scale and dividing the resource into "fair share" allotments. Currently, the data are not available to assess the absolute water sustainability of a project, thus sustainability should be measured by adherence to permitted water consumption and withdrawal volumes and permitted pollution levels. The "fair share" portion for water pollution discharges could be assessed by a study of local waterways impacted by a project; the study would estimate the maximum discharge levels allowable to meet water quality standards.

Water impacts are part of LCA models such as GaBi and EcoInvent. Water impacts have recently been added to the GREET model and these could be incorporated into the same LCA model that calculates GHG emissions.

7.5. Biodiversity

Biodiversity is a complex ecological concept because it represents the net result of a complex set of interacting ecological, evolutionary, bio geographical, and physical processes. The definition of biodiversity is variable and usually depends on the highest conservation priority (e.g. habitat health, species indices, ecosystem function, net primary productivity, etc.). Most studies of biodiversity focus on organisms within an ecosystem or ecosystem types in contrast to the approach of public policy to biodiversity, which focuses on the values and functions of ecosystems (to provide products, ecosystem services, aesthetic value, etc.). Therefore, biodiversity assessment frameworks need to translate biodiversity data representing biodiversity assets into meaningful functions. Biodiversity cannot be assessed on a life cycle basis.

The UN Convention on Biological Diversity (CBD) has identified three main categories for biodiversity that include ecosystem diversity, species diversity, and genetic diversity. The CBD also identified the ecosystem level as the fundamental unit for describing biodiversity. The CBD concluded that the three diversity types are fundamentally incomparable and cannot be aggregated to determine the overall "size" of biodiversity. Other studies have shown that different measures of biodiversity such as species richness, family richness, endemism, and percentage of rare species or non-natives result in considerably different spatial patterns in the U.S. These complexities and the lack of biodiversity data have prevented the development of a national or international forum to standardize criteria and methods to assess and monitor biodiversity. However, environmental policies protecting biodiversity exist at the national level (National Environmental Policy Act (NEPA)) and at the state level.

The species count (number of species) is the most direct and simplest indicator of biodiversity. However, species count data encounter problems when the species occurrence data is scaled to represent larger areas. Longitudinal data can be misinterpreted to indicate an increase in biodiversity when new species that are favored by people (e.g. birds) displace the original species. The number of species is a crude indicator of biodiversity, because it provides very little information about diversity in the ecosystem gene pool, ecosystem diversity, or ecosystem resilience. An analysis of biodiversity pressures can be used to measure overall sustainability and are useful in evaluating pilot projects, monitoring and mitigation measures such as establishing more protected areas, GIS mapping of certain land types, or intensified agriculture scenarios (Spangenberg 2013).

Genetic diversity is considered a better indicator of biodiversity than species richness because genetic diversity is more closely related to resilience. Since unencumbered growth broadens the gene pool in an ecosystem and selective pressures reduce the gene pool, greater genetic diversity provides better resilience to extinction than a narrow gene pool. A similar principle applies to ecosystem diversity because the more ecosystem types present in a region during changing ecosystem pressures, the more ecosystems will survive preserving greater genetic diversity.

An integrated assessment model (IAM) framework can be performed for biodiversity assessments that cover a significant geographical area (national or global). National and global tracking systems have also been developed for indicators of system health (by invasive species, or extinction rates, endangered species, etc.). A taxon based or inventory based analysis is expensive and the cost typically prohibits evaluating un-mapped regions of the world. New studies based on trophic levels and the use of genetic mapping can greatly reduce fieldwork costs by representing indicator species based on evolutionary trends and not just abundance or richness.

Biodiversity can be significantly affected not only by land use change but also by the introduction of invasive species that spread into natural areas and displace native species. This covers more than just species number, although it often affects that, but it also affects ecosystem function, species distribution and evenness, species dominance, and the like.

The mean species abundance (MSA) indicator is utilized in the GLOBIO3 model which includes correlations of distance to roads/paved areas and nitrogen deposition. Over-laying land cover, protected areas at global and regional levels, GLOBIO3 models the sum of the underlying biome values, in which each square kilometer of every biome is equally weighted (ten Brink, 2000; UNEP, 2003, 2004, Alkemade 2009). MSA is an index which represents the mean trend in population size of a representative cross section of the species, in line with the CBD 2010 indicator for species abundance. The MSA addresses homogenization by dealing only with the original species in a particular area by tracking the original species (not all of which are endemic). This avoids the increase in the opportunistic species masking the loss in the original species.

Estimating biodiversity impacts on a life cycle basis, including indirect impacts is challenging. Land use for agriculture (and associated ILUC) combined with the MSA indicator is one approach for estimating biodiversity impacts.

Sustainability certification programs depend on site specific review of species and agricultural management practices. Such biodiversity assessments are conducted on a facility specific basis. Such evaluations examine the type of habitat and potential for impact on endangered species. Sustainability standards address the review of biodiversity impacts (RSB, CSBP, RSPO).

Feedstock and fuel production impact biodiversity directly and indirectly. Direct impacts arise through land conversion from native habitats to cropland and processing facilities, which destroys habitat and displaces wildlife. Indirect biodiversity impacts occur through mechanisms caused by humans, including pollution (air, water, noise and light), water withdrawals, habitat fragmentation and the introduction of invasive species. Depleting biological resources through land conversion may result in the loss of valuable known and unknown ecosystem services. Introducing invasive species could result in negative consequences for cropland, as well as on ecologically sensitive lands.

7.6. Soil Quality

Factors for maintaining and improving soil quality include the minimization of soil organic matter loss, soil erosion, soil salination, and soil compaction. Soil organic matter content helps with soil structure and accessibility of nutrients to plants, and organic matter is essential for maintaining soil vitality. Soil erosion leads to loss of nutrients. Soil salination leads to unhealthy soils where plants are not as productive, or they cannot grow at all. Soil compaction makes it difficult for roots to reach nutrients, thus limiting a plants productive potential.

Two types of baselines for soil quality have been developed: 1) how an activity affects soil quality relative to its original state and 2) how an activity affects soil quality relative to its intended function. These baselines can both be quantified by collecting the appropriate soil data and requiring farming management plans. Sustainability certification programs can include soil quality monitoring and specifications of management practices.

Crop production can have significant impacts on soil quality, including changes to soil organic carbon, salination, nutrient loss, compaction, and erosion. Degraded soil health is typically associated with feedstock producers who seek to maximize short term yields rather than prioritizing long term stability. Proper land management during feedstock cultivation can increase the soil organic carbon and overall soil fertility. Degradation of soil resources can impair the ability of the land to support future crops or habitats.

7.7. Land Use

Land use for crop production and other activities has several sustainability impacts. Conversion of land to biofuel crop production results in a change in net carbon and other GHG emission flux compared to the prior use of land due to the changes in crop type, tillage, and fertilizer application. Land conversion can result in an increase in CO_2 when stored carbon, especially in forests, is converted to crop production. Other types of land conversion can result in a net carbon storage (for example planting deep rooted perennial grasses on degraded land). Most calculations of land use conversion (LUC) focus on GHG emissions. Other environmental effects such as criteria pollutants from burning, soil erosion, nutrient run off, and impacts on biodiversity may also occur. Converting land from one use to another also results in indirect LUC. For example growing rapeseed on pasture would require converting other land to pasture or increasing animal stocking rates if overall food production is to remain constant. Indirect LUC is estimated with agro-economic models that predict the changes in land cover type associated with changes in demand for agricultural commodities. Crop residues and cover crops result in no indirect LUC provided that they do not affect agricultural production.

7.7.1. Agro-Economic Models

Modeling the land conversion and associated GHG impacts is typically accomplished with agricultural sector models combined with spatial, regional data and associated changes to the carbon cycle. This approach applies to biofuels grown on arable land and competition with other agricultural operations must be included. A variety of potential biofuel feedstocks are not grown on arable land that would compete for other agricultural activities. Such feedstocks include:

- Wastes (municipal)
- Residues: crops, forests, landscape (excess biomass without other uses)
- Cover crops (leguminous crops grown during fallow periods)
- Harvested wood products (tree trimming products, woodchips)

Agro-economic models are used to calculate LUC emissions from a combination of land cover change combined with emission factors associated with land cover types. Emission factors facilitate emission estimates from specific sources, i.e. agricultural land. The EPA and LCFS LUC analyses both combine different agro-economic predictions with bundled emission factors representing the changes in land cover. Table 3.9 summarizes the modeling approaches used in the EPA RFS2 and ARB LCFS LUC analyses. The agro-economic models used in these analyses are FASOM, FAPRI, and GTAP. More discussion of each of these models is given in the following subsections.

7.7.1.1. FASOM

The Food and Agricultural Sector Optimization Model (FASOM) was developed by Texas A&M University (FASOM 2003). It is used by the EPA to model LUC in the U.S. caused by the implementation of the RFS2. Originally, the FASOM was designed to evaluate welfare and market impacts of alternative policies for sequestering carbon in trees. It is now used to determine how the forest and agricultural sectors will affect carbon sequestration.

FASOM is a partial equilibrium economic model of the U.S. forest and agricultural sector that tracks over 2,000 production possibilities for field crops, livestock, and biofuels for private lands in the contiguous United States. A partial equilibrium model only takes into account part of the market. An example of a partial equilibrium model is a basic supply and demand graph for one good in which the effect on other goods is not considered. It accounts for changes in CO_2, CH_4, and N_2O from most agricultural activities and tracks carbon sequestration and carbon losses over time. FASOM estimates the cascading LUC impacts of all crop production within the U.S., not just biofuel feedstock. The model takes into account crop shifting and reduced demand due to higher prices for agricultural commodities including corn, wheat, rice, and livestock. The FASOM agricultural modeling is more detailed than FAPRI or GTAP, described below. However, the model is neither accessible to broad users nor applicable to LUC outside the U.S.

Table 7.1. Comparison of Agro-Economic Models for LUC Analysis

Model	**FASOM**	**FAPRI**	**GTAP**
Application	EPA RFS2	EPA RFS2	ARB LCFS
Region	U.S.	International (U.S. model is available but not applied to RFS2)	Global
Type	Partial equilibrium model of U.S. forestry and agriculture incorporating GHG emissions	Global partial equilibrium of agricultural sector	Global computational general equilibrium (CGE) with explicit treatment of land
Economic Categories	Multiple land and crops	39 economic regions	18 AEZs applied globally
Fuel demand	Demand for feedstock on agricultural system.	Demand for feedstock, modeling of blend wall[a], price effects	Biofuel shock with surrogate petroleum tax subsidy
Co-product treatment	DGS and SBM treated as separate agricultural commodities	DGS and SBM treated as separate agricultural commodities	Feed co-product subtracted from biofuel feedstock requirements
Co-product power	U.S. agricultural system power modeled by FASOM with addition of new power consumption from biorefineries.	Credit for power export from biorefineries using GREET emission factors	New power for ag and biorefineries included in GREET calculations with regional specific emission factors.
Carbon Accounting	Endogenous, direct emissions factors comparable to GREET. Land emissions from CENTURY	MODIS satellite data combined with Winrock analysis of land conversion factors	Land emissions based on Winrock analysis of IPCC factors applied to AEZs

CGE = Computable General Equilibrium; AEZ = Agro-Economic Zone; DGS = Distillers Grains and Solubles; SBM = Soy Bean Meal; IPCC= Intergovernmental Panel on Climate Change

[a]The ethanol blend wall is maximum ethanol production rate that can be absorbed into a regulated transportation fuel. With E10, the maximum blend level is 10%. Production beyond this blend will not be absorbed into the fuel pool.

7.7.1.2. FAPRI

Iowa State University and University of Missouri have developed the Food and Agricultural Policy Research Institute (FAPRI) system of global partial equilibrium agro-economic models to describe how international agricultural land use changes over time due to policy changes and global demand. The FAPRI models have been previously employed to examine the impacts of World Trade Organization proposals, changes in the European Union's Common Agricultural Policy, and many other analyses. The EPA uses the U.S. version of FAPRI models (FAPRI

2004) in combination with satellite predictions of the frontier of agriculture, and data from Winrock International (Winrock 2009) to estimate what land types will be converted into crop land in each country and the GHG emissions associated with those land conversions. This approach combines a detailed agro-economic model with a detailed assessment of the marginal impacts of land conversion. One of the questions that a FAPRI model helps to answer is how crop production and subsequent land use will change due to the growing demand for biofuels.

These agro-economic models include ethanol, grains, oilseeds, sugarcane, and livestock. The models examine and project production, use, stocks, prices, and trade for crops associated with the production of these goods. Unlike FASOM, the FAPRI models do not include changes in fertilizer or energy use or have land type interactions built in. The models predict how much crop land will change in other countries, but they do not predict what type of land, such as forest or pasture, will be affected. The FAPRI model provides a more detailed assessment of agro-economic impacts than GTAP.

The challenge with the FAPRI system is that the model is not accessible to the public. A reduced analysis that isolates land use by crop type and co-product and relates these to inputs such as yield effects and crop prices would be useful to enable broader use of the FAPRI analysis.

7.7.1.3. GTAP

The global trade analysis project (GTAP) agro-economic model is a multiregional, multi-sector, computable general equilibrium (CGE) bilateral trade model used by a wide international community of modelers to assess changes in land use. GTAP was developed at Purdue University (Hertel 2010). GTAP features lower resolution than partial equilibrium (PE) models, but broader market coverage. The model manages a global database of land and takes into account the total land resources available. Partial equilibrium models may not place a limit on global land availability. GTAP also takes into account prior trade and trade barriers in order to better predict the trade of crops among different regions of the world.

A CGE maintains the complex structure of the markets (many goods, many factors, and many countries) while simplifying the characterization of economic behavior (Hertel 2009). Because GTAP is a CGE model, it helps predict global supply and demand market changes. For example, if an increase in biofuel crops were to suddenly occur due to a policy change, GTAP models how the global market would respond.

The CGE model used by EPA is a special version of the GTAP model: the GTAP-Bio model. This model was developed specifically for climate mitigation policy and the potential for biofuels to substitute for petroleum products, and has since been used by dozens of groups to evaluate ILUC within explicit trade and agro-ecological zones. The current database is for 2006 and results are adjusted periodically to account for yield change. Current ILUC analyses incorporate this model (University of California, Berkeley, Purdue University) to evaluate land use conversion impacts of biofuel production expansion. This effort is used by ARB for the California Low Carbon Fuel Standard (LCFS).

There are several limitations to the GTAP model that must be addressed. GTAP does not contain the level of detail found in FASOM or FAPRI. Agricultural commodities are lumped into simple categories such as oil seeds (which represent soy, rapeseed, palm oil, etc.). While GTAP biofuel analyses can attempt to represent the dominant oil seed in a region (such as palm oil for Southeast Asia), modeling of the individual biofuel crops would be more transparent and accurate.

The lack of dynamic modeling in GTAP is a common criticism (EPA 2009). For example the FAPRI model works in time steps. An important feature of time stepping in models is the changing world population and demand on agricultural products is incorporated. However, in the view of this report's authors, the importance of dynamic effects alone on LUC has not been demonstrated.

The economic sectors for biofuel production are "hard wired" into the model based on biorefinery data as well as economic statistics. Thus the mix of feedstock, process fuels, electric power, capital, and other inputs correspond to only one scenario for biofuel production. Other biofuel configurations, perhaps with more co-products or different process fuels require the development of additional economic sectors. A more flexible approach enabling the adjustment of several factors of production (i.e. not just ethanol output) would be desirable.

7.7.2. Gaps in Sustainability Analysis

Even though methods have been developed for characterizing alternative fuel production, many uncertainties in quantifying the sustainability criteria remain. Very few of these data gaps are uniquely related to aviation fuels. They are described here to provide the reader with an understanding of the issues and uncertainty in assessing sustainable fuels. In some cases, filling the gap is relatively simple and well defined, such as measuring the emissions from a stationary biomass boiler. In other cases, the needed data are much more complex and difficult to assess, such as the emissions of nitrogen-containing species from biomass cultivation or regional biodiversity indices.

The primary gaps associated with aviation fuels are treatment of emissions in upper atmosphere and logistical issues associated with fuel comingling and the global distribution of fuels and flights.

Additional studies could be commissioned to address key data gaps including:

- Emission factors for stationary biomass and synthesis gas combustion technologies to assist with accurate life cycle GHG emissions characterizations
    - Biomass combustion emissions, which have not been characterized well in available models or literature sources
    - Nitrous oxide emission factors from biomass and synthesis gas combustion needs to be validated with more data
- Agricultural emissions and the nitrogen cycle

- Agricultural emissions, particularly nitrogen-containing emissions, are difficult to model accurately or measure adequately in the field
- The effect of organic nitrogen on N2O is inconsistently applied in fuel LCA models. For example, the EPA RFS2 uses soil models to calculate N2O emissions in the U.S. and IPCC Tier 1 methods for agriculture outside the U.S.

- Regionally-specific life cycle inventory data
  - U.S. average LCI data are available for most fuels and many fertilizers but these are not incorporated into fuel LCA models.
  - LCI data are needed for U.S. regions and other countries
  - Regional electricity LCI data based on data from eGRID and the Energy Information Administration need to be developed
  - Regional fertilizer production resource mix (coal, natural gas, etc.) needs to be identified
- Co-product credit methods, including naphtha and animal feed
  - The effect of hydrocarbon co-products from petroleum refineries and from renewable fuel production is not extensively analyzed in fuel LCA. Co-products such as naphtha and residual oil are treated either with energy allocation or a simplistic estimate of process based energy inputs (refinery efficiency)
  - Many fuel pathways produce co-products that can be sold as animal feed (e.g., soybean meal, defatted algae). The life cycle impact of co-products including indirect land use requires further research.
- Average vs. marginal resource use
  - Average resource mixes by geographic region are often used as the basis for the life cycle data for all LCA inputs. However, inputs such as electric power and nitrogen fertilizer vary significantly. The marginal sources for these resources is not well represented by the average life cycle data.
- Regional biodiversity indicators could be developed with land use as a proxy for biodiversity.
  - Land use based on land cover type can represent a simple proxy for biodiversity.
  - The MSA indicator could quantify species abundance.