Resilience Analysis and Value of Information with Application to Aviation Biofuels

A Dissertation

Presented to

the faculty of the School of Engineering and Applied Science

University of Virginia

in partial fulfillment

of the requirements for the degree

Doctor of Philosophy

by

Elizabeth B. Connelly

May

2016

APPROVAL SHEET

The dissertation

is submitted in partial fulfillment of the requirements

for the degree of

Doctor of Philosophy

AUTHOR

The dissertation has been read and approved by the examining committee:

James H. Lambert

Advisor

Reid R. Bailey

Peter A. Beling

Andres F. Clarens

Lisa M. C. Peterson

Accepted for the School of Engineering and Applied Science:

Craig H. Benson, Dean, School of Engineering and Applied Science

May

2016

ABSTRACT

Resilience analytics for interdependent, complex systems must be able to address deep uncertainties that can arise from surprising emergent conditions, multiple and oftentimes competing objectives, and diverse and changing stakeholder preferences. Methods for identifying resilient priorities need to be adaptable as conditions change over time and new threats arise. Directions for future research should be based on the value of information to understanding disruptive conditions. This dissertation introduces the Resilience and Lifecycle Analysis for Priority Setting (ReLAPSe) methodology, incorporating methods for strategic planning, risk analysis, and sustainability analysis. First, iterative problem framing is suggested as a mean to capture the current state of knowledge over time and problem dynamics to support the adaptability of strategic priorities. Stakeholder engagement and analysis is incorporated to elicit preferences, identify opportunities and concerns, and obtain pertinent, domain-specific knowledge. Multi-criteria analysis and scenario analysis are integrated to study scenario-based preferences as a means to identify emergent conditions disruptive to priorities. Lifecycle and other systems analysis methods are suggested to support robust and sustainable decision-making. The ReLAPSe method is demonstrated in a case study of aviation biofuels. In the first frame of analysis, seven criteria, thirty-seven supply chain initiatives, and twenty-five emergent conditions are identified through stakeholder elicitation. The results reveal scenario s_{04}*: Green preferences* as the most disruptive, due in part to increased importance of environmental quality. In the second frame of analysis, environmental life cycle assessment is incorporated to address various aspects of environmental quality. The second frame is based on over 40 hours of elicitation with stakeholders from government, academia, and industry specializing in aviation, agriculture, environmental protection, biofuel production, waste management, and energy solutions, among other areas. In this frame, sixteen biofuel pathways, six criteria, and five scenarios are identified. The results reveal low fossil fuel costs to be the most disruptive scenario to priorities. The outputs of the two frames of analysis are used with results from stakeholder and sensitivity analysis to identify resilient strategies for aviation biofuel research and development. Generally, the ReLASPSe method is applicable to priority setting across a variety of disciplines. In particular, the integration of life cycle assessment makes the method well-suited for strategic planning for innovative and sustainable technologies.

ACKNOWLEDGEMENTS

I am grateful to my dissertation committee consisting of Professor Lisa Colosi Peterson and Professor Andres Clarens of the Civil and Environmental Engineering department, Professor Peter Beling and Professor Reid Bailey of the Systems and Information Engineering department at the University of Virginia. I would like to express my sincere gratitude and appreciation to my advisor Professor Lambert for his guidance and support throughout the development of this dissertation. I am grateful to the members of my Airport Cooperative Research Program advisory team: Lawrence Goldstein, Airport Cooperative Research Program; Mary Sandy and Sarah Pauls, Virginia Space Grant Consortium; Linda Howard, Independent Aviation Consultant; Nathan Brown, Federal Aviation Administration. I would like to express my gratitude for the support from Richard Altman, executive director emeritus of the Commercial Aviation Alternative Fuels Initiative. I am thankful to the Commonwealth Center for Advanced Logistics Systems, specifically Thomas Polmateer and Mark Manasco. Finally, I would also like to thank my parents Arthur and Jeanne Connelly for their continuous support throughout my academic career. My effort has been supported in part through the National Science Foundation, the Airport Cooperative Research Program (ACRP), and the Metropolitan Washington Chapter of Achievement Rewards for College Scientists (MWC/ARCS) Foundation.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

A4A	Airlines for America
AHTL	Algal hydrothermal liquefaction
ASTM	American Society of Testing and Materials
ATJ	Alcohol-to-jet
BT2	USDA Billion Ton Update
CAAFI	Commercial Aviation Alternative Fuels Initiative
DOE	US Department of Energy
EPA	US Environmental Protection Agency
EROI	Energy return on (energy) investment
EU ETS	European Union Emissions Trading System
F2F2	Farm to Fly 2.0
FAA	US Federal Aviation Administration
GHG	Greenhouse gas
GIS	Geographic information system
GWP	Global warming potential
HEFA	Hydroprocessed esters and fatty acids
HHM	Hierarchical holographic modeling
HTL	Hydrothermal liquefaction
ICAO	International Civil Aviation Organization
LC-GHG	Life cycle greenhouse gas
LCA	Life cycle assessment
LCC	Life cycle costing

MASBI	Midwest Aviation Sustainable Biofuels Initiative
MCDA	Multi-criteria decision analysis
MJ	Mega-Joule
MSW	Municipal solid waste
R&D	Research and development
ReLAPSe	Resilience and Lifecycle Analysis fro Priority Setting
RFS	US Renewable Fuel Standard
RIN	Renewable identification number
SAFN	Sustainable Aviation Fuels Northwest
SIP	Synthesized Iso-Paraffinic
VOI	Value of information

CHAPTER 1: INTRODUCTION

1.1 Overview

This chapter provides the introduction to this dissertation. Section 1.2 describes the problem statement being addressed. Section 1.3 describes the motivation for studying the resilience of priorities. Section 1.4 describes the purpose and scope of this dissertation. Section 1.5 describes the organization of the remainder of this dissertation, providing a diagram of the following chapters.

1.2 Problem Statement

Resilience is a term that was introduced with respect to ecology (Holling 1973) and has since taken on a wide variety of meanings depending largely on the application domain. Resilience as a concept is gaining attention from academics and policy-makers. As systems become more interconnected and complex, planning for resilience becomes ever more important for risk management. There is a need to develop resilience analytics that can support strategic planning for diverse fields and applications.

Systems engineering is an interdisciplinary field that involves the design and implementation of complex systems. Being interdisciplinary in nature means that systems engineers must integrate knowledge and methods from diverse fields. Systems integration generally refers to communication between system elements (technological, human, or organizational) to ensure proper system functioning (Sage and Lynch 1998). For human decision-making, systems integration can be viewed as communicating knowledge between different relevant fields. A current gap in systems engineering theory is the integration of the concept of resilience into strategic planning process that is generalizable to all disciplines.

Resilience analytics for complex systems must be able to address deep uncertainties that can arise from surprising emergent conditions, multiple, sometimes competing objectives, and diverse and changing stakeholder preferences. Methods for designing resilient strategic plans need to be adaptable as conditions change over time and new threats arise.

Resilience analysis is particularly important for nascent and innovative industries. Strategic plans for innovations should be designed with consideration of a wide array of potentially disruptive conditions. Lifecycle analysis, which can include environmental life cycle assessment and life cycle cost analysis, is important to identifying and understanding uncertainties that arise across the entire system life cycle. The next section will describe the motivation for performing resilience analysis of priorities to changes in mind.

1.3 Motivation

Disruptive events such as natural disasters, terrorist attacks, and other “crises” can lead to changes in the values of the public and policy-makers. These changes in mind lead to different priorities, which have the potential to vary drastically compared to the original set of priorities. For example, in the early 1970s, American oil consumption was increasing even as domestic oil production was decreasing. Policymakers appeared to discount the need for domestic production instead believing that Arab oil exporters were too dependent on revenue from the U.S. to significantly reduce supply or increase prices. After the 1973 Organization of Arab Petroleum Exporting Countries (OAPEC) embargo led to an energy crisis in the U.S., these beliefs began to shift and energy conservation measures gained appeal. That change in priorities and values was reflected by the Energy Policy and Conservation Act of 1975 and the creation of the Department of Energy in 1977. As climate change mitigation has gained support, further changes in mindset can be seen through the passage of the Energy Independence and Security Act of 2007, which among other things was intended to increase the production of clean renewable fuels.

Changes in preferences can lead to different strategies for the government as well as private industry. Instead of studying resilience *ex post facto,* future uncertainties need to be explored to inform priority setting and enhance the resilience of strategies to emergent "crises." Systems analysis and engineering appreciates the dynamic nature of mission and problem statements. This dissertation will apply systems and lifecycle thinking to increase resilience of priorities to changes in mind.

1.4 Purpose and Scope

The purpose of this dissertation is to introduce the Resilience and Lifecycle Analysis for Priority Setting (ReLASPSe) method to identify value of information about disruptions to priorities. Although resilience has taken on many definitions since it's original conception for ecological systems (Holling 1973), much of the focus has been on the environment and human psychology (Hosseini, Barker, and Ramirez-Marquez 2015). The concept of organizational resilience has addressed the need for considering resilience adaptive capacity related to decision making for supply chains, project selection, and even corporate structuring (Horne and Orr 1998; Sutcliffe and Vogus 2003; Sheffi 2005; Sheffi and Rice Jr 2005; Ponomarov and Holcomb 2009; Ouyang and Wang 2015; Connelly, Thorisson, et al. 2016), but has not touched on the resilience of the decisions themselves. Therefore, the purpose of this dissertation is to fill this gap by proposing resilience analytics for strategic decision-making, which will build on the proposal of Ritman (2014) who pointed out the need for science to inform resilient decision-making. Figure 1 describes how this work builds on previous conceptions of resilience, moving beyond resilience of physical systems.

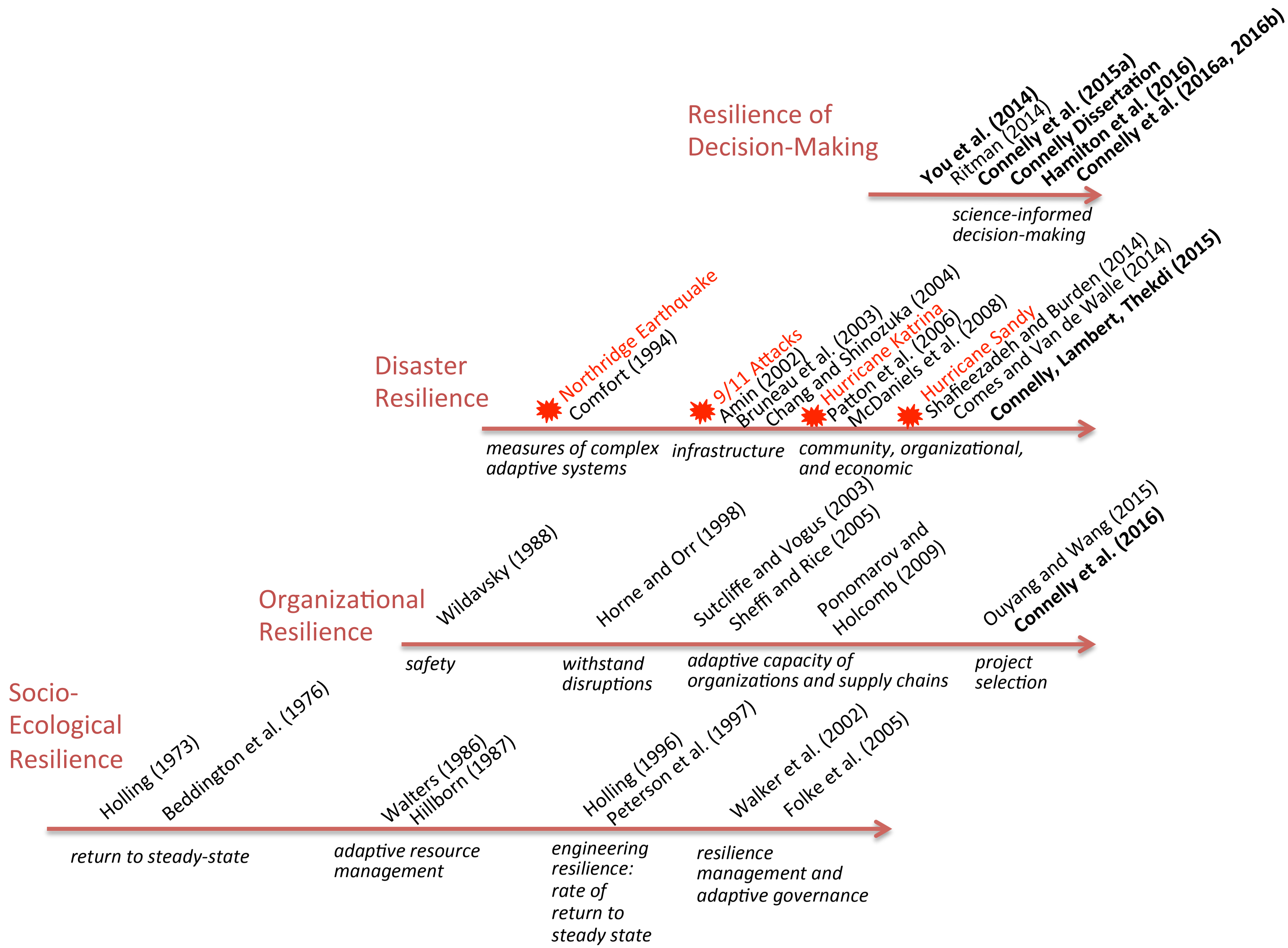

Figure 1. Contributions of this dissertation to resilience literature and concepts.

Particularly for analyzing energy systems with environmental, economic and social considerations, integrating life cycle assessment (LCA) with systems analysis methods (e.g., scenario analysis, MCDA, etc.) is useful for identifying sustainable alternatives (Santoyo-Castelazo and Azapagic 2014). Life cycle assessment methods are widely used in business strategy, research and development, and policy development (Cooper and Fava 2006) and thus applicable to a variety of stakeholders for these and other purposes. While there surely have been a number of applications, there is currently little formal description of how to incorporate life cycle assessment with decision analysis with consideration for future uncertainties. Figure 2 describes how the contributions of this dissertation fit with previous life cycle analysis and decision analysis literature.

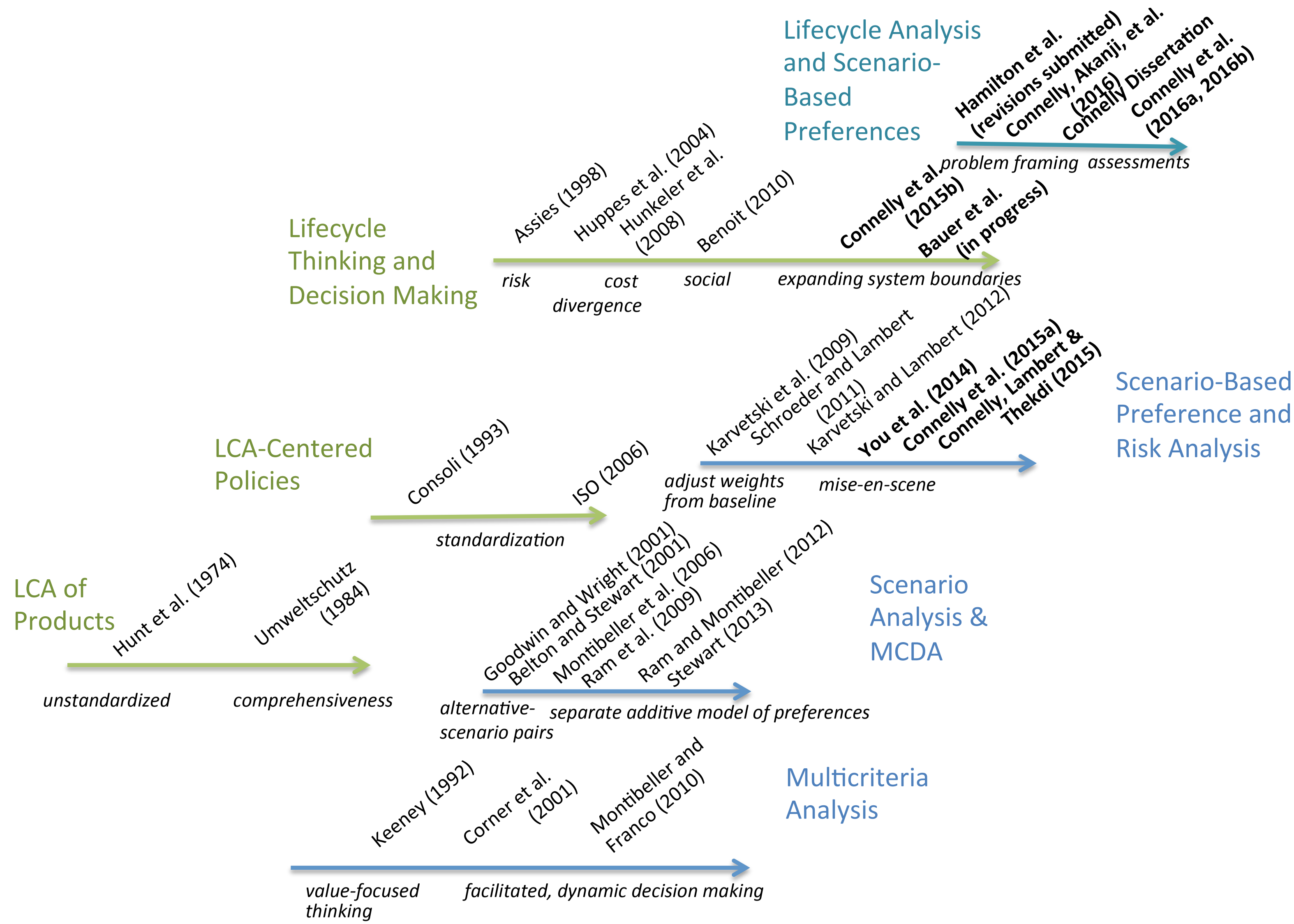

Figure 2. Contribution of dissertation to lifecycle analysis and scenario-based preferences for strategic priorities.

This dissertation will integrate lifecycle analysis with multi-criteria and scenario analysis and to apply theses methods for resilience analysis of strategic plans, with demonstration of the methods for the aviation biofuel industry. The effort will consider multiple scales and perspectives via iterative problem framing. The effort will support resilience of strategic plans and priorities where the robustness of these plans to scenario uncertainties is essential to quantify and address. Iterating the analysis for different scopes and systems boundaries will serve to demonstrate the importance of holistic systems analysis for problems of global importance by showing how the disruptiveness of uncertainties differ according to perspective. Different techniques will be applied depending upon the frame of analysis (i.e., viewpoint, scale, perspective, etc. being considered). The two frames of analysis that will be demonstrated in the dissertation consider different system boundaries:

i) Resilience analysis for initiatives and investments spanning the aviation biofuel supply chain;
ii) Resilience analysis for aviation biofuel feedstock(s) selection in the Commonwealth of Virginia.

The approach will evaluate the sensitivity of a prioritization of research and development initiatives in order to determine the most influential scenarios, showing what are the greatest needs for knowledge. The approach avoids several of the common practical shortcomings of traditional risk assessment, which include that diverse sources of expertise (political, technological, economic, etc.) are ignored, real-world alternatives are not mutually exclusive, probabilities cannot be reliably assessed or agreed, and/or that the event space of future conditions is not complete. Reframing the problem statement and scope, aided by life cycle assessment, can lead to a more holistic systems analysis with refinement of criteria, initiatives, and scenarios, compared to that from a single perspective. The results can inform decision makers on the robustness of initiatives and the disruptiveness of various emergent and future conditions, both alone and in combination.

The intent of this work is to make a number of contributions to the theory of resilience and systems engineering, resilience analysis methodologies, and application for aviation biofuels as follows:

Contribution 1 Resilience of Priorities: Conceptualization of resilience analytics as the identifications of emergent conditions disruptive to priorities (Connelly and Lambert 2016a; Connelly and Lambert 2016b). This constitutes a *major* contribution of this dissertation.

Contribution 2 Integrating Lifecycle Analysis: Integration of life cycle assessment with resilience analysis for strategic decision making (Connelly and Lambert 2016a; Hamilton et al. 2016). This is a *major* contribution of this dissertation.

Contribution 3 Resilience of Supply Chain: Demonstration of resilience analysis for aviation biofuel supply chains (Connelly, Colosi, et al. 2015a). This application is a *minor* contribution of this dissertation.

Contribution 4 Algae Biofuel LCA: Life cycle assessment of an innovative algal biofuel pathway (i.e., hydrothermal liquefaction), considering upstream and downstream factors of the system lifecycle (Connelly, Colosi, et al. 2015b). This demonstration of life cycle assessment constitutes a *minor* contribution of this dissertation.

Contribution 5 Resilience of Feedstock Priorities: Demonstration of resilience analysis integrated with life cycle assessment to prioritize potential feedstocks for aviation biofuel production (Connelly and Lambert 2016b; Collier, Connelly, and Lambert 2016). Demonstrating the integration of life cycle assessment with resilience analysis to prioritize feedstocks for ongoing F2F2 efforts in the Commonwealth of Virginia constitutes a *minor* contribution of this dissertation.

Contribution 6 F2F2 Recommendations: Identification of strategic state-level initiatives to support the development of an aviation biofuel supply chains (Connelly and Lambert 2016b). This constitutes a *minor c*ontribution of this dissertation.

Figure 3 describes how these contributions to the literature fit with regards to theory, methodology, and applications. Figure 4 describes the timeline of these contributions in addition to other efforts that have supported this dissertation. Table 1 in the following section describes how these contributions are related to the chapters of this dissertation.

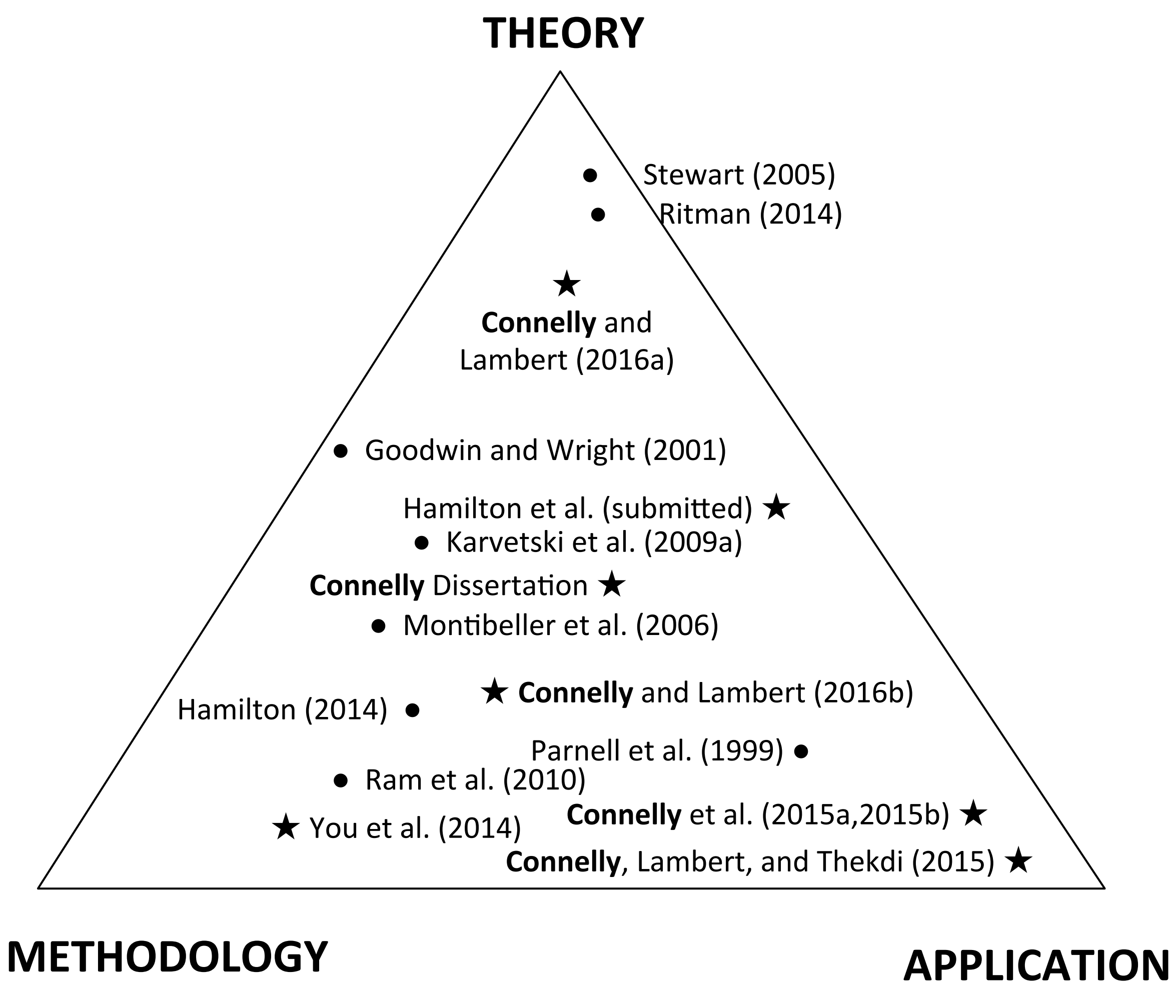

Figure 3. Contributions to the literature in the theory, methodology, and application of risk analysis methods to study the resilience of strategic priorities.

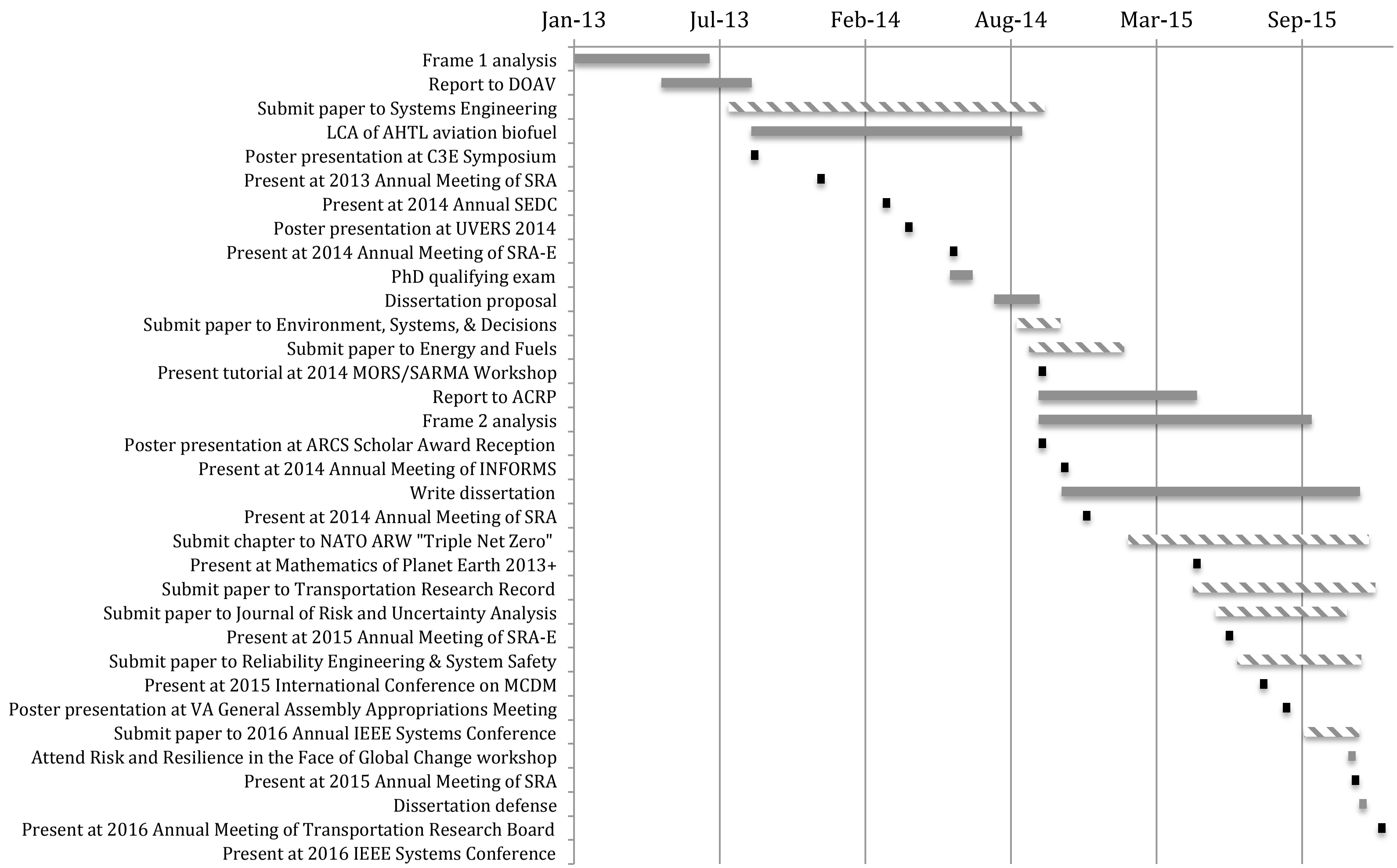

Figure 4. Timeline of effort for the completion of this dissertation. Black rectangles represent presentations, striped rectangles represent archival journal submissions, and grey rectangles represent other research efforts.

1.5 Organization of Dissertation

The remainder of this dissertation will propose a method of resilience analytics for strategic planning and demonstrate the methods for regional aviation biofuel development. Figure 5 provides a diagram of the following chapters.

Chapter 2 will review the literature on methods including: risk analysis, multi-criteria decision analysis, scenario analysis, scenario-based preferences analysis, and resilience analysis.

Chapter 3 will discuss the philosophy behind resilience analytics for strategic planning.

Chapter 4 will describe the technical approach for resilience analysis and the component methods.

Chapters 5-9 will demonstrate resilience analysis for aviation biofuels. Specifically, Chapter 5 will apply scenario-based preferences analysis to aviation biofuel supply chains.

Chapter 6 will demonstrate environmental life cycle assessment for an innovative aviation biofuel conversion pathway, algae hydrothermal liquefaction.

Chapter 7 will demonstrate how life cycle assessment results and other supplementary data can be integrated with scenario-based preferences analysis of aviation biofuel feedstocks.

Chapter 8 will demonstrate scenario-based preferences analysis of aviation biofuel feedstocks and will describe potential disruptions to feedstock prioritization.

Chapter 9 will provide an overview of sensitivities and disruptive conditions to aviation biofuel research and development strategies and will recommend initiatives for regional or state research and development.

Chapter 10 will discuss validation of the presented approach for resilience analysis and will describe limitations of the methods.

Chapter 11 will provide a summary of the dissertation, will describe the contributions of this work and will recognize areas for future research.

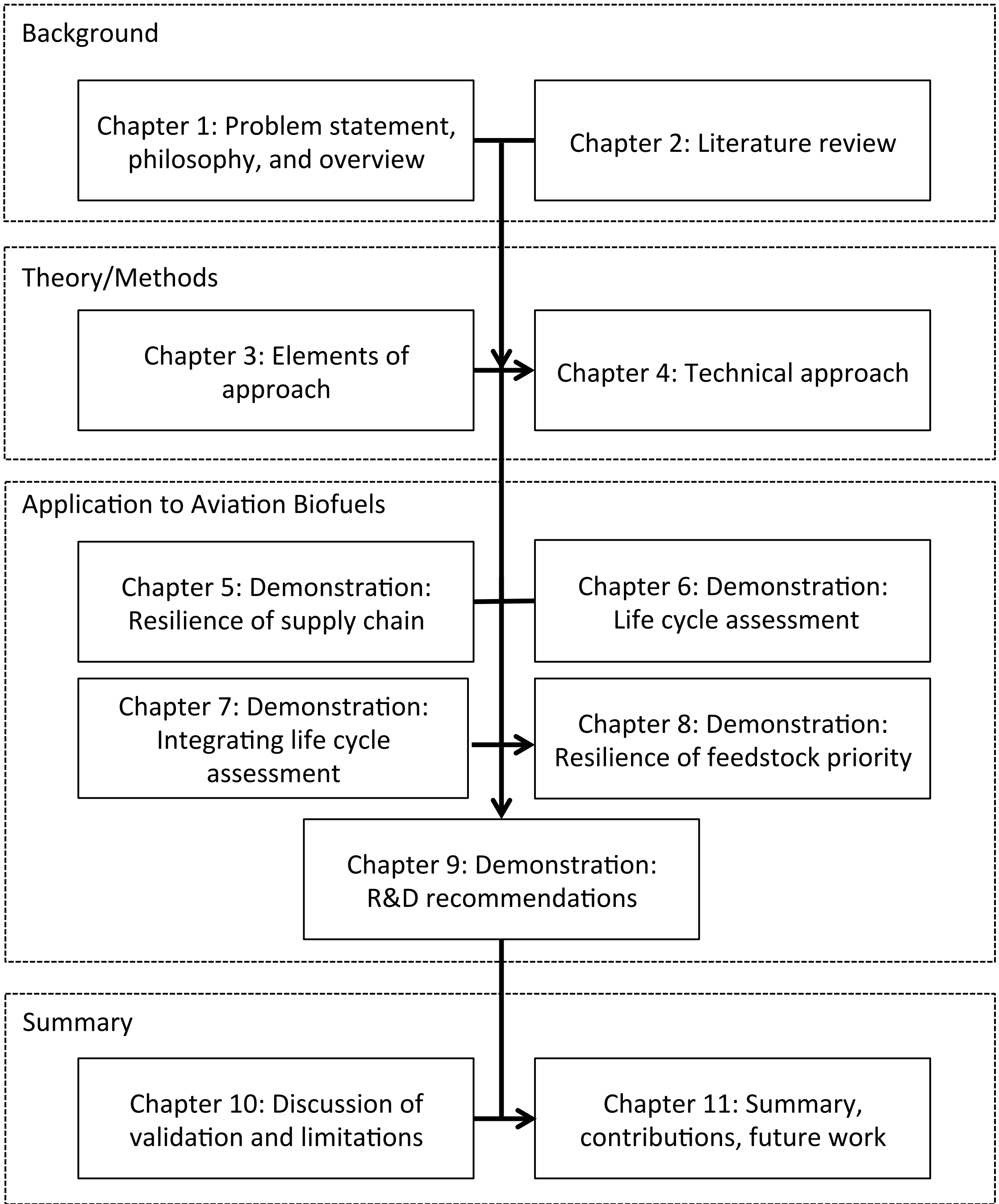

Figure 5. Diagram of dissertation chapters

Table 1. Relevance of contributions to each chapter of this dissertation. The icons indicates strong (●) and medium (○) relevance, blank indicates minimal relevance.

	Contribution 1 Resilience of Priorities	Contribution 2 Integrating Lifecycle Analysis	Contribution 3 Resilience of Supply Chain	Contribution 4 Algae Biofuel LCA	Contribution 5 Resilience of Feedstock Priorities	Contribution 6 F2F2 Recommendations
Chapter 1	○	○				
Chapter 2	○					
Chapter 3	●	○				○
Chapter 4	●	●	○			
Chapter 5	●		●			○
Chapter 6		○		●		○
Chapter 7	○	●		○	○	
Chapter 8	●	●			●	○
Chapter 9	○	○	○	○	○	●
Chapter 10	○	○				
Chapter 11	○	○				

CHAPTER 2: LITERATURE REVIEW

2.1 Overview

This chapter provides a literature to support resilience analysis. Section 2.2 describes system-based approaches to risk analysis, considering risk as the influence of scenarios on priorities. Section 2.3 describes the use of multi-criteria decision analysis for strategic prioritization of initiatives. Section 2.4 describes scenario analysis as a means to explore uncertainties that could impact strategic plans. Section 2.5 describes how MDCA and scenario planning can be integrated into multiple framings of scenario-based preferences analysis to explore the impact of changing preferences on priorities. Section 2.6 describes the variety of application domains for resilience analysis and the current gaps in the literature.

2.2 Systems-Based Risk Analysis

The concept of *risk* has traditionally been defined as the measure of probability and severity of adverse effects (Lowrance 1976). Kaplan and Garrick (1981) describe a quantitative definition with their triplet of questions: (i) what can go wrong; (ii) what is the likelihood; and (iii) what are the consequences. The systems engineering community, on the other hand, introduced risk identification, which is mostly qualitative as opposed to probabilistic risk assessment. For example, Haimes, Kaplan, and Lambert (2002) describe the use of Hierarchical Holographic Modeling (HHM) as a framework to identify, prioritize, assess, and manage risk scenarios of a large-scale system. Further, Kaplan, Haimes, and Garrick (2001) integrate HHM with scenario development for risk analysis and Haimes (2009) describes the use of multi-criteria modeling for risk analysis and assessment.

In 2009, the International Standards Organization defined *risk* as the effect of uncertainty on objectives (ISO 2009). More recently, *risk* has been reconsidered as the influence of scenarios of on priorities (Martinez, Lambert, and Karvetski 2011; Karvetski and Lambert 2012; Thekdi and Lambert 2014; Schroeder and Lambert 2011; You et al. 2013; Hamilton, Lambert, et al. 2013; Hamilton, Thekdi, et al. 2013; Hamilton, Lambert, and Valverde 2015; J.H. Lambert et al. 2012; Lambert et al. 2013; Teng, Thekdi, and Lambert 2012). Analyzing risk, under this definition, has involved multi-criteria analysis, stakeholder preference analysis, and scenario analysis to capture the disruptiveness of future uncertainties to current priority setting. Using these methods iteratively and at multiple scales increases the usefulness of the techniques for strategic planning by incorporating views and values that can change over time (Hamilton 2014).

Haimes (2009b) describes a systems-based approach to understand the relationship between risk, vulnerability, and resilience, which centers on using risk scenarios to represent an initiating event and analyzing the impacts of that event on the system. Aven (2011), however, claims that the definitions of risk, vulnerability, and resilience introduced by Haimes (2009a; 2009b) do not adequately take into account uncertainty. Specifically, resilience must incorporate the concept of uncertainty and surprises.

Uncertainties for which quantification is not possible, from lack of consensus or information on probability distributions of system variables, have been termed deep uncertainties and studied in the context of systems-based risk analysis (Cox 2012; Karvetski and Lambert 2012; You 2013; Lempert et al. 2006). Deep uncertainties complicate decision-making and are necessary to identify and characterize in order to select robust strategies (Lempert et al. 2006).

Value of information (VOI) analysis has been suggested as a method to evaluate the benefits of reducing uncertainty through collecting additional information. Identifying areas for further research or information collection provides useful insights for risk management decisions (Yokota and Thompson 2004). Various forms of VOI analysis and info-gap decision theory (Ben-Haim 2001) have been used for exploring uncertainty and supporting robust decision making, especially with respect to the environment and climate change (Korteling, Dessai, and Kapelan 2013; Lempert et al. 2006; McDaniels et al. 2012). While the formal methods of VOI analysis can be computationally intensive, risk management can benefit from filtering risks not based on probability and severity but instead on the value of information of disruptions to priorities.

2.3 Multi-Criteria Analysis

The earliest lifecycle phases in systems engineering consist of problem definition, identifying objectives, identifying alternatives, and constructing a value framework by which to refine alternatives (Sage and Armstrong 2000). Stakeholder input is essential for these preliminary stages of strategic development (Buede 2011). Multi-criteria decision analysis (MCDA) provides a value framework by which stakeholders can make strategic decisions (Keeney 1992; Kleinmuntz 2007). Montibeller and Franco (2010) describe the use of MCDA to address the cognitive burden of evaluating a large set of interconnected strategic decisions.

Multi-criteria analysis is particularly well suited for problems that are multi-stakeholder, multi-requirement in nature, such as those related to bioenergy systems (Scott et al. 2012). Wang et al. (2009) discuss the use of MCDA as a means for facilitating sustainable energy decision-making addressing technical, economic, environmental, and social objectives. MCDA has previously been applied to sustainable energy planning (Espen 2007; Tsoutsos et al. 2009), renewable energy systems (Scott, Ho, and Dey 2012; Troldborg, Heslop, and Hough 2014; Perimenis et al. 2011; San Cristóbal 2011), and biofuel supply chains (Hughes and Shupe 2010; Haddad and Fawaz 2012; Mendes et al. 2012), among other areas.

However, there are shortcomings of traditional MCDA methods for strategic decisions including the assumption that alternatives are mutually exclusive and collectively exhaustive, the reliance on accurate probabilities of outcomes, and the use of expected value to select the best alternative (Montibeller and Franco 2010). Strategic planning often occurs in cases where these assumptions do not all hold. Specifically, when the probability of outcomes can be difficult to estimate with any accuracy and may be influenced by future emergent conditions. Multi-criteria analysis needs to be able to address uncertainties without necessarily making assumptions about the likelihood of occurrence (Stewart 2005).

2.4 Scenario Analysis

Schwarz (1991) introduced scenario-based planning for strategic decision-making. Scenario analysis, unlike predictions or forecasts, respects uncertainty inherent in complex systems (Swart et al. 2004). Schoemaker (1991) emphasized that scenarios should *collectively* bound the perceived range of possible futures, as opposed to representing mutually exclusive or exhaustive futures. Scenario planning, however, remains useful even without representing the full range of possible futures. Goodwin and Wright (2001) describe the usefulness of scenario analysis to address uncertain conditions without the use of subjective probabilities, which are subject to cognitive biases (e.g., overestimation). Scenario planning is able to address deep, structural uncertainties for which probabilities cannot reliable be assigned in addition to representing multiple viewpoints on possible futures (Bryant and Lempert 2010; Karvetski and Lambert 2012).

Heijden (1996) describes the use of participatory scenario planning as a means for business and organizations to deal with uncertainty affecting strategic planning. The use of scenario analysis has also been demonstrated for a multi-level, multi-actor climate change adaptation context (Vervoort et al. 2014). Saritas and Aylen (2010) suggest using scenario analysis in the development of research and development strategies, demonstrating the usefulness specifically for sustainable technologies. Lee, Song, and Park (2014) also promote the use of scenarios for technology research and development plans in general. Strategic decision-making for allocating resources for research and development, especially for emerging technologies and industries that are subject to high levels of uncertainty, can benefit from the use of scenario analysis. Peterson, Cumming, and Carpenter (2003) discuss several examples of scenario planning for corporate strategies and policy making and conclude with the following three major benefits of scenario planning: (i) increased understanding of uncertainties; (ii) incorporation of multiple perspectives into the planning process; and (iii) greater resilience of decisions to surprise.

2.5 Integrated Scenario-Based Preferences Under Multiple Time Frames

Integration of decision analysis with scenario planning has been suggested as a flexible, simple, and transparent approach for strategy evaluation and selection (Goodwin and Wright 2001). In the context of investment or R&D strategies, the integration can identify which strategies are robust across various alternate future scenarios (Parnell et al. 1999; Ram, Montibeller, and Morton 2010). Durbach and Stewart (2012) were able to use simulation to verify the usefulness of scenario models in multicriteria analysis and find that the combination results in increased robustness. Past studies have focused on small sets of scenarios, typically three or less, and a single decision maker (Comes and Hiete 2009; Montibeller, Gummer, and Tumidei 2006; Goodwin and Wright 2001).

Stewart (2013) discusses various models of scenario-based MCDA, including scenario-based weighting, and suggests the following four guidelines:

i) Construction of 4-6 scenarios;

ii) Scenarios defined in terms of exogenous drivers (i.e., emergent conditions);

iii) Scenarios cover ranges of outcomes and key associations between variables;

iv) When there are substantial differences in the fundamental values of stakeholders, scenarios should represent different ideal worlds.

Scenario-based MCDA, in line with the above guidelines, has been applied to energy security and infrastructure investments (Karvetski and Lambert 2012; Lambert et al. 2012; Karvetski, Lambert, and Linkov 2011) and climate change impacts on transportation infrastructure assets (Lambert et al. 2013; You et al. 2013; Karvetski et al. 2011), among others. Dyer et al. (1992) consider increasing robustness of traditional MCDA problem formulation by moving away from a reliance on a fixed set of decision alternatives with the application of fuzzy set logic or other techniques.

Iterative analyses can increase robustness in decision-making, especially when considering different combinations of future scenarios (Lempert 2003; Groves and Lempert 2007). Analyzing different scenarios as new information provides insight on potential disruptive emergent conditions is essential for long-term strategic decision-making. In addition, the consideration of multiple problem frames serves to identify when decision makers are exhibiting irrational reversals of preference as described by Tversky and Kahneman (1981). Re-framing the problem, especially through introducing new criteria, can help to ensure the robustness of priorities.

Preferences have been observed to shift throughout stakeholder engagement and information exchange (Phillips and Costa 2007; Tompkins, Few, and Brown 2008). Thus, over time it is important to consider different scenarios associated with shifts in preferences. Hamilton (2014) introduces the notion that scenario identification can evolve with each iteration of scenario-based preference analysis. This dissertation furthers employs iterative analysis in combination with life cycle assessment to guide the formation of an R&D roadmap for innovative biofuels.

2.6 Resilience Analysis

The concept of resilience was first introduced with respect to ecology and the natural environment (Holling 1973). The majority of resilience theory with respect to socio-ecological systems has focused on the return and rate of return to a steady-state, for example in predator-prey models (Beddington, Free, and Lawton 1976; Holling 1996; Peterson, Allen, and Holling 1997). Since then, resilience has been discussed in a variety of contexts and the term has been increasing in popularity (over ten-fold) since 1995 (Longstaff, Koslowski, and Geoghegan 2013). In their review of resilience literature, Hosseini, Barker, and Ramirez-Marquez (2015) distinguish four resilience application domains: organizational, social, economic, and engineering. In particular, resilience to natural and other disasters has recently gained attention (Raj et al. 2015; Fiksel, Croxton, and Pettit 2015; Hamel and Välikangas 2003; Comfort 1994; Amin 2002; Bruneau et al. 2003; Chang and Shinozuka 2004; Shafieezadeh and Ivey Burden 2014; T. A. Comes and Van De Walle 2014; Connelly, Lambert, and Thekdi 2015), especially with regards to supply chains.

Folke (2006) describes how managing for resilience involves sustaining desirable pathways for societal development under unpredictable and surprising future scenarios. The original conception of resilience, introduced with respect to ecology by Holling (1973), later evolved to highlight the need for adaptive management processes which emphasizes preparing for surprises and uncertainty (Folke 2006). Stressors caused by climate change have been a major focus of psychosocial and social-ecological resilience research in recent years (Matin and Taylor 2015). Fath, Dean, and Katzmair (2015) describe stages of an adaptive cycle for social systems and conclude that continuous modeling is needed for resilience of social or business organizations. Vogus and Sutcliffe (2007) relate organizational resilience to safety, as the capacity to investigate, learn, and act on some unknown stressor or hazard.

Depending on the system being studied, the definition of resilience varies. Woods (2015) groups current definitions of resilience into the following four conceptual perspectives: (i) how a system rebounds from a disruptive event; (ii) the robustness of a system in responding to stressors; (iii) how a system extends performance via adaptability to respond to surprise challenges; (iv) sustained adaptability as emergent conditions from layered networks continue to evolve. Common among the four definitions is the need for a resilient system to be able to continuously change or adapt in anticipation of potentially disruptive events. Longstaff, Koslowski, and Geoghegan (2013) similarly conclude that a common theme among resilience definitions is "the survival or persistence of something over time even if there is a change, a surprise and/or uncertainty."

Systems engineering involves analyzing complex systems and understanding their current and emergent vulnerabilities. There is a need for defined systems analysis frameworks to address the risks to systems of systems (Dahmann, Rebovich, and Turner 2014) and encourage system resilience (Madni and Jackson 2009). As the complexity of systems grows, challenges for risk management increases (Madni and Jackson 2009). Haimes (2009) views resilience enhancement as an integral part of risk management. Madni and Jackson (2009) distinguish resilience engineering from risk management with the claim that resilience engineering is proactive and forward-looking rather than based on historical probabilities of failure. While risk analysis tends to focus on threats, resilience analysis can also explore how even opportunities are surprising and potentially disruptive, in a less adverse context.

Although resilience definitions have been grouped based on application or field of study, the interconnectedness of systems means there is the need to understand holistic resilience. For example, Castellacci (2015) attempt to gain a higher-level understanding of resilience by exploring the relationship between organizational resilience, innovation, and national institutions which include economic, social, and engineered systems. Recognizing the many factors that contribute to resilience, Folke et al. (2010) discuss how transformational change can involve changes in perceptions, societal preferences, and political, organizational, and institutional arrangements that change the state (and possibly variables) of complex systems. Following this line of thought, resilience analytics must allow for system dynamics and interactions. Duijnhoven and Neef (2014) describe how with complex systems there are alternative, complementary, and conflicting values and views of the problem (i.e. perspectives on system resilience) and cite the need for a holistic resilience management approach.

Similarly, a conclusion from the resilience literature review performed by Bhamra, Dani, and Burnard (2011) is a need for a resilience conceptualization that can transcend the variety of contexts to which it has been previously discussed, which include individual, organizational, supply chain, community, and ecological. Linkov et al. (2013) cite the need for resilience metrics that capture both planning and recovery, and list one major obstacle to defining such a metric is the fragmentation of resilience knowledge into different domains. Hosseini, Barker, and Ramirez-Marquez (2015) remark on generalized definitions of resilience spanning multiple disciplines, which tend to focus on the ability of a system to absorb shocks or bounce back from emergent disruptions. They conclude, however, that further research is needed to support generalized guidelines for planning for resilience. This sentiment is echoed by dos Santos and Partidário (2011) who assert the need for the resilience to be incorporated into policy and planning processes. They claim that resilience is now becoming a broader theoretical framework, beyond simply recovery from disturbance and return to equilibrium. Woods (2015) concludes that there is an ongoing need for the design of architectures that sustain adaptive capacities over time. Policy and other decision makers are ultimately responsible for designing resilient systems, which will depend on their interpretation of resilience (Duijnhoven and Neef 2014).

While decision-making and strategic planning have been performed with consideration for resilience of systems, little to no attention has been paid to the resilience of the strategic plans. Resilience is a concept that has been applied to ecological systems, human psychology, and infrastructure systems, but has not yet been conceptualized as the robustness of strategic plans. Of the seventy-four papers resilience-related papers reviewed by Bhamra, Dani, and Burnard (2011), seventeen covered the topic of strategy. These papers, however, address strategies to enhance the resilience of ecological systems, communities in the face of crises or disasters, supply chains and business operations. Enterprise or organizational resilience comes closest to addresses the resilience of strategic plans. Starr, Newfrock, and Delurey (2003) argue that “a resilient organization effectively aligns its strategy, management systems, governance structure, and decision-support capabilities so that it can uncover and adjust to continually changing risks, endure disruptions to its primary earnings drivers, and create advantages over less adaptive competitors.” Clearly, Starr et al. (2003) recommend strategic plans that are adaptable, but they do not specifically address how decision makers can ensure such resiliency of strategic plans. While adaptability of business strategies are cited to enhance enterprise resilience (Hamel and Välikangas 2003; Starr, Newfrock, and Delurey 2003), there has been little discussion in the organizational resilience literature as to how to develop resilient business strategies in the face of changing conditions and missions.

2.7 Chapter Summary

This chapter has reviewed literature on risk-based systems analysis and resilience analysis. Combining multicriteria analysis and scenario analysis for multiple problem framing can address current needs in resilience analytics. The following chapter will describe how these methods combined with life cycle analysis create a framework for resilience analytics to support strategic planning.

CHAPTER 3: ELEMENTS OF APPROACH

3.1 Overview

This chapter describes elements for resilience analysis of strategic plans. Section 3.2 describes the importance of life cycle analysis to support resilient decision making. Section 3.3 describes the role of decision and scenario analysis. Section 3.4 describes the purpose and benefits of iterative problem framing to encourage resilient and adaptable planning. Section 3.5 describes the role of resilience analytics in multi-stakeholder strategic planning.

3.2 Lifecycle Analysis for Resilience

Effective resilience analysis needs to incorporate considerations that span the entire system lifecycle. Madni and Jackson (2009) find empirical evidence to support the need for resilience analysis to explicitly address risks and disruptions throughout the system lifecycle. Environmental life cycle assessment and life cycle cost analysis in particular can help to identify potential risks to the system. Specifically, life cycle assessnent has been suggested as a part of resilience analysis for the design of sustainable innovations (Fiksel 2006; Fiksel 2003).

Youn, Hu, and Wang (2011) discuss the importance of considering life cycle costs when evaluating system resilience design alternatives. Designing systems with a high number of redundancies, while meant to increase reliability and resilience, also increases life cycle costs and can make resilience engineering prohibitively expensive. The tradeoffs between cost and system performance should be evaluated when deciding on strategic plans. Dovers and Handmer (1992) discuss the importance of risk analysis and systems lifecycle thinking to address environmental, social, political, and economic changes, as these changes can impact resilience and sustainability.

3.3 Decision and Scenario Analysis for Resilience Analytics

Resilient decision-making requires the ability to both anticipate and deal with unexpected influences Giezen et al. (2015). Fiksel, Croxton, and Pettit (2015) discuss the shortcomings of risk management and resilience techniques as being unable to address emergent risks arising from improbable and uncertain events. Scenario analysis provides a means of characterizing emergent conditions alone and in combination, to discover disruptions to strategic decisions. Haimes (2009), like Walker et al. (2002), endorse the use of scenario analysis for understanding and evaluating resilience.

Walker et al. (2002) describes the role for decision analysis and scenario analysis in resilience management of in social-ecological systems as identifying policy scenarios that maximize expected utility. Such an application of decision analysis requires making assumptions on the probability of system trajectories for each policy scenario. There are a number of additional issues with using decision analysis in this way, which include differences in stakeholder preferences or utility functions and a lack of consideration for preference changes due to emergent conditions (Walker et al. 2002) .

Scenario-based preferences modeling avoids the need for defining utility functions or probability distributions in facilitating decision making. Combining MCDA and scenario analysis supports strategic planning. Resilience analysis is able to identify which scenarios are disruptive to strategic plans proactively. By including resilience analysis in the strategic planning process, stakeholders are aware of potentially disruptive events and are enabled to address these risks.

3.4 Iterative Problem Framing for Resilience Analytics

Incorporating multiple problem frames into resilience analysis allows stakeholders and decision-makers involved in strategic planning to update candidate strategies through a continuous learning process. Duijnhoven and Neef (2014) acknowledge that resilience management should consider frames dependent on stakeholders, problem definition, time frame, and current state of the system. Linkov et al. (2013) also discuss the importance of the learning process to enable continuous improvement of the state of the system and future planning.

Various approached to resilience analysis have previously incorporated iterative problem framing. Walker et al. (2002) describe an iterative approach to social-ecological system resilience management which includes cycles of problem framing, scenario analysis, measuring resilience, and stakeholder evaluation. For strategic planning, Hamel and Välikangas (2003) describe resilience as being able to continuously anticipate and adjust to trends that can permanently impair performance via the dynamic reinvention of business strategies. Robust system design is an iterative process that should involve stakeholders reconsidering criteria, requirements, and alternatives over the entire system life cycle (Sols 2015).

3.5 Integrative Resilience Analysis for Strategic Priorities

Woods (2015) explains “the value of the differing concepts [of resilience] depends on how they are productive in steering lines of inquiry toward what will prove to be fundamental findings, foundational theories, and engineering techniques.” The conceptualization of resilience as rebound and robustness directs inquiry to reactive and restoration phases, as opposed to encouraging proactive planning for resilience. Not only is strategic planning needed to promote resilience of physical systems, resilience analysis is needed for strategic planning that considers uncertainties and potential disruptive conditions.

Walker et al. (2002) describe the importance of stakeholder engagement in discovering resilient pathways or strategies. Stakeholder elicitation serves to reveal knowledge and mental models for designing strategies to address a variety of concerns and potential future scenarios. Further, stakeholder engagement is key for achieving a collectively and socially accepted solution (Walker et al. 2002). Resilience analytics brings disruptive scenarios of preference changes to the forefront of multi-stakeholder strategic planning. This conception of resilience analysis can be used to support strategic planning for diverse stakeholders. Figure 6 describes how the elements discussed in this chapter can be integrated for resilience analysis of priorities.

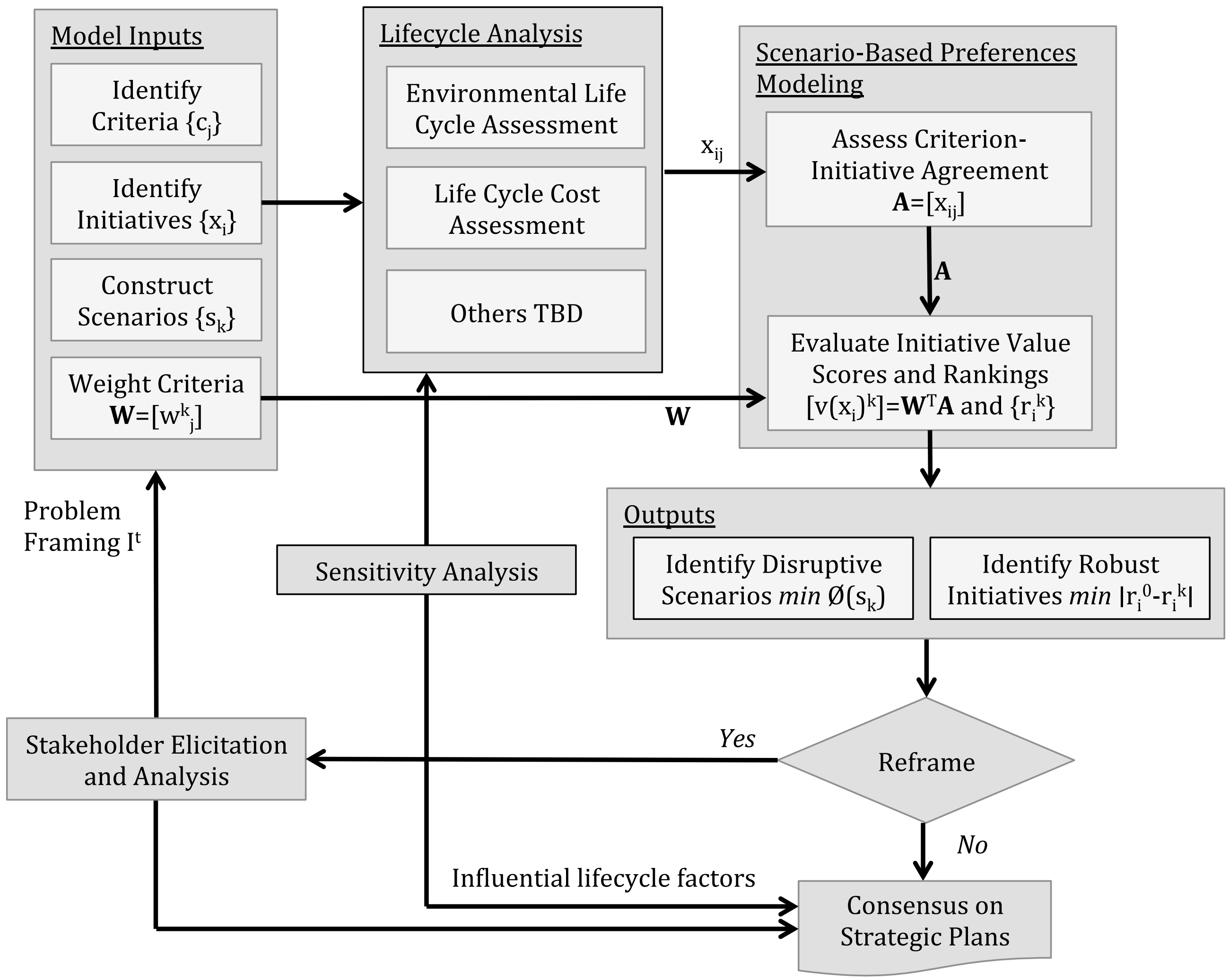

Figure 6. Conceptual diagram for ReLAPSe methodology

3.6 Chapter Summary

This chapter describes elements to an approach for resilience analysis of strategic plans that builds on past risk analysis methods. Specifically, the approach will incorporate elements cited in the literature: (i) multicriteria decision analysis; (ii) scenario analysis; (iii) life cycle assessment and other supplementary analytical techniques; (iv) iterative problem framing. These methods allow for continuous updating of the problem statement and system boundaries based on current knowledge and stakeholder analysis. This method provides a means of supporting resilience for planning across a variety of disciplines and hinges on the defined needs of decision-makers. The next section will describe the technical approach to resilience analysis.

CHAPTER 4: TECHNICAL APPROACH

4.1 Overview

The chapter describes the methodology for resilience analytics for strategic research and development planning. Section 4.2 describes preliminary problem framing of scenario-based preferences modeling. Section 4.3 describes the methodology for environmental life cycle assessment. Section 4.4 reviews how life cycle assessment can be integrated into risk analysis, MCDA, and scenario-based preferences analysis. Section 4.5 discusses subsequent problem framing for scenario-based preferences analysis. Section 4.6 describes how these methods can be combined to constitute resilience analytics for strategic planning of research and development efforts.

4.2 Frame I(t) of Scenario-Based Preferences Analysis

The technical approach begins with the initial frame of scenario based preferences analysis, which will be referred to as frame I(t). The notation is adapted and extended from the scenario-based preferences analysis introduced by Karvetski et al. (2009), Schroeder and Lambert (2011), Parlak et al. (2012), Lambert et al. (2012), and Connelly (2013). Figure 7 describes a technical approach for analysis of scenario-based preferences.

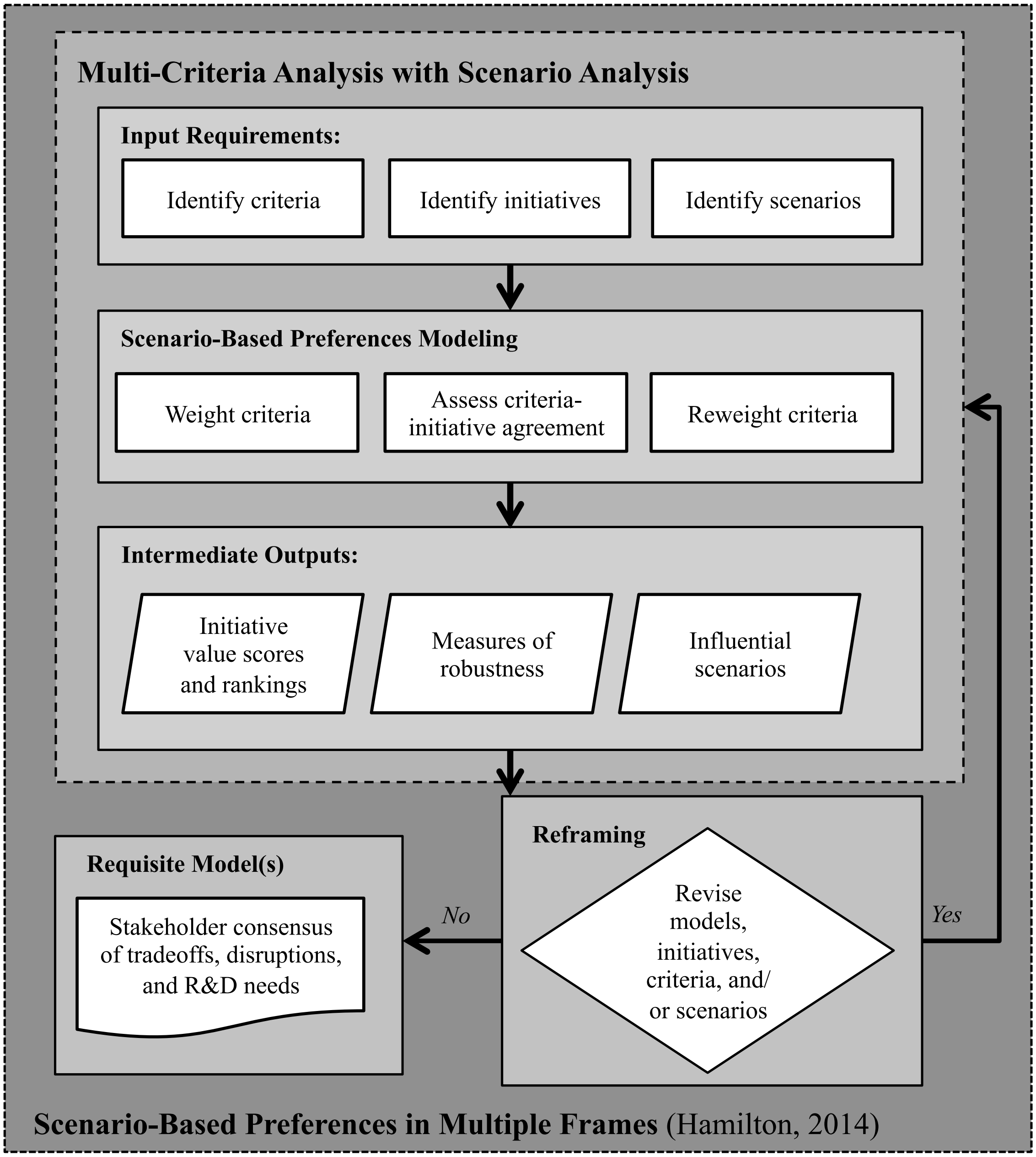

Figure 7. Scenario-based preferences analysis in multiple frames based on methodology introduced by Hamilton (2014).

From the results of stakeholder elicitation and analysis, the set $S_c=\{c_1,\ldots,c_m\}$ is defined to represent the set of *m* criteria used for evaluating initiatives. Examples of criteria may include cost, economic development, environmental sustainability, and others. The set $S_x=\{x_1,\ldots,x_n\}$ represents the set of *n* initiatives being considered. An *m* x *n* matrix *A*, containing score x_{ji} is used to evaluate how each initiative x_i addresses each criterion c_j.

The set $S_{ec}=\{ec_1,\ldots,ec_p\}$ represents *p* emergent conditions that are used for scenario building. The set $S_s=\{s_1,\ldots,s_q\}$ represents a variety of scenarios to address future uncertainties, as a combination of one or more emergent conditions.

The importance of each criterion may vary in accordance with each scenario s_k, where $s_k \in S_s$. The term w_i^0 represents the weight of each criterion in a *baseline* scenario, s_0. An increase or decrease of importance for each criterion in the weight for each criterion is reflected by the factor multipliers α_1, α_2 where $0 > \alpha_2 > \alpha_1 > 1$ as described in Equation 1.

$$w_i^k = \begin{cases} \alpha_1 {w_i}^{0\prime}, & \text{for increase in importance} \\ \alpha_2 {w_i}^{0\prime}, & \text{for somewhat increase in importance} \\ {w_i}^{0\prime}, & \text{for no change in importance} \\ \frac{1}{\alpha_2} {w_i}^{0\prime}, & \text{for somewhat decrease in importance} \\ \frac{1}{\alpha_1} {w_i}^{0\prime}, & \text{for decrease in importance} \end{cases} \tag{1}$$

The normalized weights w_i^k are then used for the multi-criteria value function. Thus, the value function $v(x_i)$ is defined for each scenario s_k where $v(x_i)^k \in [0,100]$, as follows:

$$v(x_i)^k = 100 \times \textstyle\sum_{j=1,m} w_j^k x_{j,i} \tag{2}$$

The value function is then used to rank initiatives for R&D performance in response to scenarios. Let r_i^0 represent the ranking of initiative x_i in the *baseline* scenario, and r_i^k is the rank of initiative x_i in scenario s_k. Top rank is assigned such that $r_i^k = 1$ if $v(x_i)^k > v(x_j)^k$ for all $i \neq j$, meaning that an initiative receives a preferable ranking (i.e., nominally lower) if it has a higher value score than another initiative.

The impact of a future scenario s_k can be quantified by aggregating the change in the rank order of decision alternatives under this scenario relative to the baseline scenario. Karvetski et al. (2011) first proposed a squared error metric to quantify the scenario influence. You et al. (2013) extended this by introducing a coefficient for this metric so that the value is bounded in [0, 1] and comparable across problems of different scale. However, the bounded metric only functions given full rankings (i.e., permutations). Further, the bounded metric is biased when alternatives tie for some positions in the ranking. Unfortunately, ties are common when priority setting relies on categorical or natural-language based assessments. For rank distance, the Gamma statistic and Kendall Tau-b are commonly used to measure the distance between two sets of ordinal values when ties are allowed (Somers 1962). The Gamma statistic simply ignores the tied paired, which tends to underestimate the disruptiveness of a scenario in this context. Kendall Tau-b performs adjustments for ties based on original Kendall Tau distance (Laurencelle 2009). Moreover, the values of the Kendall Tau coefficient are nearly normally distributed for small n and the distribution is easier to work with (Chok 2010).

You et al. (2014) developed a metric based on Kendall Tau-b to determine the vulnerability of systems to scenarios of stressors. The metric is based on number of concordance rankings, the number of discordance rankings, and number of rankings tied in the priority-setting result under baseline scenario as well as the number of rankings tied in the priority-setting result under scenario $\mathrm{s_k}$. Concordance and discordance refers to the relationship between pairs of ranking values. Two pairs of rankings $\left(\mathrm{r_i^0}, \mathrm{r_i^k}\right)$ and $\left(\mathrm{r_j^0}, \mathrm{r_j^k}\right)$ are said to be concordant if both $r_i^0 > r_i^k$ and $r_j^0 > r_j^k$ or both $r_i^0 < r_i^k$ and $r_j^0 < r_j^k$. The pairs are said to be tied if either $r_i^0 = r_i^k$ or $r_j^0 = r_j^k$. Otherwise, the pairs $\left(r_i^0, r_i^k\right)$ and $\left(r_j^0, r_j^k\right)$ are discordant.

Kendall and Smith (1939) discuss the appropriateness of comparing two sets of ordinal rankings using the Spearman coefficient. Sheskin (2003) also describe Spearman's rank correlation coefficient as a common measure of the similarity between project rank sets derived from multi-criteria methods. Svensson (2001) describes the appropriateness of the Spearman rank-order correlation coefficient for measuring association, as at least as appropriate as the Kendall Tau-b. For this dissertation the Spearman rank-order correlation coefficient will be used to measure the disruptiveness of a scenario s_k:

$$\phi(s_k) = 1 - \frac{6\sum_{i=1}^{n}\left(r_i^k - r_i^0\right)^2}{n(n^2-1)} \tag{3}$$

The value of $\phi(s_k)$ approaches 1 as the changes in initiatives' rankings under the scenario decrease. For example, $\phi(s_k) = 1$ when the ranking of all initiatives under scenario s_k is the same as in the baseline scenario. Thus, lower values of $\phi(s_k)$ indicate that scenario s_k is disruptive to priorities. Further, the rankings also reveal how priorities change under various scenarios and identify initiatives that are most robust to the portfolio of scenarios analyzed.

4.3 Life Cycle Assessment

Life cycle assessment (LCA) is a tool for calculating and analyzing the environmental impacts associated with products, processes, or systems. Figure 4 describes the life cycle assessment methodology. The concept of LCA was introduced in the 1970s and began as a way to compare products' environmental impacts, based on systems analysis of the product from "cradle to grave" (Guinee et al. 2011). In the 1990s, there were efforts to standardize life cycle assessment techniques, encouraging it to become a more accepted and applied analytical tool. In 1994, the European Union passed legislation promoting the use of life cycle assessment of packaging (*European Parliament and Council Directive 94/62/EC of 20 December 1994 on Packaging and Packaging Waste* 1994). Ever since, life cycle assessment has proven useful to political, commercial, and individual decision-makers. For example, the US Renewable Fuel Standard depends on assessing lifecycle greenhouse gas emissions of renewable fuel pathways, providing industry decision-makers incentive to consider life cycle impacts of their activities.

Life cycle costing (LCC) is described as a second pillar of sustainability assessment of products, services, and systems, complementary to environmental life cycle assessment (Hunkeler, Lichtenvort, and Rebitzer 2008). Social or socio-economic life cycle assessment constitutes the third pillar of sustainable development (Benoît 2010). These methods build on the importance of life cycle thinking for assessing impacts of providing products or services or introducing new systems. Guinee et al. (2011), while agreeing with the importance of multi-faceted consideration of externalities, describes that these approaches "may have consistency problems with environmental life cycle assessment in terms of system boundaries, time perspectives, calculation procedures, etc."

The accuracy of life cycle assessment is important for supporting and enforcing policies, product claims, and consumption decisions that aim to minimize the negative environmental and other consequences of the system being studied. To date, however, there remain issues with life cycle assessment methodologies that compromise the quality and degrade confidence in results from these assessments.

Reap et al. (2008a; 2008b) provide a list of 15 problems associated with life cycle assessment. By identifying these issues, the authors highlight areas for future research (i.e., techniques to avoid and mitigate the problems), as well as articulating problems that decision-makers need to consider. In their survey, they categorize the problems according to which of the four phases of life cycle assessment in which the issues occur: (i) goal and scope definition, (ii) life cycle inventory, (iii) life cycle impact, and (iv) interpretation.

The fifteen problems common of life cycle assessment are listed in Table 1. Based on problem magnitude, likelihood, and chance of detection, the authors rank the problems in terms of severity. Four of the problems were considered to stand out above the others in terms of severity: allocation, spatial variation, local environmental uniqueness, and data availability and quality. The authors add to this list functional unit definition and boundary selection to constitute what they call "critical problems requiring particular attention."

To address the problems of functional unit definition, boundary selection, and allocation, the authors suggest integrative research on classifying types of life cycle assessment and identifying the most appropriate approach to these goal and scope and life cycle inventory analysis problems. Alleviating the problems for life cycle impact assessment will involve spatially explicit models, which could be overly complex and expensive to actually be feasible. The development of standardized databases that describe uncertainty distributions and other details of data (e.g., collection method, sampling frequency, date, etc.) with provisions for being updated would offer a partial solution to data quality issues.

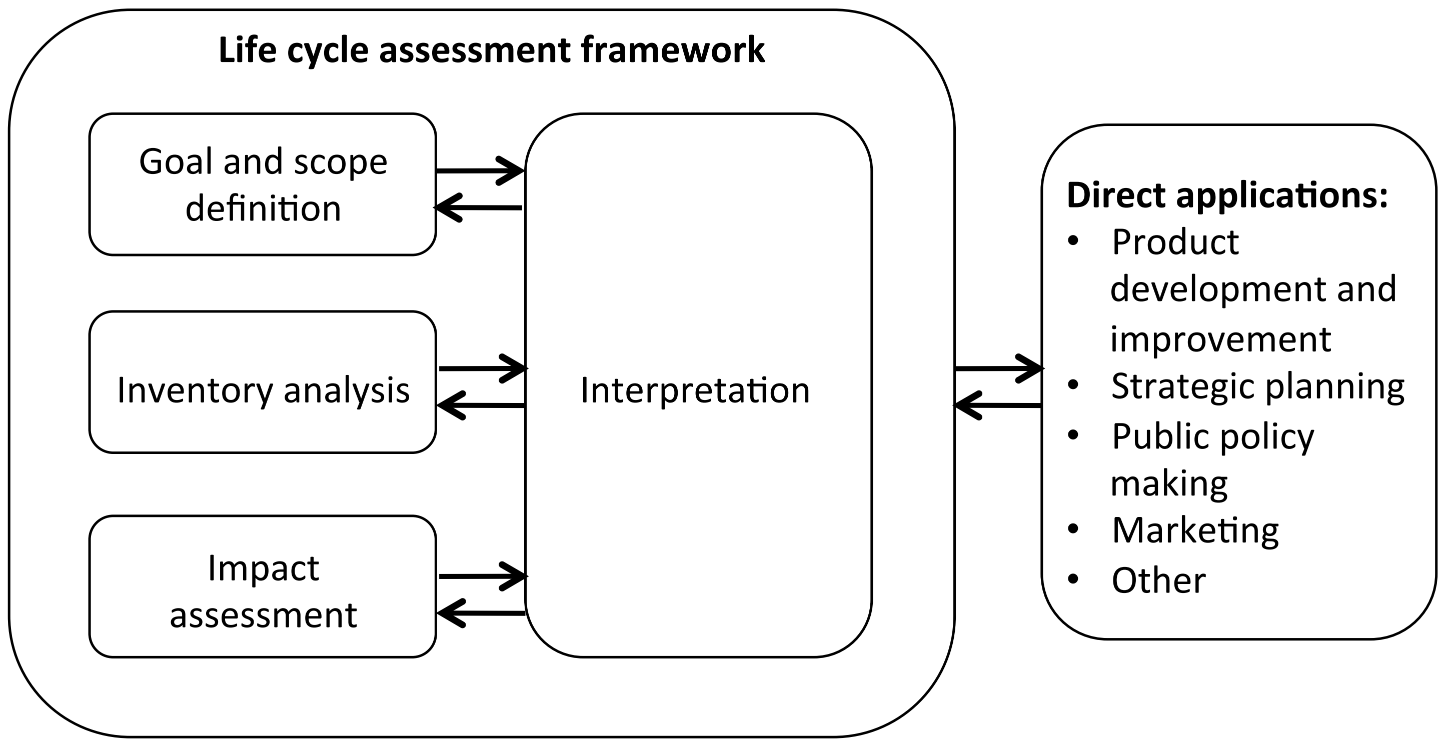

Figure 8. Life cycle assessment methodological framework and application, adapted from Guinee et al. (2011).

Table 2. Current issues associated with life cycle assessment (Reap et al. 2008a; 2008b).

Issues	Phase of LCA
1) Functional unit definition 2) Boundary selection 3) Social and economic impacts 4) Alternative scenario considerations	Goal and scope definition
5) Allocation 6) "Cutoff" criteria 7) Local technical uniqueness	Life cycle inventory analysis
8) Impact category and methodology selection 9) Spatial variation 10) Local environmental uniqueness 11) Dynamics of the environment 12) Time horizons	Life cycle impact assessment
13) Weighting and valuation 14) Uncertainty in the decision process	Life cycle interpretation
15) Data availability and quality	All

4.4 Integration of Life Cycle Assessment with Scenario-Based Preference Analysis

Life cycle assessment was invented as a technique for comparing environmental burdens of various products or services by analyzing all inputs and outputs throughout the entire life cycle. With a similar emphasis on goal definition and boundary selection in preliminary steps, life cycle assessment constitutes a method of systems analysis (Gibson, Scherer, and Gibson 2007; Guinée 2002a). Benoit and Rousseaux (2003) provide an analogy between LCA and MCDA methodologies, which is expanded here to show the relation to systems analysis in Table 2. These assessments are useful to political, commercial, and individual decision-makers, especially when environmental sustainability is valued.

Table 3. Expansion of the analogy between LCA and MCDA presented by Benoit and Rousseaux (2003) to show the relationship with systems analysis.

LCA **(Guinée 2002b)**	MCDA **(Benoit and Rousseaux 2003)**	Systems Analysis **(Gibson, Scherer, and Gibson 2007)**
1. Goal and scope definition	1. Definition of the objectives 2. Definition of the systems to be compared	1. Determine goals 3. Develop alternative solutions
2. Inventory analysis	4. Criteria evaluation	2. Establish criteria
3. Impact analysis		
3.1 Impact classification	3. Building coherent family of criteria	
3.2 Impact characterization	4. Criteria evaluation	
3.3 Impact valuation/aggregation	5. Modeling preferences and aggregating results of criteria	4. Rank alternatives
4. Interpretation	6. Sensitivity and robustness analysis	5. Iterate
LCA does not perform decision making →Application of decision analysis	7. Synthesis of results and formulation of recommendations	6. Action

Jeswani et al. (2010), and others, argue for the integration of methods such as MCDA with LCA in order to strengthen sustainability analysis and decision-making. Hermann, Kroeze, and Jawjit (2007) acknowledge the complementary characteristics of LCA and MCDA – LCA is objective, reproducible, and (in theory) standardized; MCDA incorporates subjectivity of stakeholders' opinions and values. Much of the research on and integration of LCA and MCDA has been in using MCDA as a means of weighting life cycle impact categories. In particular, the AHP method of MDCA has been applied for developing environmental criteria weights for solid waste management (Contreras et al. 2008) and environmentally preferred purchasing decisions (Gloria, Lippiatt, and Cooper 2007), among other applications. Others have also described alternative MCDA methods to develop weights for life cycle impact categories to support environmental decision making (Myllyviita et al. 2012; Seager and Linkov 2008). For the most part, it appears that the LCA community and others interested in "clean production" have realized the role MDCA can play in making sustainability decisions, but it has largely been overlooked by the MCDA community. For example, the *Journal of Multi-Criteria Decision Analysis* has not published a single paper demonstrating the use of environmental life cycle assessment for sustainability decision-making.

LCA-based decision-making with the inclusion of multi-criteria and uncertainty analysis has recently been studied in the context of biofuel technologies (Holma et al. 2013). In that study, only environmental tradeoffs were analyzed in comparing lignocellulosic biodiesel to algae biodiesel. Santoyo-Castelazo and Azapagic (2014) suggest a decision-framework that includes LCA, MCDA, scenario analysis and others to address the environmental, economic, and social considerations involved in the sustainable development of energy systems. Troldborg, Heslop, and Hough (2014) also discuss how LCA can provide important input information into MDCA with respect to environmental criteria, but warn that variability and uncertainty in life cycle impacts must be considered.

Motuzienė et al. (2015) describe how, though MCDA is a useful tool for multidimensional assessment of alternatives, LCA is not commonly used to provide information on the environmental attributes Part of this could be due to the large amount of data that must be collected (Hermann, Kroeze, and Jawjit 2007). Motuzienė et al. (2015) suggest a method that combines LCA, LCC, and MCDM for building envelop selection for the design of energy efficient homes. They use the LCA results related to primary energy demand, global warming, ozone depletion, and life cycle cost to evaluate the value of an alternative with respect to the LCA-based criterion. They do not, however, show how MCDA can be used to evaluate both LCA-based and non-LCA-based criteria simultaneously.

As discussed, life cycle assessment methods can be useful in evaluating the ability of an initiative or alternative to address environmental criteria (such as GHG emissions, energy use, freshwater use, etc.) among other non-environmental criteria used in MCDA or scenario-based preference modeling. Life cycle assessment provides quantitative measures for assessing how well an alternative or initiative in MCDA meets an environmental criteria. For example, consider a problem with criteria c_1*: reduce GHG emissions* and initiatives x_{01}*: aviation biofuel from algae hydrothermal liquefaction* and x_{02}*: aviation biofuel from algal lipids*. First of all, life cycle assessment results describe the level of LC-GHG emissions from both aviation biofuel pathways and reveal, for example, that x_{01} is preferred to x_{02} with respect to criteria c_1. Secondly, life cycle assessment reveals the magnitude of LC-GHG emissions, which can serve as an argument to either use or not use the criteria in future iterations of MCDA or scenario-based preference modeling.

When dealing with more than two initiatives, qualitative ratings can be developed and mapped to quantitative ranges of LC-GHG emissions to assess of how well initiatives meet the criteria. For example, an aviation biofuel pathway with LC-GHG emissions of 20-30 gCO_2e/MJ could qualify as *addressing* a GHG criterion, while those with <20 gCO_2e/MJ could qualify as *strongly addressing* the same criterion. In some cases, the range for a given initiative could be prohibitively large, due to difference among studies such as system boundaries, allocation methods, or other incommensurate factors.

Or, criterion-alternative assessments can be based on the normalized results of life cycle assessment. For example, Miettinen and Hämäläinen (1997) and Gloria, Lippiatt, and Cooper (2007) suggest a linear value function normalizing life cycle impact assessment (LCIA) results of alternatives for the criterion-alternative assessments. This method, however, fails to incorporate the uncertainty and variability inherent in life cycle assessment results. There less reliance on exactness of results in designating ranges of LCIA results that are then mapped to a small set of assessment values in the range from 0 to 1.

Partitioning the initiatives into quartiles (which correspond to the four qualitative assessments) with respect to their LCA-based impacts provides the best means to incorporating life cycle data into existing scenario-based preferences decision support tools, which have previously been applied for multi-stakeholder strategic planning (Lambert et al. 2012; Hamilton, Lambert, et al. 2013). Appendix D describes the technical implementation of the decision support tool with LCA integration. The tool allows for stakeholders to change the LCA-based initiative-criterion assessment based on their own judgment Chapter 7 describes the approach taken in this dissertation to integrating life cycle assessment and other supplementary analytics into scenario-based preferences modeling for aviation biofuels.

4.5 Frame I(t+1) of Scenario-Based Preferences Analysis

After identifying opportunities to integrate life cycle assessment and other supplementary analytical techniques (e.g., life cycle costing, stakeholder analysis, etc.), subsequent frames of scenario-based preference analysis can use this information to make more objective initiative-criteria assessments. After collecting additional data, or performing complementary analytics, subsequent problem framing (Frame I(t+1)) can maintain or change the system boundaries, initiatives, criteria, and/or scenarios in order to match the dynamic nature of the problem. For example, this dissertation will demonstrate two problem frames where one studies the entire aviation biofuel supply chain and the subsequent narrows the focus to feedstock options.

With the new problem framing (i.e., changes in the inputs and/or system boundaries), scenario-based preferences analysis proceeds with the same technical approach as described in Section 4.2. The inputs to the model (e.g., criteria, initiatives, and scenarios) should be updated based on learning from previous frames. Continuous stakeholder engagement and analysis can also help revise the problem boundary, inputs, assessments, and preference weights used in the model. Multiple problem framings allow these revisions, based on the current state of knowledge, to propagate through to inform strategic decisions.

4.6 Resilience Analysis for Strategic Priorities

There is a need for resilience to be conceptualized in a manner than is generally appropriate for a wide domain of application areas (Bhamra, Dani, and Burnard 2011; Hosseini, Barker, and Ramirez-Marquez 2015). The approach for resilience analysis presented here supports the design of resilient strategic plans that can be applicable to engineering, business organizations, political and social institutions, among others. Current resilience literature cites the need for several aspects to be addressed by resilience analytics and which are incorporated in the proposed approach:

- Iterative updating to capture the current state of knowledge over time and problem dynamics (Linkov et al. 2013; Sols 2015; Walker et al. 2002);
- Stakeholder engagement and analysis to understand current needs, concerns, understanding, etc. (Sols 2015; Walker et al. 2002);
- Multi-criteria analysis to assess the tradeoffs between initiatives (Madni and Jackson 2009; Walker et al. 2002);
- Scenarios of emergent conditions to address future uncertainties, and the impact on stakeholder preferences (Haimes 2009; Walker et al. 2002; Fiksel, Croxton, and Pettit 2015);
- Lifecycle and systems analysis to support robust and sustainable decision-making (Walker et al. 2002; Sols 2015; Fiksel, Croxton, and Pettit 2015).

Resilience analytics is defined in this dissertation and elsewhere (Connelly and Lambert 2016a; Connelly and Lambert 2016b; Hamilton et al., expected 2016) as a means to identify the emergent conditions and deep uncertainties that are potentially most disruptive to system engineering priorities. The results indicate where additional information could be most valuable in enhancing the resilience of priorities. The method seeks to identify the scenario(s) that are most disruptive to priorities, relative to the baseline scenario. Equation 4 describes the objective function to identify the most disruptive scenario, where the variables are defined as in Section 4.2.

$$\min \phi(s_k) \; \forall \; s_k \in S_s \tag{4}$$

The method recommended in this dissertation entails iterative scenario-based preferences analysis with complementary analytics and data collection as a means to inform resilient strategies for research and development. Systems analysis literature has long recognized that models are transient instances of the current knowledge of possible initiatives, criteria, measured outcomes, stakeholder preferences, information inputs, and uncertainties. Each of these decision model instances is represented by a particular problem frame. The methods for resilience analytics described in this dissertation recommends both identifying uncertain factors for the *a priori* set of initiatives and creatively designing new initiatives that mitigate negative risks or take advantage of opportunistic risk for prioritize initiatives when faced with uncertainty.

Figure 7 describes the approach for resilience analysis using iterative scenario-based preferences modeling with life cycle assessment and other supplementary analytics. Continuous updating of modeling inputs through subsequent problem framing increases the resilience of strategic decisions to changes in stakeholder preferences. Information on disruptive scenarios and the variability of priorities can reveal research and development needs for a sustainability roadmap. The dotted lines in the figure indicate areas in which this methodology differs from that introduced by Hamilton (2014). Apart from integrating life cycle analysis and sensitivity analysis, this methodology focuses on resilience of priorities to changes in mind.

The concept of resilience analytics introduced in this dissertation aims to mitigate risks by identifying disruptive emergent conditions and keeping these at the forefront of decision-making. Beyond identifying which scenarios of preference changes are most disruptive to priorities, it is important to also consider what is disruptive to other model inputs. For example, sensitivity analysis can be used to identify which parameters in LCA, or other analytical techniques, most impact the results which are then used in scenario-based preferences analysis.

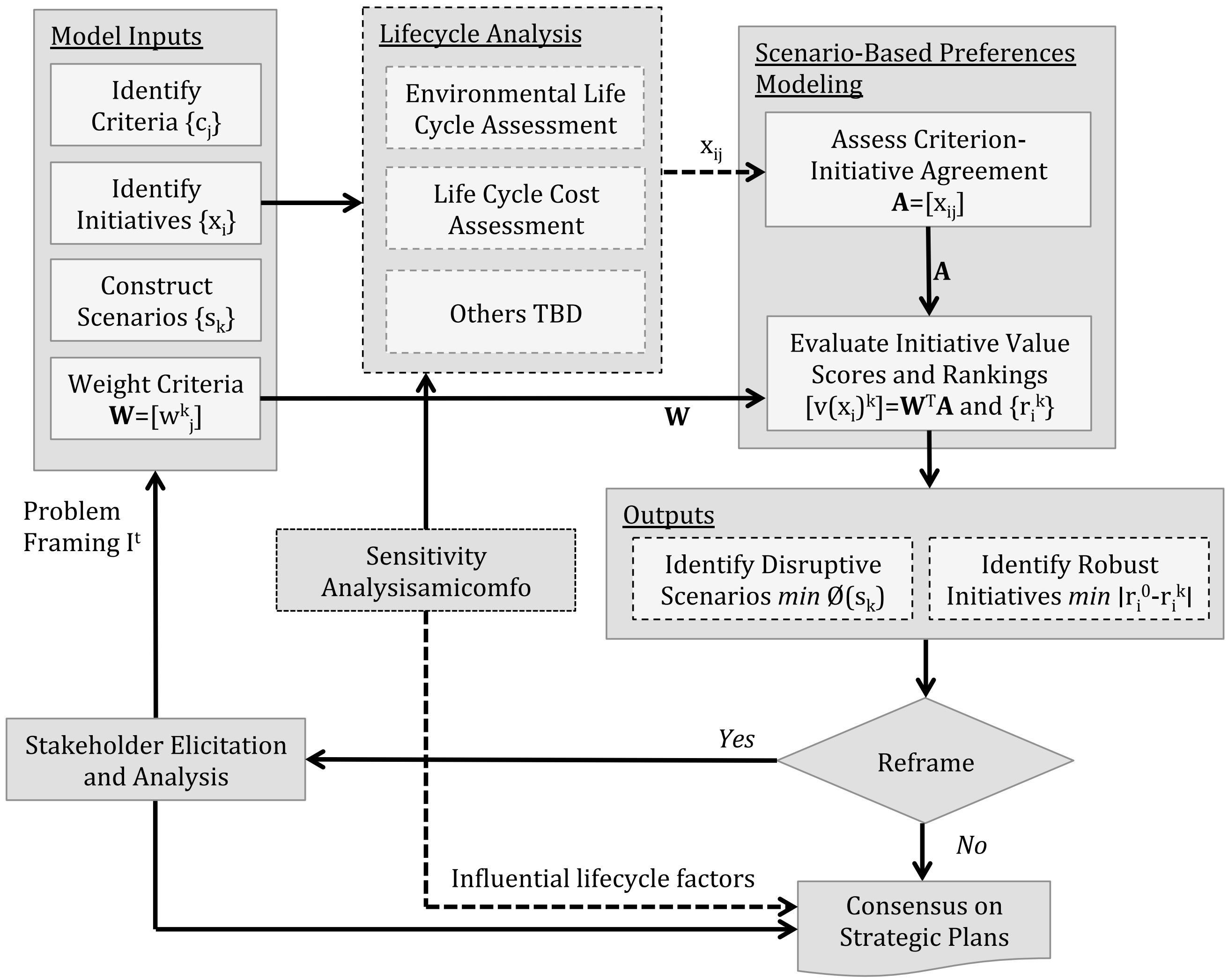

Figure 9. Conceptual model of resilience analysis for priority setting. The dashed lines indicate elements of the approach that were added to scenario-based preferences modeling.

4.7 Chapter Summary

This chapter introduced methods for resilience analysis to support strategic planning. The conceptual model involves iterative scenario-based preferences modeling integrated with life cycle assessment and other problem-appropriate analytics. A preliminary problem framing is discussed in the following chapter. A subsequent problem framing (Chapter 8) will then be used to describe opportunities to integrate life cycle assessment in planning for sustainable technologies.

CHAPTER 5: DEMONSTRATION: RESILIENCE OF SUPPLY CHAIN

5.1 Overview

This chapter will demonstrate resilience analysis described in Chapter 4. This demonstration constitutes the first frame of iterative scenario-based preference analysis for aviation biofuel supply chains. Section 5.2 provides the background for the problem frame. Section 5.3 describes the initiatives used to populate the model. Section 5.4 describes the multiple, sometimes competing, criteria for aviation biofuel supply chains. Section 5.5 describes the emergent conditions and scenarios constructed to capture changes in stakeholder preferences. Section 5.6 applies scenario-based preference analysis to this problem frame and specifies the calculations described by the equations in Section 4.2. Section 5.7 presents the results and Section 5.8 summarizes the chapter.

5.2 Background

The production of aviation biofuel in a general sense involves several key steps as outlined in Figure 8. Bio-based, typically agricultural, feedstocks are the raw materials for all biofuels. Transportation and logistics associated with moving the biomass and/or fuel and storing it are important given the large scale at which fuels are produced. Production, or conversion, steps are typically followed by blending processes wherein biofuels are combined with conventional petroleum-derived fuels. The blends are ultimately transported to their point of use at airports.

In August 2012, the Virginia Department of Aviation (DOAV) requested that the Virginia Center for Transportation Innovation and Research (VCTIR) conduct a cost-benefit analysis of pursing aviation biofuel industry in the Commonwealth of Virginia. The airports of the Commonwealth may need to supply this fuel in the coming years and opportunities may develop for the Commonwealth to be a producer and supplier of this fuel. Of particular concern to the stakeholders is losing airline hubs to airports in states that can provide a supply of aviation fuel if the Commonwealth fails to develop this emerging industry. A preliminary exploration of the logistics and economics of leveraging existing infrastructure and developing new infrastructure and agriculture capacity within Virginia to produce a "drop-in" aviation biofuel that could be used in the airports in the Commonwealth was completed in September 2013 (Clarens et al. 2013).

Connelly (2013) used those motivations and findings to propose a multi-criteria course of action analysis to support associated decision-making. The following sections describe the risk analysis performed and published (Connelly, Colosi, et al. 2015a) to support those efforts, constituting the first problem frame of aviation biofuel supply chain scenario-based preference analysis.

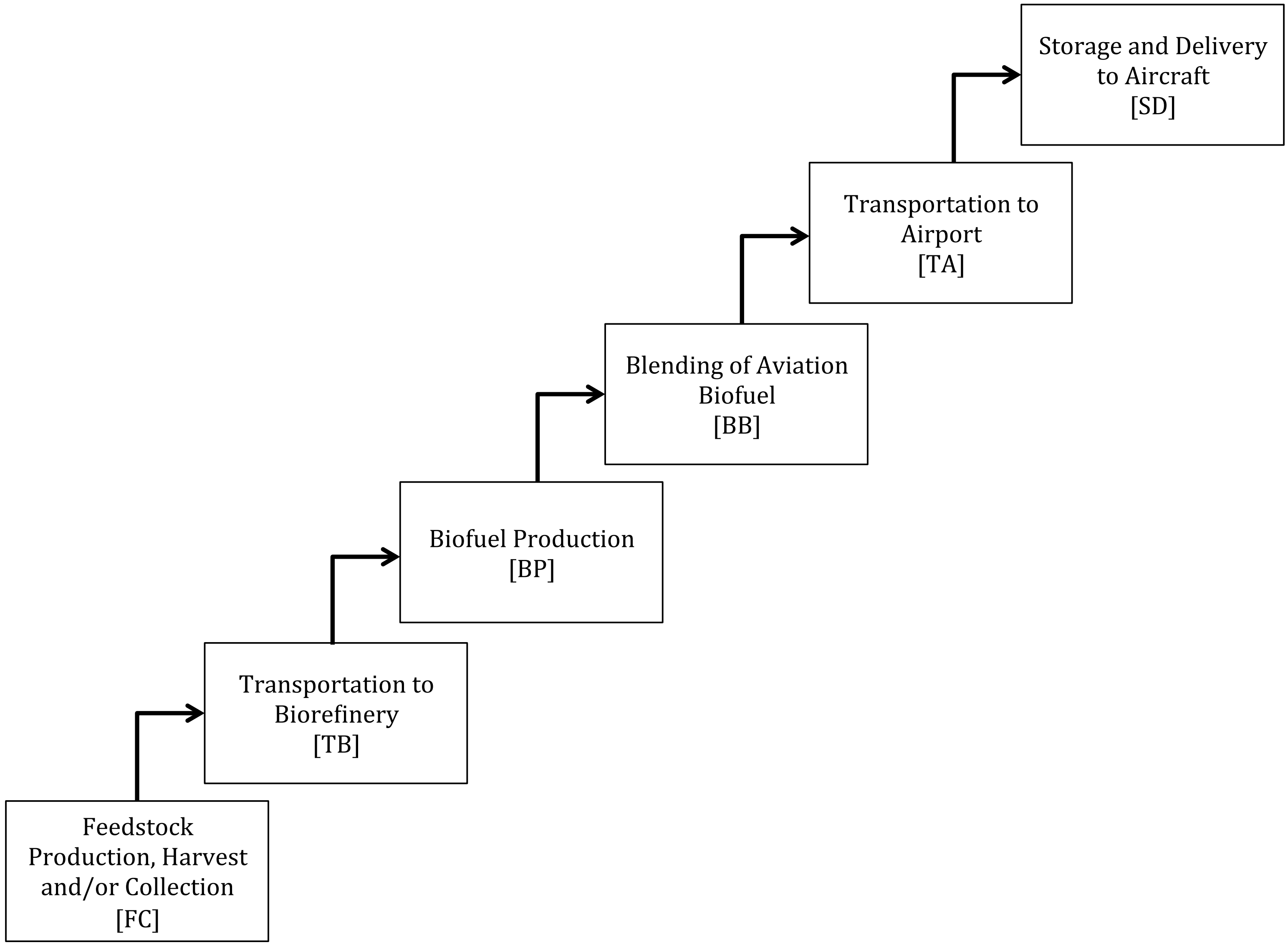

Figure 10. Conceptual supply chain for aviation biofuel, adapted from Elgowainy et al. (2012)

5.3 Initiatives

The set $S_x=\{x_1,\ldots,x_n\}$ represents the set of *n* alternative initiatives being considered for enhancing the aviation biofuel industry. Table 3 summarizes the initiatives that are being considered in the analysis. The initiatives relate to one or more of the stages of the aviation biofuel supply chain shown in Figure 5, as indicated by the two letter code in the third column of the table. Table 4 summarizes the initiatives that are relevant to each stage in the supply chain. These initiatives address decisions related to feedstock selection, production, and transportation, conversion technology, facility siting, fuel distribution, and political and regulatory actions. This list will be extended into the future as more initiatives are identified to support the development of an aviation biofuel industry. The list is based on research papers and reports from academic researchers, interest groups, and government agencies, among others, as indicated in the last column of the table. Initiatives include the cultivation of various feedstocks, collection of waste or residue feedstocks, location decisions for bio-refineries, investment in conversion technologies, fuel transportation infrastructure, and supportive legislation and policies all of which are relevant to developing an aviation biofuel industry.

Table 4. Frame 1 initiatives for aviation biofuel industry development. Two letter codes indicate one or more corresponding stages in the supply chain (Figure 10), with FC representing *Feedstock Production, Harvesting, and/or Collection*, TB representing *Transportation to Biorefinery*, BP representing *Biofuel Production*, BB representing *Blending of Aviation Biofuel*, TA representing *Transportation to Airport*, and SD representing *Storage and Delivery to Aircraft*.

Initiative	Description	Stage	Reference
$\mathbf{x_{01}}$	Invest in R&D of more productive feedstocks (i.e., higher yielding per area of land)	FC	Rosillo-Calle et al. 2012; Air Transport Action Group 2011b; U.S. Department of Energy 2012
$\mathbf{x_{02}}$	Cultivate lignocellulosic feedstocks (e.g., switchgrass, miscanthus, etc.)	FC	Bauen et al. 2009; SWAFEA 2011; Rosillo-Calle et al. 2012
$\mathbf{x_{03}}$	Cultivate oilseed crops as feedstock (e.g., camelina, jatropha, soybean, canola, pennycress, etc.)	FC	Air Transport Action Group 2011a; Hendricks et al. 2011; Rosillo-Calle et al. 2012
$\mathbf{x_{04}}$	Cultivate halophyte feedstocks (e.g., seashore mallow, salicornia, etc.)	FC	Hendricks et al. 2011; Air Transport Action Group 2011b
$\mathbf{x_{05}}$	Cultivate algae as feedstock	FC	Air Transport Action Group 2011a; Rosillo-Calle et al. 2012; Haddad 2011
$\mathbf{x_{06}}$	Develop collection infrastructure for woody residue biomass as feedstock (e.g., wood chips)	FC/TB	U.S. Department of Energy 2011; JI Hileman et al. 2009; Swanson et al. 2010
$\mathbf{x_{07}}$	Develop collection infrastructure for agricultural residue biomass as feedstock (e.g., corn stover, wheat straw)	FC/TB	Air Transport Action Group 2011a; Rosillo-Calle et al. 2012; Swanson et al. 2010
$\mathbf{x_{08}}$	Develop collection infrastructure for municipal solid waste (MSW) as feedstock	FC/TB	Air Transport Action Group 2011a; Macfarlane et al. 2011; Rosillo-Calle et al. 2012

$\mathbf{x_{09}}$	Provide long-term contracts for feedstock supply (volume and price)	FC	Miller et al. 2013; U.S. Department of Energy 2011; Stratton et al. 2010
$\mathbf{x_{10}}$	Develop workforce	FC/BP	Macfarlane et al. 2011; Stubbins 2009; U.S. Department of Energy 2012
$\mathbf{x_{11}}$	Locate bio-refinery in close proximity of feedstock cultivation	TB/BP	Melin & Hurme 2011; T. J. Skone et al. 2011; Miller et al. 2012
$\mathbf{x_{12}}$	Locate bio-refinery in close proximity of city or metropolitan area	TB/BP	Gerber et al. 2013; Macfarlane et al. 2011; Miller et al. 2012
$\mathbf{x_{13}}$	Distribute preprocessing depots with transportation infrastructure to bio-refineries	TB/BP	U.S. Department of Energy 2012
$\mathbf{x_{14}}$	Invest in hydroprocessing (HEFA) bio-refining technologies	BP	Air Transport Action Group 2011a; Miller et al. 2013; Pearlson et al. 2013
$\mathbf{x_{15}}$	Invest in Fischer-Tropsch (FT) bio-refining technologies	BP	Miller et al. 2013; Air Transport Action Group 2011b; Liu et al. 2013
$\mathbf{x_{16}}$	Invest in alcohol-to-jet (ATJ) bio-refining technologies	BP	Air Transport Action Group 2011a; Miller et al. 2013; Macfarlane et al. 2011
$\mathbf{x_{17}}$	Invest in fermentation renewable jet (FRJ) bio-refining technologies	BP	Miller et al. 2013; Miller et al. 2012; Hendricks et al. 2011
$\mathbf{x_{18}}$	Invest in pyrolysis bio-refining technologies	BP	Miller et al. 2013; Air Transport Action Group 2011a; Hendricks et al. 2011
$\mathbf{x_{19}}$	Invest in hydrothermal liquefaction (HTL) bio-refining technologies	BP	Young & Heimlich 2010; Bauen et al. 2009; Biddy et al. 2013
$\mathbf{x_{20}}$	Develop market for co-products (e.g., chemicals)	BP	Macfarlane et al. 2011; U.S. Department of Energy 2012; Agusdinata et al. 2011

$\mathbf{x}_{21}$	Diversify demand for biofuels (e.g., marine shipping, railroad, avgas, etc.)	BP	Macfarlane et al. 2011; Rye & Batten 2012; Miller et al. 2012
$\mathbf{x}_{22}$	Provide low-cost financing for bio-refineries	BP	Miller et al. 2013; Air Transport Action Group 2011b; U.S. Department of Agriculture 2012
$\mathbf{x}_{23}$	Provide tax credits for biofuels	BP	Miller et al. 2013; Air Transport Action Group 2011b; U.S. Department of Agriculture 2010
$\mathbf{x}_{24}$	Commit to aviation biofuel purchase agreements	BP	Hammel 2013; Pearlson 2011; Macfarlane et al. 2011; Air Transport Action Group 2011b
$\mathbf{x}_{25}$	Establish airports as biofuel fueling stations for non-aircraft vehicles	BP	Miller et al. 2013; T. Skone & Gerdes 2008
$\mathbf{x}_{26}$	Encourage user-friendly biofuel accounting methods	BP	International Air Transport Association 2013; Air Transport Action Group 2011b
$\mathbf{x}_{27}$	Co-locate bio-refinery with petroleum refinery	BP/BB	Gutierrez et al. 2007; Miller et al. 2012; de Miguel Mercader et al. 2010
$\mathbf{x}_{28}$	Locate bio-refinery in proximity of pipeline access	BP/BB/TA	Miller et al. 2012; U.S. EPA 2010; Shonnard et al. 2010
$\mathbf{x}_{29}$	Locate bio-refinery in close proximity of sea port for biofuel distribution via barge	BP/TA	Miller et al. 2012; Shonnard et al. 2010; T. J. Skone et al. 2011
$\mathbf{x}_{30}$	Locate bio-refinery in close proximity of rail line for biofuel distribution via train	BP/TA	Miller et al. 2012; Shonnard et al. 2010; T. J. Skone et al. 2011
$\mathbf{x}_{31}$	Site blending facility on airport grounds	BB	Macfarlane et al. 2011; Air Transport Action Group 2011a
$\mathbf{x}_{32}$	Site blending facility at bio-refinery	BB	Macfarlane et al. 2011; Air Transport Action Group 2011a

$\mathbf{x}_{33}$	Site blending facility at existing fuel terminal	BB	Macfarlane et al. 2011; Air Transport Action Group 2011a
$\mathbf{x}_{34}$	Convert petroleum pipeline to biofuel pipeline for biofuel distribution	TA	Macfarlane et al. 2011; JI Hileman et al. 2009
$\mathbf{x}_{35}$	Establish trucking infrastructure for fuel distribution	TA	Miller et al. 2012; Shonnard et al. 2010; T. J. Skone et al. 2011
$\mathbf{x}_{36}$	Increase number of storage tanks on airport grounds	SD	Watson 2011; Hendricks et al. 2011
$\mathbf{x}_{37}$	Establish coalitions encompassing all parts of the supply chain	FC-SD	Air Transport Action Group 2011b; Hammel 2013
⋮	Others		

Table 5. Frame 1 initiatives grouped by corresponding stage in the aviation biofuel supply chain

Stage	Relevant Initiatives
Feedstock Production, Harvest, and/or Collection	x_{01}: Invest in R&D of more productive feedstocks
	x_{02}: Cultivate lignocellulosic feedstocks
	x_{03}: Cultivate oilseed crops as feedstock
	x_{04}: Cultivate halophyte feedstocks
	x_{05}: Cultivate algae as feedstock
	x_{06}: Develop collection infrastructure for woody residue biomass as feedstock
	x_{07}: Develop collection infrastructure for agricultural residue biomass as feedstock
	x_{08}: Develop collection infrastructure for municipal solid waste (MSW) as feedstock
	x_{09}: Provide long-term contracts for feedstock supply
	x_{10}: Develop workforce
	x_{37}: Establish coalitions encompassing all parts of the supply chain
Transportation to Bio-Refinery	x_{06}: Develop collection infrastructure for woody residue biomass as feedstock
	x_{07}: Develop collection infrastructure for agricultural residue biomass as feedstock
	x_{08}: Develop collection infrastructure for municipal solid waste (MSW) as feedstock
	x_{11}: Locate bio-refinery in close proximity of feedstock cultivation
	x_{12}: Locate bio-refinery in close proximity of city or metropolitan area
	x_{13}: Distribute preprocessing depots with transportation infrastructure to bio-refineries
	x_{37}: Establish coalitions encompassing all parts of the supply chain

Biofuel Production	x_{10}: Develop workforce
	x_{11}: Locate bio-refinery in close proximity of feedstock cultivation
	x_{12}: Locate bio-refinery in close proximity of city or metropolitan area
	x_{13}: Distribute preprocessing depots with transportation infrastructure to bio-refineries
	x_{14}: Invest in hydroprocessing (HEFA) bio-refining technologies
	x_{15}: Invest in Fischer-Tropsch (FT) bio-refining technologies
	x_{16}: Invest in alcohol-to-jet (ATJ) bio-refining technologies
	x_{17}: Invest in fermentation renewable jet (FRJ) bio-refining technologies
	x_{18}: Invest in pyrolysis bio-refining technologies
	x_{19}: Invest in hydrothermal liquefaction (HTL) bio-refining technologies
	x_{20}: Develop market for co-products
	x_{21}: Diversify demand for biofuels
	x_{22}: Provide low-cost financing for bio-refineries
	x_{23}: Provide tax credits for biofuels
	x_{24}: Commit to aviation biofuel purchase agreements
	x_{25}: Establish airports as biofuel fueling stations for non-aircraft vehicles
	x_{26}: Encourage user-friendly biofuel accounting methods
	x_{27}: Co-locate bio-refinery with petroleum refinery
	x_{28}: Locate bio-refinery in proximity of pipeline access
	x_{29}: Locate bio-refinery in close proximity of sea port for biofuel distribution via barge

	x_{30}: Locate bio-refinery in close proximity of rail line for biofuel distribution via train
	x_{37}: Establish coalitions encompassing all parts of the supply chain
Blending of Aviation Biofuel	x_{27}: Co-locate bio-refinery with petroleum refinery
	x_{28}: Locate bio-refinery in proximity of pipeline access
	x_{31}: Site blending facility on airport grounds
	x_{32}: Site blending facility at bio-refinery
	x_{33}: Site blending facility at existing fuel terminal
	x_{37}: Establish coalitions encompassing all parts of the supply chain
Transportation to Airport	x_{28}: Locate bio-refinery in proximity of pipeline access
	x_{29}: Locate bio-refinery in close proximity of sea port for biofuel distribution via barge
	x_{30}: Locate bio-refinery in close proximity of rail line for biofuel distribution via train
	x_{34}: Convert petroleum pipeline to biofuel pipeline for biofuel distribution
	x_{35}: Establish trucking infrastructure for fuel distribution
	x_{37}: Establish coalitions encompassing all parts of the supply chain
Storage and Delivery to Aircraft	x_{36}: Increase number of storage tanks on airport grounds
	x_{37}: Establish coalitions encompassing all parts of the supply chain

5.4 Criteria

The set $S_c=\{c_1,\ldots,c_m\}$ is defined as the set of *m* criteria. The criteria are adapted from several sources, including from the Federal Aviation Administration (FAA) vision for the future of the U.S. aviation system (Federal Aviation Administration 2011) and The White House (2011) Blueprint for Energy Security. The criteria are:

i) *reliability* of supply of jet fuel by considering the sufficiency and sustainability of quantity of aviation biofuel (U.S. Department of Energy 2012);

ii) *safety* of air travel by considering the appropriateness of the quality of aviation biofuel (e.g., flash point, freeze point, combustion heat, viscosity, sulfur content, density, etc.) (Air Transport Action Group 2011b);

iii) *environmental sustainability* of producing aviation biofuel (e.g., greenhouse gas emissions, land use change, freshwater use, pesticides, fertilizers, threats to biodiversity, deforestation, etc.) (Hendricks, Bushnell, and Shouse 2011; Macfarlane, Mazza, and Allan 2011; Air Transport Action Group 2011b; U.S. Department of Energy 2012);

iv) *employment and economic development* (U.S. Department of Energy 2012);

v) *costs* across system lifecycles, to both airport owners, carriers, and passengers (U.S. Department of Energy 2012);

vi) *regulatory compliance* in meeting international standards, certifications, and regulations; and

vii) *security* of supply that could be vulnerable to willful attacks by terrorists or other adversaries.

Table 6 summarizes the criteria to be used to prioritize among initiatives that support the development of an aviation biofuel industry.

5.5 Emergent Conditions and Scenarios

Table 7 describes a set S_{ec} representing emergent conditions with potential importance to the development of a biofuel industry. The emergent conditions address potential threats and opportunities of concern to airports (Kincaid et al. 2012), airlines (Air Transport Action Group 2011a), feedstock and biofuel producers (Rosillo-Calle et al. 2012), among other stakeholders. These emergent conditions include uncertainties in airline actions, competition between airports, air travel and jet fuel demand, and changes in the price of aviation biofuel and petroleum jet fuel.

Select emergent conditions are combined to form scenarios in the set $S_s=\{s_1,\ldots,s_q\}$, representing scenarios to address future uncertainties related to developing a regional aviation biofuel industry. Tables 8-13 describe these scenarios. The first scenario takes into consideration the recent RINs issued by the U.S. EPA for aviation biofuel (H. Wang and Kolhman 2013) by which aviation biofuel can qualify for credits that can be traded under the Renewable Fuel Standard (RFS) program. The other scenarios consider emergent conditions related to the application of the European Union Emissions Trading System (EU ETS) to U.S.-originating flights, airport competition, changes in passenger preferences and travel patterns, and supply restrictions.

Table 6. Criteria used to evaluate the initiatives for regional aviation biofuel industry development (Frame 1), based on the FAA mission and vision for the future (Federal Aviation Administration 2011) and the White House goals for energy security (The White House 2011).

Criterion	Description	FAA (2011)	The White House (2011)
c_1	Production quantity	✓	
c_2	Production quality	✓	
c_3	Environmental quality	✓	✓
c_4	Economic development		✓
c_5	Life-cycle costs		✓
c_6	Regulatory compliance and global collaboration	✓	
c_7	Safety and security	✓	✓
⋮	Others		

Table 7. Emergent conditions used to build scenarios for Frame 1 of aviation biofuel industry development, organized into categories of market forces and competition, regulations and tariffs, and technologies and resources.

Category	Emergent Condition	Description	Reference
Market Forces and Competition	EC_{01}	Competition between airports	Kincaid et al. 2012
	EC_{02}	Shift in customer preferences to favor biofuel-powered flights	Kincaid et al. 2012
	EC_{03}	Change in air traffic mix (e.g., decrease in international trips)	Kincaid et al. 2012
	EC_{04}	Entry or expansion of a low-cost carrier	Kincaid et al. 2012
	EC_{05}	Relocation of airline hub	Kincaid et al. 2012
	EC_{06}	Restructuring or failure of an incumbent airline	Kincaid et al. 2012
	EC_{07}	Long-term change in demand for air travel	Kincaid et al. 2012; Rosillo-Calle et al. 2012; Penner et al. 2001
	EC_{08}	Change in demand for jet fuel	Rosillo-Calle et al. 2012; Penner et al. 2001
	EC_{09}	Change in the price of petroleum jet fuel	Rosillo-Calle et al. 2012; Air Transport Action Group 2011b
	EC_{10}	Competition for biofuel feedstock from other industries	Rosillo-Calle et al. 2012; Penner et al. 2001
	EC_{11}	Alteration of airline service agreement	Kincaid et al. 2012
	EC_{12}	Shock event (e.g., terrorist attack, severe weather event, etc.)	Kincaid et al. 2012
	EC_{13}	Development or expansion of market for co-products	Macfarlane et al. 2011; U.S. Department of Energy 2012
	EC_{14}	Biofuel market conditions shift to favor production of aviation biofuel	Macfarlane et al. 2011; Air Transport Action Group 2011b

Regulations and Tariffs	EC_{15}	Implementation of carbon taxes and/or emissions cap and trade system	Kincaid et al. 2012
	EC_{16}	Introduction of biofuel-related legislation (e.g., tax exemptions, subsidies, etc.)	Rosillo-Calle et al. 2012
	EC_{17}	Political factors impede commercial-scale aviation biofuel refining	Macfarlane et al. 2011
	EC_{18}	Increase in the strictness of emission standards	Kincaid et al. 2012; Young & Heimlich 2010
	EC_{19}	Certification of additional aviation biofuel conversion techniques (e.g., ATJ, FRJ, HTL, pyrolysis, etc.) and/or higher blend levels	Penner et al. 2001; Rosillo-Calle et al. 2012
	EC_{20}	Policy or legislation requiring set amount of biofuel use in aviation sector	Air Transport Action Group 2011b
Technologies and Resources	EC_{21}	Change in supply or availability of feedstock	U.S. Department of Energy 2011; Air Transport Action Group 2011b
	EC_{22}	Advances in conversion technology	Macfarlane et al. 2011; JI Hileman et al. 2009; Air Transport Action Group 2011b
	EC_{23}	Development in aircraft technology, air traffic control, and/or passenger facilitation	Kincaid et al. 2012
	EC_{24}	Change in cost of growing and/or harvesting feedstock	Rosillo-Calle et al. 2012; Air Transport Action Group 2011b; U.S. Department of Energy 2011
	EC_{25}	Change in cost of producing (i.e. refining) aviation biofuel	Macfarlane et al. 2011; Air Transport Action Group 2011b; U.S. Department of Energy 2012
	⋮	Others	

Table 8. Descriptions of Frame 1 baseline scenario s_{00}

Scenario	
	s_{00}: Baseline
Description	
	Absence of regulations related to an aviation biofuel industry
Emergent Conditions	
	None
Influences	
	Commercialization of aviation biofuel is slow to stagnant, relying only on existing market forces.

Table 9. Description of Frame 1 scenario of expected regulations s_{01}

Scenario	
	s_{01}: Expected regulations
Description	
	U.S. regulations or policies offer tax credits or other incentives that effectively make aviation biofuel more cost competitive with conventional jet fuel.
Emergent Conditions	
	EC_{16}: Introduction of biofuel-related legislation (e.g., tax exemptions, subsidies, etc.)
Influences	
	The cost of aviation biofuel to the consumer decreases. Thus, airlines are more willing to buy aviation biofuel (demand increases), signaling for producers to increase aviation biofuel production.

Table 10. Description of Frame 1 European Union Emissions Trading System scenario s_{02}

Scenario	
	s_{02}: EU ETS
Description	
	EU ETS is expanded to include U.S.-originating flights to Europe.
Emergent Conditions	
	EC_{15}: Implementation of carbon taxes and/or emissions cap and trade system
Influences	
	Flights to Europe using conventional jet fuel increase in price. The demand for aviation biofuel thus increases in order to keep these international flights affordable, even if the aviation biofuel is more expensive (per gallon) than conventional jet fuel.

Table 11. Description of Frame 1 airport competition scenario s_{03}

Scenario	
	s_{03}: Airport competition
Description	
	Select airports have a competitive advantage in terms of access to aviation biofuel.
Emergent Conditions	
	EC_{01}: Competition between airports
	EC_{05}: Relocation of airline hub
	EC_{15}: Implementation of carbon taxes and/or emissions cap and trade system
Influences	
	Because only certain airports can provide aviation biofuel, thus offering cheaper flights to Europe (due to the EU ETS), airlines relocate their international hubs from less competitive airports.

Table 12. Description of Frame 1 consumer green preference scenario s_{04}

Scenario

s_{04}: Green preferences

Description

Environmental awareness causes a change in consumer preferences, favoring domestic flights flown on aviation biofuel.

Emergent Conditions

EC_{02}: Shift in customer preferences to favor biofuel-powered flights

EC_{13}: Change in air traffic mix (e.g., decrease in international trips)

Influences

Consumers choose to fly less frequently, especially staying away from long international flights. Preference is given to flights powered by aviation biofuel, asymmetrically increasing demand for these flights while overall demand decreases.

Table 13. Description of Frame 1 insufficient aviation biofuel supply scenario s_{05}

Scenario

s_{05}: Insufficient supply

Description

Supply of aviation biofuel cannot meet demand due to lack of commercial scale bio-refineries and/or availability of feedstock

Emergent Conditions

EC_{17}: Political factors impede commercial-scale aviation biofuel refining

EC_{21}: Change in supply or availability of feedstock

Influences

Supply of aviation fuel cannot meet demand, driving prices up. Increased demand for viable feedstocks and increasing benefit for retrofitting or converting existing refineries to bio-refineries.

5.6 Calculations

The qualitative ratings of how well each initiative addresses each criterion are given in Table 13. The ratings given are the result of stakeholder analysis, and remain customizable for other decision makers and into the future. Rating choices for the initiatives consist of a *strongly addresses*, *addresses, somewhat addresses*, and *does not address* each criterion. For example, initiative *x_{01}: Invest in R&D of more productive feedstocks*, is rated as *strongly addressing* criteria *c_{01}: Production quantity* and *c_{05}: Life-cycle costs*, *addressing* criteria *c_{03}: Environmental quality* and *c_{06}: Regulatory compliance and global collaboration*, *somewhat addressing* criterion *c_{04}: Economic development*, and *not addressing* criteria *c_{02}: Production quality* and *c_{07}: Safety and security*.

These qualitative ratings are translated to a quantitative assessment matrix. Table 14 describes how the qualitative rating corresponds to quantitative value score x_{ij} that are used to evaluate how each initiative x_i addresses each criterion c_j. These scores are used to populate the 7x37 matrix *A* (Figure 9) as it is described in Section 4.2.

Table 14. Fulfillment of Frame 1 criteria for each initiative, with ● indicating the initiative *strongly addresses* the criterion, ⦿ indicating the initiative *addresses* the criterion, ○ indicating the initiative *somewhat addresses* the criterion, and omission indicating that the initiative *does not address* the criteria.

		c_1 Production quantity	c_2 Production quality	c_3 Environmental quality	c_4 Economic development	c_5 Life-cycle costs	c_6 Regulatory compliance and global collaboration	c_7 Safety and security
x_{01}	Invest in R&D of more productive feedstocks	●		⦿	○	●	⦿	
x_{02}	Cultivate lignocellulosic feedstocks	⦿			●			○
x_{03}	Cultivate oilseed crops as feedstock	⦿			●			○
x_{04}	Cultivate halophyte feedstocks	⦿		○	⦿		●	○
x_{05}	Cultivate algae as feedstock	●		○	⦿			○
x_{06}	Develop collection infrastructure for woody residue biomass as feedstock	○		⦿			○	○
x_{07}	Develop collection infrastructure for agricultural residue biomass as feedstock	○		⦿				○
x_{08}	Develop collection infrastructure for municipal solid waste (MSW) as feedstock	●		⦿				⦿
x_{09}	Provide long-term contracts for feedstock supply	●					○	
x_{10}	Develop workforce	○			●			⦿
x_{11}	Locate bio-refinery in close proximity of feedstock cultivation			○		⦿		
x_{12}	Locate bio-refinery in close proximity of city or metropolitan area			○		⦿		

		c_1 Production quantity	c_2 Production quality	c_3 Environmental quality	c_4 Economic development	c_5 Life-cycle costs	c_6 Regulatory compliance and global collaboration	c_7 Safety and security
x_{13}	Distribute preprocessing depots with transportation infrastructure to bio-refineries	⊙						⊙
x_{14}	Invest in hydroprocessing (HEFA) bio-refining technologies	○	●		○		⊙	○
x_{15}	Invest in Fischer-Tropsch (FT) bio-refining technologies	○	●		○		⊙	○
x_{16}	Invest in alcohol-to-jet (ATJ) bio-refining technologies	○	⊙		○			○
x_{17}	Invest in fermentation renewable jet (FRJ) bio-refining technologies	○	○		○			○
x_{18}	Invest in pyrolysis bio-refining technologies	○	○		○			○
x_{19}	Invest in hydrothermal liquefaction (HTL) bio-refining technologies	○	○		○			○
x_{20}	Develop market for co-products				⊙	●		
x_{21}	Diversify demand for biofuels	○			⊙			
x_{22}	Provide low-cost financing for bio-refineries				⊙			
x_{23}	Provide tax credits for biofuels				⊙	●		
x_{24}	Commit to biojet fuel purchase agreements	○						
x_{25}	Establish airports as biofuel fueling stations for non-aircraft vehicles				⊙			

		c_1 Production quantity	c_2 Production quality	c_3 Environmental quality	c_4 Economic development	c_5 Life-cycle costs	c_6 Regulatory compliance and global collaboration	c_7 Safety and security
x_{26}	Encourage user-friendly biofuel accounting methods				○			
x_{27}	Co-locate bio-refinery with petroleum refinery					◉		
x_{28}	Locate bio-refinery in proximity of pipeline access			●		◉		
x_{29}	Locate bio-refinery in close proximity of sea port for biofuel distribution via barge			○		◉		
x_{30}	Locate bio-refinery in close proximity of rail line for biofuel distribution via train			○		◉		
x_{31}	Site blending facility on airport grounds							
x_{32}	Site blending facility at bio-refinery							
x_{33}	Site blending facility at existing fuel terminal					◉	◉	
x_{34}	Convert petroleum pipeline to biofuel pipeline for biofuel distribution					◉		
x_{35}	Establish trucking infrastructure for fuel distribution					◉		
x_{36}	Increase number of storage tanks on airport grounds	◉				◉		○
x_{37}	Establish coalitions encompassing all parts of the supply chain						●	◉

Table 15. Translation of qualitative rating of the degree of agreement between aviation biofuel supply chain initiatives and criteria to quantitative scores.

Qualitative rating	Symbol (from Table 14)	Quantitative rating
does not address		0
somewhat addresses	○	0.33
addresses	⦿	0.67
strongly addresses	●	1

$A[1\text{-}18]=$

1.0	0.7	0.7	0.7	1.0	0.3	0.3	1.0	1.0	0.3			0.7	0.3	0.3	0.3	0.3	0.3
													1.0	1.0	0.7	0.3	0.3
0.7			0.3	0.3	0.7	0.7	0.7			0.3	0.3						
0.3	1.0	1.0	0.7	0.7					1.0				0.3	0.3	0.3	0.3	0.3
1.0										0.7	0.7						
0.7			1.0		0.3			0.3					0.7	0.7			
	0.3	0.3	0.3	0.3	0.3	0.3	0.7	0.0	0.7			0.7	0.3	0.3	0.3	0.3	0.3

$A[19\text{-}37]=$

0.3		0.3			0.3												0.7	
0.3												0.7	0.7	0.7				
				0.7					1.0	0.3	0.3							
0.3	0.7	0.7	0.7	0.7		0.7	0.3											
	1.0			1.0				0.7	0.7	0.7	0.7				0.7	0.7	0.7	
															0.7			1.0
0.3																	0.3	0.7

Figure 11. Frame 1 assessment matrix *A* where entry j,i represents the degree to which initiative x_i addresses criterion c_j using the translated ratings described in Table 13. Numbers are rounded for visibility in the figure, but not for the calculations, and only non-zero entries are shown.

Each criterion is weighted to determine the relative influence of the criteria. The relative influence of each criterion may change during each of the five scenarios introduced in Tables 7-12. For the baseline scenario s_{00}, each criterion is considered to have equal influence. Thus, for the baseline, each criterion is assigned a weight of approximately $w_i^{0'}$=0.143 $\forall i$. Identifying whether the influence of the criteria *increases, increases somewhat, stays the same, decreases somewhat,* or *decreases*, under other scenarios, the weight of the criteria is adjusted according to Equation 5.

$$w_i^k = \begin{cases} 9{w_i}^{0\prime}, & \text{for } \textit{increase} \text{ in influence} \\ 3{w_i}^{0\prime}, & \text{for } \textit{somewhat increase} \text{ in influence} \\ {w_i}^{0\prime}, & \text{for } \textit{no change} \text{ in influence} \\ \frac{1}{3}{w_i}^{0\prime}, & \text{for } \textit{somewhat decrease} \text{ in influence} \\ \frac{1}{9}{w_i}^{0\prime}, & \text{for } \textit{decrease} \text{ in influence} \end{cases} \tag{5}$$

After applying Equation 5, the weights w_i^k under each scenario k are normalized to $w_i^{k\prime}$ such that $\sum_{i=1}^{m} w_i^{k\prime} = 1$. Reassessing the weights under each scenario results in the 7x6 matrix W. The first column of W represents the weights in the baseline scenario. The other columns represent the reconsidered weights under scenarios 1, 2, 3, 4, and 5 respectively.

$$W = \begin{bmatrix} 0.143 & 0.415 & 0.432 & 0.249 & 0.199 & 0.475 \\ 0.143 & 0.012 & 0.009 & 0.031 & 0.265 & 0.010 \\ 0.143 & 0.415 & 0.009 & 0.187 & 0.265 & 0.010 \\ 0.143 & 0.069 & 0.054 & 0.249 & 0.031 & 0.010 \\ 0.143 & 0.009 & 0.009 & 0.004 & 0.006 & 0.010 \\ 0.143 & 0.012 & 0.432 & 0.249 & 0.033 & 0.010 \\ 0.143 & 0.069 & 0.054 & 0.031 & 0.199 & 0.475 \end{bmatrix} \tag{6}$$

The value score matrix is computed by multiplying the transpose of the weight matrix W^T by the assessment matrix *A,* as demonstrated in Table 16.

Table 16. Performance scores of the Frame 1 aviation biofuel supply chain initiatives under each scenario. Scores are out of 100, with 100 representing the best performing initiative.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}
s_{00}	52	29	29	43	33	24	19	33	19	29	14	14	19	38	38	24	19	19
s_{01}	73	37	37	50	62	44	44	74	42	25	14	14	32	20	20	19	19	19
s_{02}	75	36	36	78	49	31	17	47	58	23	1	1	32	48	48	19	18	18
s_{03}	63	43	43	65	49	30	22	39	33	35	6	6	19	37	37	20	19	19
s_{04}	41	23	23	34	38	32	31	51	21	23	9	9	27	43	43	32	23	23
s_{05}	50	49	49	50	64	33	32	80	48	49	1	1	63	34	34	33	32	32
Median	60	37	37	50	49	32	29	50	40	26	7	7	31	38	38	21	19	19
Mean	59	36	36	53	49	32	27	54	37	31	8	8	32	37	37	24	22	22

	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}	x_{30}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{36}	x_{37}
s_{00}	19	24	14	10	33	5	10	5	10	24	14	14	10	10	10	19	10	24	24
s_{01}	19	5	18	5	33	14	5	2	1	42	14	14	1	1	1	1	1	31	6
s_{02}	18	5	18	4	5	14	4	2	1	2	1	1	1	1	1	29	1	31	47
s_{03}	19	17	25	17	29	8	17	8	0	19	6	6	2	2	2	17	0	18	27
s_{04}	23	3	9	2	20	7	2	1	0	27	9	9	18	18	18	3	0	20	17
s_{05}	32	2	17	1	2	16	1	0	1	2	1	1	1	1	1	1	1	48	33
Median	19	5	18	4	23	12	4	2	1	20	7	7	1	1	1	6	1	29	26
Mean	22	9	17	6	21	11	6	3	2	19	8	8	5	5	5	12	2	29	25

5.7 Results

Table 17 illustrates the rank order of initiatives based on the value scores of each initiative for the five scenarios and the baseline scenario. Figure 10 demonstrates the range of rankings that each initiative is assigned under the scenarios. The following three initiatives were ranked highest under at least one scenario: (i) *Invest in R&D of more productive feedstocks*, (ii) *Cultivate halophyte feedstock*, and (iii) *Develop collection infrastructure for municipal solid waste (MSW) as feedstock*. Figure 11 illustrates the robustness of initiatives for the initiatives with a median rank higher than 10. While initiative x_{08}*: Develop collection infrastructure for municipal solid waste (MSW) as feedstock* ranks the highest under the most scenarios (s_{01}, s_{04}, and s_{05}), initiative x_{01}*: Invest in R&D of more productive feedstocks* has the highest median rank. Further, initiative x_{01} is robust in that the largest change in rank from the baseline scenario is 3, which is also true only of initiative x_{05}*: Cultivate algae as feedstock*. In terms of average change in rank from the baseline scenario, initiatives x_{05}*: Cultivate algae as feedstock*, x_{17}*: Invest in fermentation renewable jet (FRJ) bio-refining technologies*, x_{18}*: Invest in pyrolysis bio-refining technologies*, and x_{19}*: Invest in hydrothermal liquefaction (HTL) bio-refining technologies* are the most robust.

Table 17 illustrates the absolute value of the change in prioritization of initiatives caused by the scenarios relative to the baseline scenario. In terms of average change in rank of initiative, scenario s_{04}*: Green preferences* is the most disruptive combination of emergent conditions. And, it also accounted for the largest change in rank, causing initiative x_{20}*: Develop market for co-products* to decrease in priority from 11th in the baseline scenario to 31st in the case of the "greening" of consumer preferences. Scenario s_{05}*: Insufficient* *supply*, on the other hand, is the least disruptive scenario in terms of the prioritization of aviation biofuel supply chain initiatives.

Table 18 provides a summary of the scenario-based preference analysis results. As scenario s_{04}*: Green preferences* is the most disruptive scenario across all initiatives relative to the baseline scenario, the results suggest initiatives for expanding the supply of certain feedstocks (e.g., MSW, halophytes, and algae) and investing in proven and certified conversion technologies, as these initiatives remain relatively highly ranked under all scenarios analyzed. These initiatives are top priorities under scenario s_{04}*: Green preferences* because they are expected to be the least harmful to the environment in addition to the least technically risky. For the most part, the top initiatives under the most disruptive scenario also tend to be those that are ranked highly overall. This would suggest that there should be an emphasis on producing and harvesting feedstock, as well as investing in R&D to increase the productivity of these feedstocks. Although other innovative conversion technologies might prove to be more efficient and cost effective in the future, based on the five future scenarios selected for this analysis, investing in the certified technologies, initiatives x_{14} and x_{15}, are high ranking and robust decisions. Although s_2*: Insufficient supply* is the least disruptive scenario across all initiatives relative to the baseline scenario, agencies should further study the long-term implications of the scenario with regard to possibly diminishing amount of available land for feedstock production.

Table 17. Performance rank of Frame 1 aviation biofuel supply chain initiatives. The highest scoring initiative for each scenario is highlighted in gray.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}
s_0	1	8	8	2	5	11	17	5	17	8	24	24	17	3	3	11	17	17
s_1	2	9	9	4	3	5	6	1	8	14	22	22	12	15	15	17	18	18
s_2	2	9	9	1	4	12	21	7	3	15	29	29	11	5	5	16	17	17
s_3	2	4	4	1	3	11	15	6	10	9	29	29	18	7	7	16	18	18
s_4	4	12	12	6	5	7	9	1	18	12	25	25	11	2	2	7	12	12
s_5	4	6	6	5	2	13	16	1	10	6	26	26	3	11	11	13	16	16
Median	2	9	9	3	4	11	16	3	10	11	26	26	12	6	6	15	17	17

	x_{19}	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}	x_{30}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{36}	x_{37}
s_0	17	11	24	29	5	36	29	36	29	11	24	24	29	29	29	17	29	11	11
s_1	18	28	21	29	11	26	29	31	36	7	22	22	33	33	33	32	36	13	27
s_2	17	24	20	25	23	22	25	27	33	28	29	29	33	33	33	14	33	12	8
s_3	18	23	14	25	12	27	25	27	36	17	29	29	33	33	33	24	36	22	13
s_4	12	31	29	33	19	30	33	35	36	10	25	25	21	21	21	32	36	20	24
s_5	16	23	20	30	22	21	30	37	30	23	26	26	30	30	30	25	30	9	13
Median	17	24	21	29	16	27	29	33	35	14	26	26	32	32	32	25	35	13	13

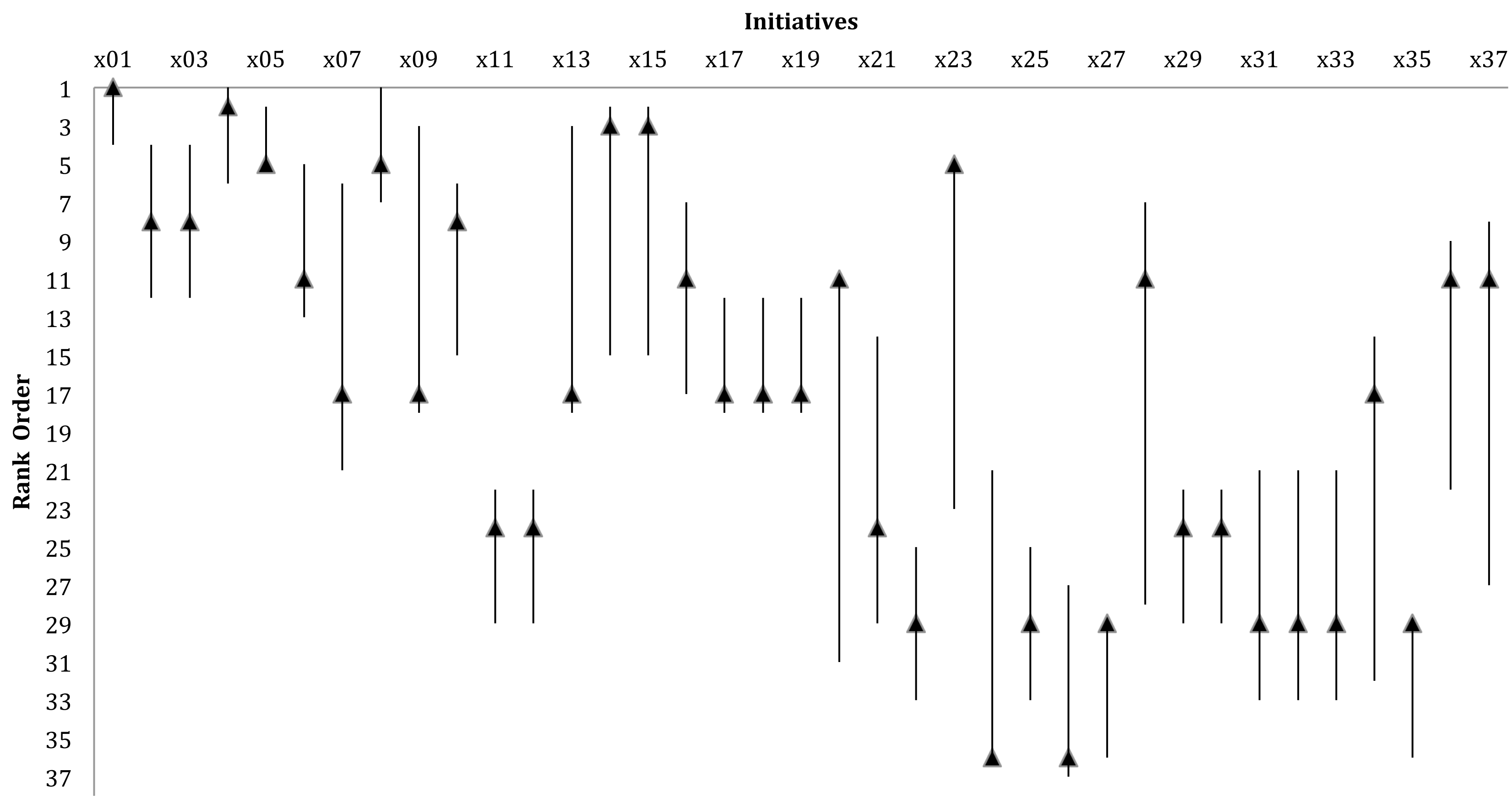

Figure 12. Comparison of rank order of Frame 1 aviation biofuel supply chain initiatives and robustness to changes in rank. The triangle marks the baseline scenario rank, with the high-low lines indicating the rank of rank orders under the set of scenarios.

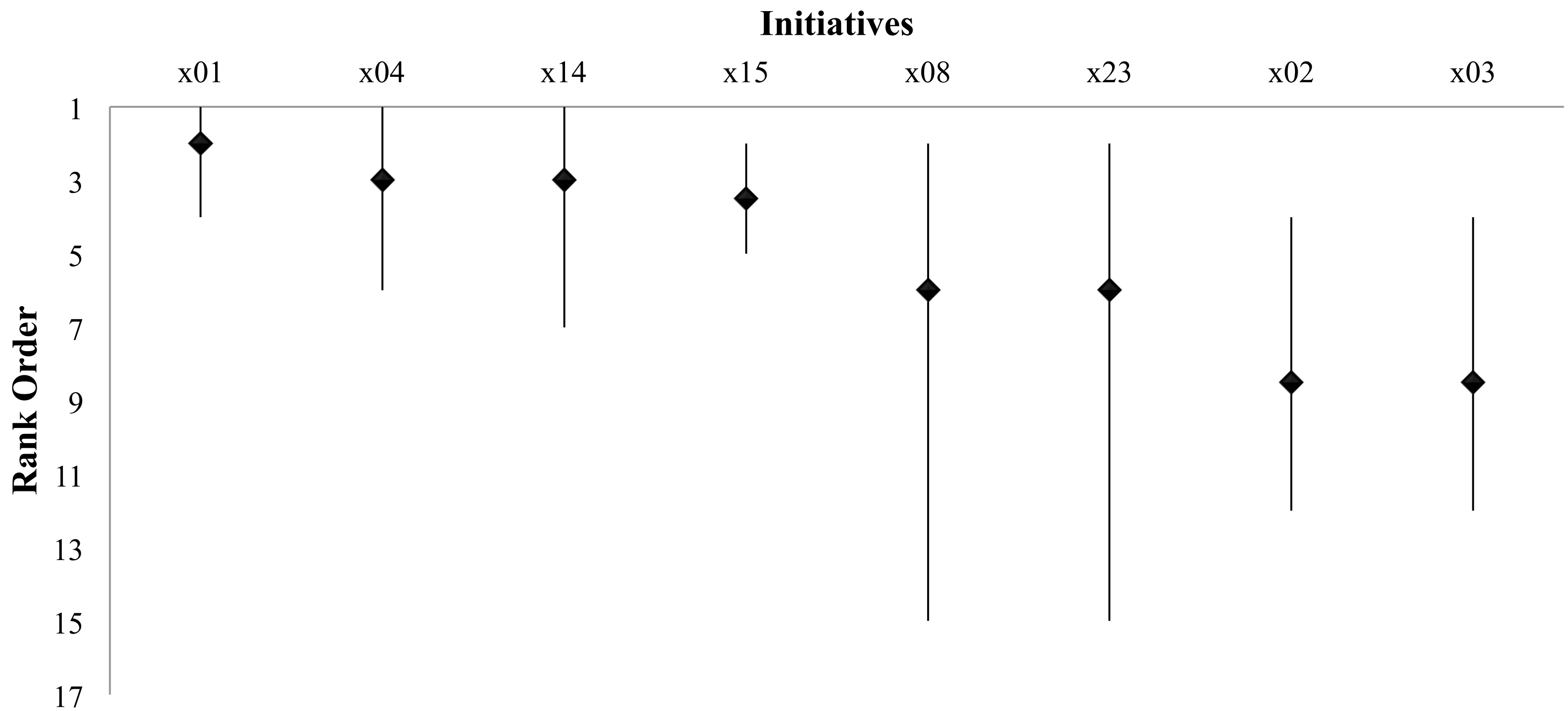

Figure 13. Comparison of Frame 1 aviation biofuel supply chain initiatives with median rank (represented by the diamond) of 10 or better.

Table 18. Changes in rank (in absolute terms) of the Frame 1 aviation biofuel supply chain initiatives in response to the set of scenarios s_{01}-s_{05} as compared to the baseline scenario. The values in the last column are the Spearman rank correlation coefficient, where lower values of $\phi(s_k)$ correspond to more disruptive scenarios.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	x_{17}	x_{18}	x_{19}
s_1	1	1	1	2	2	6	11	4	9	6	2	2	5	12	12	6	1	1	1
s_2	1	1	1	1	1	1	4	2	14	7	5	5	6	2	2	5	0	0	0
s_3	1	4	4	1	2	0	2	1	7	1	5	5	1	4	4	5	1	1	1
s_4	3	4	4	4	0	4	8	4	1	4	1	1	6	1	1	4	5	5	5
s_5	3	2	2	3	3	2	1	4	7	2	2	2	14	8	8	2	1	1	1

	x_{20}	x_{21}	x_{22}	x_{23}	x_{24}	x_{25}	x_{26}	x_{27}	x_{28}	x_{29}	x_{30}	x_{31}	x_{32}	x_{33}	x_{34}	x_{35}	x_{36}	x_{37}	$\phi(s_k)$
s_1	17	3	0	6	10	0	5	7	4	2	2	4	4	4	15	7	2	16	0.79
s_2	13	4	4	18	14	4	9	4	17	5	5	4	4	4	3	4	1	3	0.80
s_3	12	10	4	7	9	4	9	7	6	5	5	4	4	4	7	7	11	2	0.88
s_4	20	5	4	14	6	4	1	7	1	1	1	8	8	8	15	7	9	13	0.79
s_5	12	4	1	17	15	1	1	1	12	2	2	1	1	1	8	1	2	2	0.83

Table 19. Summary of results from Frame 1 analysis of aviation biofuel supply chain initiatives.

Highest ranked initiatives	x_{01}: Invest in R&D of more productive feedstocks x_{04}: Cultivate halophyte feedstocks x_{08}: Develop collection infrastructure for municipal solid waste (MSW) as feedstock
Lowest ranked initiatives	x_{24}: Commit to aviation biofuel purchase agreements x_{26}: Encourage user-friendly biofuel accounting methods x_{27}: Co-locate bio-refinery with petroleum refinery x_{35}: Establish trucking infrastructure for fuel distribution
Greatest increase in rank relative to baseline scenario	x_{24}: Commit to aviation biofuel purchase agreements
Greatest decrease in rank relative to baseline scenario	x_{20}: Develop market for co-products
Most disruptive scenario across all initiatives relative to baseline scenario	s_{04}: Green preferences
Least disruptive scenario across all initiatives relative to baseline scenario	s_{05}: Insufficient supply

5.8 Chapter Summary

This chapter has described the application of the methods from Section 4.2 to establishing an aviation biofuel industry, with particular considerations given to the concerns of stakeholders in the Commonwealth of Virginia. One of the identified criteria for evaluating initiatives is environmental quality. The following chapter describes how life cycle assessment can be used to address aspects of environmental quality. The results of this frame will be used to inform a subsequent frame of analysis (Chapter 8). In addition the results will be used in strategic decision-making through the identification of disruptive scenarios (Chapter 9).

CHAPTER 6: DEMONSTRATION: ALGAE BIOFUEL LIFE CYCLE ASSESSMENT

6.1 Overview

This chapter will demonstrate the methods of life cycle assessment to analyze the global warming potential (GWP) of aviation and other biofuels produced from the hydrothermal liquefaction of whole algae (AHTL). Section 6.2 discusses the background for assessing LC-GHG emissions of biofuel pathways, particularly the AHTL pathway. This chapter explores how policies such as the Renewable Fuel Standard (RFS2) can impact biofuel business decisions, and how compliance with RFS2 is evaluated by the EPA. Section 6.3 describes the purpose and scope of the LCA in terms of policy compliance when considering certain *upstream* and *downstream* factors. Section 6.4 describes the lifecycle processes being modeled. Section 6.5 describes the energy demand and GWP results overall and for each lifecycle stage. Section 6.6 interprets the results with respect to the RFS2 framework. The results of sensitivity analysis are also described in Section 6.6.

6.2 Background

The United States represents a significant share of the global biofuel economy, constituting 48 percent of global biofuels consumption and 46 percent of global biofuels production (U.S. Energy Information Administration 2014). As a result, the policies and regulations adopted by the United States have influence over the global biofuel industry, especially where innovative pathways are involved. An emergent pathway of great interest is the conversion of algae biomass to biocrude using hydrothermal liquefaction (HTL) to produce a suite of drop-in fuels. This and other algae-to-biofuel pathways seem to offer a variety of benefits relative to conventional terrestrial crop biofuels. HTL is being studied extensively because of its importance to the nascent algae biofuels industry (Zhou et al. 2010; Alba et al. 2012; Frank et al. 2013; Roberts et al. 2013) and relative benefits compared to other algae biofuel technologies. Currently, however, the performance of this pathway is poorly characterized in the context of existing U.S. regulations.

The Renewable Fuels Standard (RFS) program is the primary means by which the EPA assesses the environmental performance of fuel production pathways. It was created under the Energy Policy Act of 2005 and expanded (to become RFS2) under the Energy Independence Security Act (EISA) of 2007. The stated objectives of the EISA include increasing the production of "clean" renewable fuels, and the central tenant of this rule is the application of lifecycle greenhouse gas (LC-GHG) performance threshold standards to ensure improvements in GHG emissions for new fuel pathways relative to the petroleum fuels they replace.

Algae are an attractive feedstock for biofuels because of their (i) high productivity per acre, (ii) cultivation possible on non-arable land, thus minimizing competition with conventional agriculture and food production, (iii) utilization of waste water or other non-freshwater supply, (iv) potential carbon recycling from industrial emissions, and (v) compatibility for the production of a variety of fuels and valuable co-products (Clarens et al.

2010). Most conversion efforts to date have focused on producing biodiesel from algae by extracting and upgrading algal lipids (Liu et al. 2013; Stephenson et al. 2010). But, this has proven to be problematic because of the extensive dewatering and drying of the algae biomass prior to oil extraction, which has made the algae bioenergy industry largely abandon pathways focused on lipid extraction. In contrast, pathways utilizing hydrothermal liquefaction (HTL), which consists of liquefying whole algae in a high-pressure (up to 2000 psig), high-heat environment (175-450°C), are attractive because they do not require drying of the biomass prior to conversion and the process utilizes the entire cell biomass as opposed to the lipid fraction alone (Zhou et al. 2010; Alba et al. 2012; Frank et al. 2013; Roberts et al. 2013).

Despite the growing interest in HTL pathways by the industry, the EPA has yet to certify any algae HTL (AHTL) pathways under RFS2. Several important LCA analyses of this pathway have been published in recent years. Argonne National Laboratory's *Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)* spreadsheet analysis tool is used by the EPA to aid in the evaluation of LC-GHG emissions for biofuels that are under consideration for certification. Preliminary modeling of an AHTL pathway using GREET suggests that the resulting fuels could offer more than 50% reduction in LC-GHG emissions relative to petroleum fuels (Frank et al. 2013). Lifecycle studies (Fortier et al. 2014; Liu et al. 2013; Delrue et al. 2013; Davis et al. 2014) report varying LC-GHG results for similar pathways, in part due to differing modeling assumptions (e.g., feedstock productivity, processing conditions, and finished product(s), etc.). These disparities make it difficult to compare the results at face value and to determine whether the AHTL pathway could be used to produce qualifying fuels under RSF2.

Based on LC-GHG emissions, RFS2 defines four categories of renewable fuels: (i) renewable fuel, (ii) advanced biofuel, (iii) biomass-based diesel, and (iv) cellulosic biofuel. Each year, the EPA sets specified volume targets for each of these categories. “Obligated parties,” including all producers or importers of petroleum fuels, must then produce or obtain the required amount of certified biofuels to meet their “renewable volume obligations” (RVOs). Fuels that have been certified by the EPA generate so-called Renewable Identification Numbers (RINs) corresponding to an appropriate category and are then available for sale to entities possessing RVOs so that they can meet their obligations. Due to the nested nature of the renewable fuel classifications, and the unique supply and demand for each, some RINs are more valuable than others. Generally, biofuel producers are incentivized to produce *biomass-based diesel* as opposed to just *advanced biofuel* or *renewable fuel,* because RINs generated under the former definition can be used to meet RVOs under the latter. For RFS2 to effectively reduce the GHG emissions from transportation fuels, it is important for certification of fuel pathways to be based on an accurate accounting of LC-GHG emissions that include both upstream and downstream factors, to guide business decisions accordingly.

When calculating the LC-GHG emissions of a biofuel pathway, the EPA applies carbon credits to biomass feedstocks that sequester existing stocks of ambient CO_2 from the atmosphere. That is, they make the assumption that the amount of CO_2 taken up (sequestered from) the atmosphere during photosynthesis and growth of the feedstock is the same amount of CO_2 released to the atmosphere when the fuel is subsequently combusted to release energy. Algae, however, differ from terrestrial feedstocks used for biofuel production because large-scale cultivation requires that concentrated CO_2 be fed in to the cultivation ponds (Pena, Frieden, and Bird 2013). Unlike terrestrial crops, which obtain their carbon exclusively from the atmosphere, algae ponds must have it delivered. Therefore, accounting for LC-GHG emissions of algae-based fuels should include any upstream burdens associated with the supply of carbon dioxide. Potential sources of CO_2 include industrial activities such as power generation (e.g., coal-fired power plants), natural gas processing, ammonia production, ethanol production, hydrogen production, or extracted CO_2 from dedicated wells. The largest source of commercial quantities of CO_2 is that extracted from natural underground wells. Of all these sources, only the CO_2 from ethanol production is biogenic in nature, though algae cultivation using the other industrial sources does not represent a net addition to atmosphere CO_2 stocks, as it would be otherwise vented. Extracting CO_2 from underground deposits, however, does increase the level of CO_2 in the atmosphere. The choice of which CO_2 to use directly impacts the LC-GHG performance of algae biofuels in a manner that is unique compared to conventional terrestrial biofuel feedstocks (e.g., corn), which use ambient CO_2 exclusively. This work builds on current AHTL studies by explicitly considering upstream burdens from CO_2 supply, as shown in Figure 9.

In addition to upstream burdens, downstream decisions affect the life cycle impacts of transportation biofuels derived from algae. There is new evidence that aviation emissions, occurring in the upper troposphere and lower stratosphere, have greater climate change consequences than the same emissions occurring at the ground level (Jardine 2005). While the emissions profiles of terrestrial algae biofuels and aviation algae biofuels are similar, it is the climate change impacts that occur from combustion in the atmosphere as compared to ground-level that cause aviation biofuels to be less advantageous than ground-transportation biofuels relative to their petroleum counterparts.

Although jet fuel is not an "obligated" fuel under RFS2, qualified pathways can be used to produce aviation biofuel that generate RINs to meet diesel RVOs. For the case of aviation biofuels, it is important, however, to consider the climate change consequences of atmospheric emissions. Decisions about the production of renewable gasoline and diesel versus jet fuel should be based on the relative global warming potential of each distillate, where global warming potential is more relevant to climate change mitigation than simply GHG emissions. Stratton, Wolfe, and Hileman (2011) developed ratios to scale the climate forcing impacts of non-CO_2 combustion emissions for both petroleum and bio-based jet fuels during atmospheric combustion. These ratios can be multiplied by the CO_2 combustion emissions in order to calculate the well-to-wake global warming implications of aviation fuel and guide decision-making on the use of biofuels in aviation.

With the above background, the purpose of this Chapter is to use a life-cycle assessment approach to characterize the role AHTL biofuels can play in the United States biofuel economy, with a focus on several upstream and downstream factors and the existing fuels certification framework. First, the LC-GHG emissions of three co-produced AHTL distillates (i.e., diesel, jet fuel, and gasoline) are calculated. Specific to aviation biofuels, the global warming potential of non-CO_2 combustion emissions in the atmosphere is also accounted for. Based on these results, the degree to which AHTL biofuels are consistent with the RFS2 regulatory framework and climate mitigation efforts is examined. Finally, the influence these findings could have on decision-making related to biofuel production and the sustainability of transportation fuels is discussed.

6.3 Goal Definition and Scoping

The first component of life cycle assessment is goal definition and scoping. The purpose of this life cycle assessment is to determine the global warming potential (GWP) of aviation biofuel produced from the hydrothermal liquefaction (HTL) of whole algae. One of the goals is to compare the GWP of algal HTL (AHTL) aviation biofuel to conventional and other renewable jet fuels to determine the relative attractiveness of AHTL aviation biofuel with respect to alternatives. A secondary goal is to determine the eligibility of AHTL aviation and other biofuels for Renewable Identification Numbers (RINs), which are based on LC-GHG emissions and offer biofuel producers financial incentives under the Renewable Fuel Standard (RFS2). Such information will provide insight to the business decisions of potential and/or current biofuel producers.

The system boundaries for this LCA are drawn to include upstream and downstream factors in addition to the conventional feedstock production and biofuel conversion stages of the life cycle. Figure 12 shows the system boundaries of this LCA. Past studies on AHTL fuel (Delrue et al. 2013; Frank et al. 2013; Liu et al. 2013; Fortier et al. 2014) have traditionally considered the following stages: (i) algae cultivation, (ii) algae harvest and dewatering, (iii) hydrothermal liquefaction, (iv) upgrading via hydrotreatment. Because biomass typically absorbs atmospheric carbon dioxide during the growth or cultivation phase, biofuels are often credited with an equivalent amount of carbon released during the combustion phase of the biofuel, assuming that amount was originally fixed by the biomass (Carter et al. 2011). That is to say that the LC-GHG emissions calculations for biofuel often assume net zero carbon emission for combustion, ultimately consisting only on the emissions produced in cultivating and converting biomass to biofuels. For algae fuels however, carbon dioxide (CO_2) is supplied for biomass cultivation and the source of the carbon dioxide should be explicitly considered in LCA. Further, there is evidence that aviation emissions, occurring in the upper troposphere and lower stratosphere, have greater climate change consequences than the same emissions occurring at the ground level (Jardine 2005). Thus, in determining the climate change implications, or global warming potential, of biofuels, it could be important to account for the location (terrestrial versus atmospheric) of combustion.

The following LCA will explicitly consider the upstream and downstream factors of CO_2 source and combustion impacts for aviation fuels to determine the GWP of AHTL biofuels (i.e., renewable gasoline, renewable diesel, and aviation biofuel). The results will be examined with respect to the RFS2 in order to envisage biofuel production business decisions (e.g., distillate maximization).

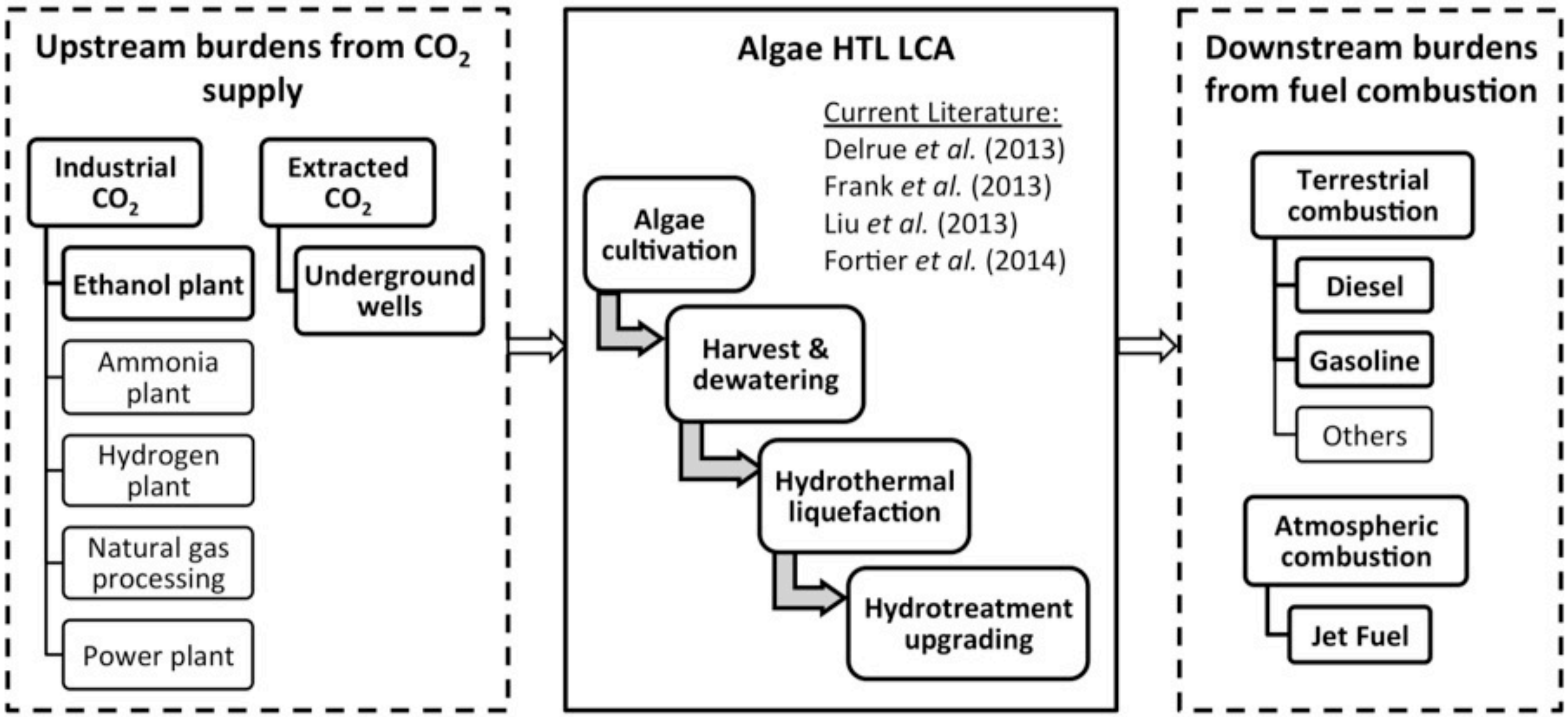

Figure 14. System boundaries of the present life cycle assessment of algae hydrothermal liquefaction biofuels explicitly considering the upstream burdens from CO_2 sources for algae growth and the downstream burdens associated with fuel combustion, which depend on whether the fuel is combusted atmospherically or terrestrially.

6.4 Process Modeling

All stages of fuel production and distribution, in addition to the upstream burdens from CO_2 supply for algae cultivation and downstream burdens association with the combustion impacts of each type of fuel are modeled in this life cycle assessment, as shown in Figure 12. The first three stages of algae HTL (i.e., algae cultivation, harvest and dewatering, and hydrothermal liquefaction) are based on the model by Liu et al. (2013) the hydrotreatment and distillation stages are based on petroleum refining processes (Pellegrino et al. 2007), and the fuel transportation and distribution and combustion stages are consistent with Argonne GREET (Wang 2013) modeling.

The overall model architecture is based on Liu et al. (2013). As such, the model is built in a spreadsheet using Microsoft Excel with the Crystal Ball plug-in. Crystal Ball enables users to perform Monte Carlo simulation for complex models by defining statistical distributions for input parameters. The software automates sampling from the defined input distributions and generates distributions of targeted output parameters. The Monte Carlo simulation was conducted using 100,000 trials. Some of parameters for the present analysis differ from those used by Liu et al. (2013), as detailed in Section 5.4.2.

6.4.1 Functional unit and allocation

The functional unit for this analysis corresponds to 1 MJ of final fuel product, consistent with previous work by Liu et al. (2013), Shonnard et al. (2010), and Han et al. (2013). This energy-based functional unit avoids the bias that aircraft operation and efficiency can have on the results. Algae cultivation occurs in open ponds, and all stages of fuel production are accounted for, including refining efficiency and heating values of different fuel productions. Two metrics are reported: energy (MJe/MJ) and emissions of greenhouse gases (kg CO_2e/MJ) per hectare per year.

Because traditional refining produces multiple fuel products simultaneously, and three (gasoline, diesel, and jet fuel) are considered in this study, it is necessary to allocate energy inputs and emissions outputs among the various distillates. Wang et al. (2004) applied three different allocation methods, including by mass, energy content, and market value. We choose to present the results of energy-based allocation because the approach has previously been used for RFS2 pathway evaluations. Allocation by energy content is based on the percent of MJ from the upgraded biocrude that is distilled into the final fuel products. We assume that the distillation of the upgraded biocrude does not result in the loss or gain of energy, so we can use the energy content of the biocrude final products to determine allocation based on energy. Table 20 lists the specific energies used for the calculations according to Equation 7. Table 20 also describes the allocation factors based on energy content.

$$\%\ \text{MJ} = (\text{Specific energy of product} \times \text{Yield})/\text{Specific energy of biocrude} \qquad (7)$$

6.4.2 Process modeling scenarios

In order to examine the LC-GHG emissions of the AHTL biofuel pathway with respect to current US regulations (e.g., the RFS2) it is important to understand how the EPA approaches calculating LC-GHG emissions. First of all, the EPA applies carbon credits to biomass feedstocks that sequester existing stocks of ambient CO_2 from the atmosphere. That is, they make the assumption that the amount of CO_2 taken up (sequestered from) the atmosphere during photosynthesis and growth of the feedstock is the same amount of CO_2 released to the atmosphere when the fuel is subsequently combusted to release energy.

Algae, however, differ from terrestrial feedstocks used for biofuel production because large-scale cultivation requires that concentrated CO_2 be fed in to the cultivation ponds (Pena, Frieden, and Bird 2013). Unlike terrestrial crops, which obtain their carbon exclusively from the atmosphere, algae ponds must have it delivered. Therefore, accounting for LC-GHG emissions of algae-based fuels should include any upstream burdens associated with the supply of carbon dioxide. Potential sources of CO_2 include industrial activities such as power generation (e.g., coal-fired power plants), natural gas processing, ammonia production, ethanol production, hydrogen production, or extracted CO_2 from dedicated wells. The largest source of commercial quantities of CO_2 is that extracted from natural underground wells. Of all these sources, only the CO_2 from ethanol production is biogenic in nature, though algae cultivation using the other industrial sources does not represent a net addition to atmosphere CO_2 stocks, as it would be otherwise vented. Extracting CO_2 from underground deposits, however, does increase the level of CO_2 in the atmosphere. The choice of which CO_2 to use directly impacts the LC-GHG performance of algae biofuels in a manner that is unique compared to conventional terrestrial biofuel feedstocks (e.g., corn), which use ambient CO_2 exclusively. This work builds on current AHTL studies by explicitly considering upstream burdens from CO_2 supply, as shown in Figure 12.

Two scenarios related to carbon dioxide (CO_2) supply for algae cultivation are considered, one for industrial-sourced CO_2 and one for CO_2 extracted from natural deposits. These scenarios differ from one another based on the amount of energy and GHG emissions associated with supplying CO_2. Both are considered to be technically feasible. Middleton et al. (2014) calculate the burdens associated with CO_2 from ethanol production as 0.86 MJ and 0.07 kg CO_2e per kg of CO_2. These burdens are assigned to CO_2 in the first scenario, “Industrial CO_2”, and represent the minimum impacts associated with CO_2 supply. In keeping with the treatment used by GREET and Frank et al. (2011) the carbon from these industrial sources is treated as atmospheric, based on the assumption that in the absence of algae cultivation, the industrial sources would emit the CO_2 into the atmosphere. For the second scenario, “Extracted CO_2”, we consider CO_2 from natural deposits, which represents the most burdensome option of the possible sources at 1.74 MJ and 0.21 kg CO_2e per kg CO_2 (Middleton et al. 2014). Because this CO_2 is extracted from underground wells, and it is the sole product from these wells, it should not be considered biogenic. Thus, in the extracted CO_2 scenario, we do not give a biogenic carbon credit to the LC-GHG emissions of the AHTL biofuels. Table 21 describes the differences of the two CO_2-source scenarios.

Table 20. Energy content of HTL biocrude and refined products for determining energy-based allocation factors.

Product	Specific energy (MJ/kg)	Yield (% wt)	% MJ of biocrude
Upgraded biocrude	43.8	100	100
Aviation biofuel	44.2	24	24.2
Renewable diesel	44.0	51	51.2
Renewable gasoline	34.6	10	7.9

Table 21. Energy and emissions assumptions for industrial and extracted CO_2 scenarios

	Industrial CO_2	Extracted CO_2
Life cycle energy (MJ/kg)	0.86	1.74
Life cycle GHG (kg/kg)	0.07	0.21
Biogenic carbon credit	Yes	No
Percent of market share	7.5	70

6.4.3 Input parameters

A range of parameter values from earlier work is incorporated into the model in an attempt to assemble the best possible representation of what the AHTL fuel pathway will look like. The input parameters are assigned to triangular distributions (Table 22) or uniform distributions (Table 23) based on reported values from the literature. Generally, uniform distributions are assumed when little data was available in which case the minimum and maximum values represent ±10% of the baseline value assigned from the literature. Resulting distributions are then incorporated into a spreadsheet-based Monte Carlo model.

Table 22. Variable input parameters for LCA model of algae hydrothermal liquefaction fuels, assumed to follow triangular distribution in sensitivity analysis.

Variable	Base	Min	Max	Sources
Productivity (g/m^2-day)	25	2	50	Frank et al. (2013); Delrue et al. (2013); Sills et al. (2013)
Nitrogen in biomass (%wt)	7.8	4.8	9.8	Frank et al. (2013); Davis et al. (2014); Jones et al. (2014)
Phosphorus in biomass (%wt)	1.09	0.58	1.6	Liu et al. (2013); Davis et al. (2014); Jones et al. (2014)
Carbon in biomass (%wt)	52	41	55	Liu et al. (2013); Frank et al. (2013); Davis et al. (2014); Jones et al. (2014)
Ash content (%wt)	29	5	50	Frank et al. (2013); Fortier et al. (2014); Davis et al. (2014)
Nutrient recycle efficiency (%)	60	30	90	Liu et al. (2013); Delrue et al. (2013); Davis et al. (2014)
P_2O_5 energy demand (MJ/kg)	12.72	12.72	15.8	Liu et al. (2013); GREET (Wang 2013b)
P_2O_5 GHG emissions (kg/kg)	0.933	0.9	0.933	Liu et al. (2013); GREET (Wang 2013b)
NH_3 energy demand (MJ/kg)	42.97	42.97	43.20	Liu et al. (2013); GREET (Wang 2013b)
NH_3 GHG emissions (kg/kg)	2.68	2.09	2.68	Liu et al. (2013); GREET (Wang 2013b)
Biocrude yield (%wt)	41	21	61	Fortier et al. (2014); Davis et al. 2014); GREET (Wang 2013b)
Carbon in biocrude (%)	72.1	65	79.2	Liu et al. (2013); Frank et al. (2013); Elliott et al. (2013)
Upgraded biocrude yield (%wt)	81	75	90	Fortier et al. (2014); Davis et al. (2014); Jones et al. (2014)
Carbon in upgraded biocrude (%wt)	84.75	84.2	85.4	Elliott et al. (2013)
Non-CO_2 atmospheric combustion multiplier	2.22	0.6	3.80	Stratton et al. (2011)

Table 23. Variable input parameters for LCA model of algae hydrothermal liquefaction fuels, assumed to follow uniform distribution in sensitivity analysis.

Parameter	Baseline Value	Minimum Value	Maximum Value
Biocrude density (kg/L) (Elliott et al. 2013; Jena and Das 2011)	0.9565	0.9430	0.9700
Upgraded biocrude density (kg/L) (Huber et al. 2006)	0.861	0.796	0.926
Upgraded biocrude energy content (MJ/kg) (Huber et al. 2006)	43.8	42.3	45.3
Biodiesel density (kg/L) (Delrue et al. 2013)	0.895	0.870	0.920
Biodiesel energy content (MJ/kg) (Delrue et al. 2013)	44	38	45
Aviation biofuel density (kg/L) (Huber et al. 2006; Hileman et al. 2010; Kinder and Rahmes 2009)	0.7570	0.7164	0.8756
Aviation biofuel energy content (MJ/kg) (Huber et al. 2006; Hileman et al. 2010; Kinder and Rahmes 2009)	44.1	42.3	45.3
Renewable gasoline density (kg/L) (Wang 2013a)	0.7480	0.6732	0.8228
Renewable gasoline energy content (MJ/kg) (Wang 2013a)	34.620	31.158	38.082
Renewable gasoline yield (%wt) (Zhu et al. 2013)	10	5	15

6.5 Impact Assessment

Energy demand and global warming potential (GWP) were calculated for AHTL jet, diesel and gasoline products, under the industrial and extracted CO_2 scenarios. Tables 24 and 25 describe the results by life cycle stage for AHTL jet fuel under the industrially–sourced CO_2 and extracted CO_2 scenarios, respectively. The relative burdens among life cycle stages for AHTL diesel and gasoline are similar to that of the AHTL jet fuel. The only difference in results of the two scenarios is in the cultivation stage, which includes the CO_2 input for algae growth. Results are presented for aviation biofuel because there are two results for GWP of the combustion stage, which is not the case for either of the terrestrial biofuels.

Previously published work by Stratton et al. (2011), indicates that non-CO_2 emissions arising during atmospheric combustion, including NO_x, soot, sulfate, and water vapor emissions and contrail formations, contribute to overall GWP impacts. These contributions can be accounted for using so-called combustion multipliers for each type of emission. Because aviation biofuel and petroleum jet fuel differ in terms of the amount of the aforementioned emissions, Stratton et al. (2011), calculate a combustion multiplier of 2.22 for aviation biofuel and a lower combustion multiplier of 2.07 for petroleum jet fuel. Figure 13 depicts the life cycle GWP results for petroleum and AHTL diesel, gasoline, and jet fuel (both with and without the combustion multiplier), considering both scenarios of CO_2 sourcing. Error bars represent the variability in results based on the sensitivity analysis with parameter distributions described in Tables 22 and 23.

The energy demand results of the AHTL LCA are presented in Figure 14 in terms of energy return on (energy) investment (EROI). EROI represents the ratio of energy output to energy input. An EROI greater than one indicates that the energy output of a system is greater than its corresponding energy input; more energy is produced than consumed. The results of this LCA show that AHTL fuels can be produced efficiently (i.e., EROI>1), however petroleum fuel production in higher return or EROI (Liu et al. 2013; Guilford et al. 2011; Trivedi et al. 2015). Similar to GWP, AHTL biofuel produced from industrially sourced CO_2 perform better than those that require extracted CO_2 for algae cultivation.

Table 24. Energy demand and GWP by stage for AHTL jet fuel under the industrial CO_2 scenario, where the parenthetical combustion GWP is calculated using the combustion multiplier for atmospheric combustion effects

Life Cycle Stage	Energy Use (MJ/MJ output)	GWP (gCO2e/MJ output)
Cultivation	0.35	23.47
Harvest & Dewatering	0.16	9.45
HTL	0.13	4.63
Upgrading	0.11	5.61
Transportation & Distribution	0.01	0.51
Combustion	1	70.46 (156.43)

Table 25. Energy demand and GWP by stage for AHTL het fuel under the extracted CO_2 scenario where the parenthetical combustion GWP is calculated using the combustion multiplier for atmospheric combustion effects

Life Cycle Stage	Energy Use (MJ/MJ output)	GWP (gCO2e/MJ output)
Cultivation	0.43	37.02
Harvest & Dewatering	0.16	9.45
HTL	0.13	4.63
Upgrading	0.11	5.61
Transportation & Distribution	0.01	0.51
Combustion	1	70.46 (156.43)

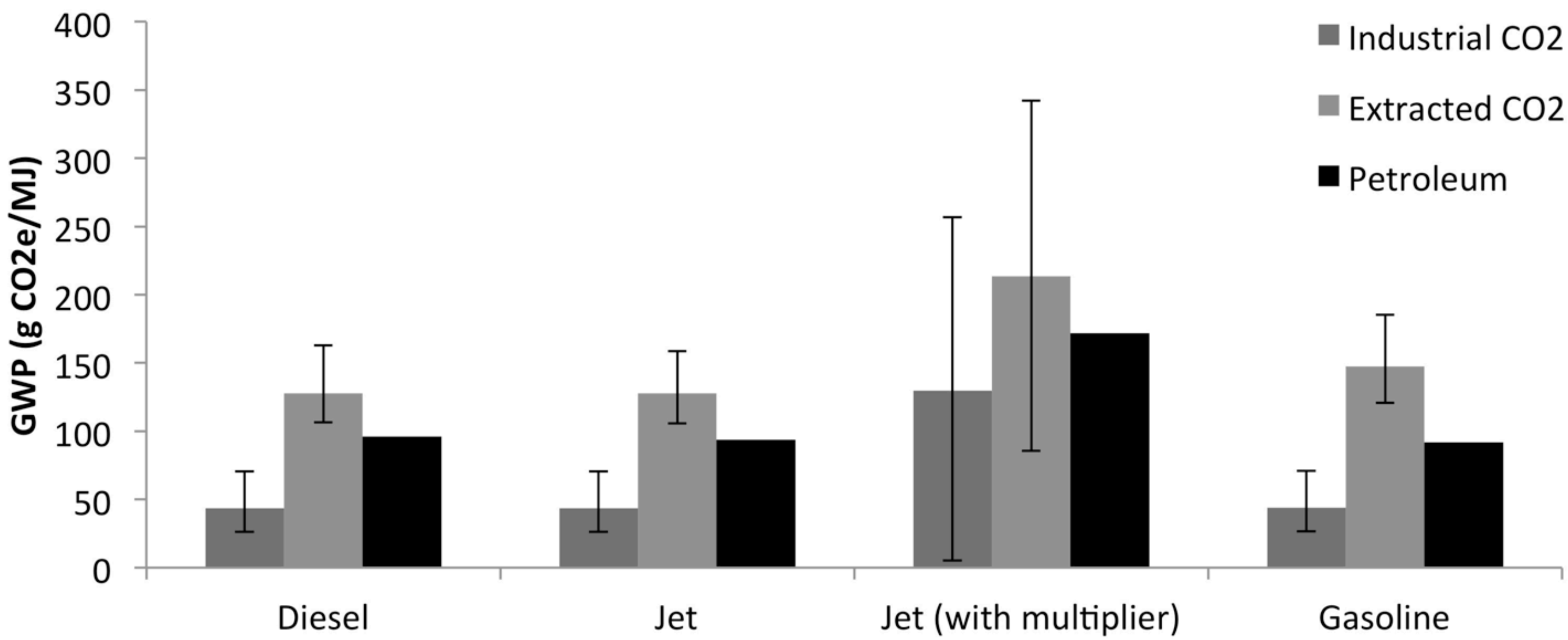

Figure 15. The global warming potentials (GWP) of AHTL biofuels and petroleum-based fuels are presented to compare climate change impacts due to lifecycle of each. Jet fuels are presented "with multiplier" and without the non-CO_2 atmospheric combustion emissions included in the GWP. The industrial CO_2 scenario is based on CO_2 from ethanol production. Extracted CO_2 is from natural, underground deposits. The error bars describe the results of sensitivity analysis.

Table 26. Percent reductions in LC-GHG required for certification under RFS2, with appropriate qualification by D code categorization, for AHTL biofuels under industrial and extracted CO2 supply scenarios.

	Scenario 1 (Industrial CO2)			Scenario 2 (Extracted CO2)		
	GWP (gCO2e/MJ)	% Reduction	RFS2 D Code	GWP (gCO2e/MJ)	% Reduction	RFS2 D Code
Diesel	43.67	55%	4	127.85	-33%	None
Jet	43.67	53%	4	127.69	-36%	None
Jet (with multiplier)	129.64	25%	6	213.66	-24%	None
Gasoline	44.01	52%	5	147.32	-60%	None

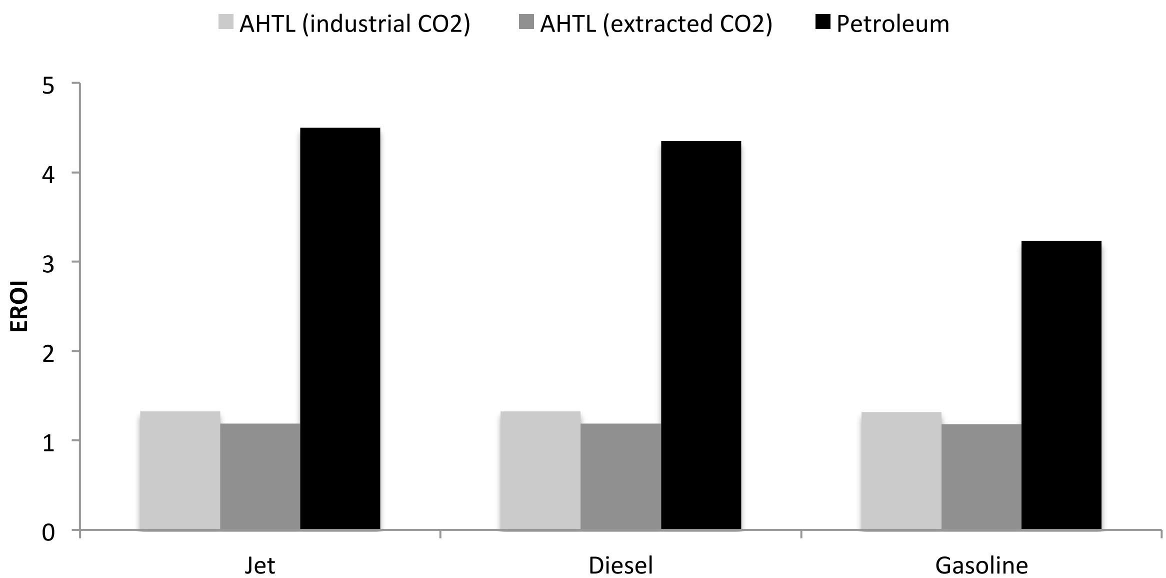

Figure 16. The energy return on investment (EROI) of AHTL biofuels and petroleum-based fuels, where EROI>1 indicates that more energy is produced than consumed over the lifecycle of fuel production. Petroleum EROIs are based on Liu et al. (2013) and GREET data.

6.6 Interpretation of Results

6.6.1 Evaluation LC-GHG emissions against the RFS2 framework

The Renewable Fuels Standard (RFS) program, created under the Energy Policy Act of 2005, was the first renewable fuel volume mandate in the United States. The program was expanded, to what is now known as RFS2, under the Energy Independence Security Act (EISA) of 2007. According to EISA, the EPA, who is responsible for developing and implementing the regulations, must apply lifecycle greenhouse gas (GHG) performance threshold standards to ensure that each category of renewable fuels indeed offers an improvement in GHG emissions compared to the petroleum fuel it replaces (representative of the transportation fuel in 2005).

Currently there are six certified pathways for producing diesel, jet fuel, or heating oil from algal oil under RSF2. The existing certified pathways focus on trans-esterification, hydrotreating, and downstream processing of extracted lipids, resulting in production of biomass-based biodiesel (RIN D4) or advanced biofuel (RIN D5), depending on processing conditions. Although EPA has yet to certify any algae HTL (AHTL) pathways under RFS2, this process is of growing interest over the past few years. Argonne National Laboratory's *Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET)* spreadsheet analysis tool is used by the EPA to aid in the evaluation of LC-GHG emissions for biofuels that are under consideration for certification.

RFS2 defines four categories of renewable fuels: (i) renewable fuel, (ii) advanced biofuel, (iii) biomass-based diesel, and (iv) cellulosic biofuel. Each year, the RFS2 sets specified targets (by volume). In essence, the standards dictate renewable volume obligation (RVO) percentages that are calculated by dividing the targets by the total estimated supply of nonrenewable gasoline and diesel. These percentages are applied to a refiner's or importer's gasoline and diesel supply from the calendar year to determine their RVOs. The obligated parties must obtain and surrender sufficient Renewable Identification Numbers (RINs) within two months (60 days) of the end of the calendar year to meet their RVOs.

The RIN system uses 38-character alphanumeric codes that are assigned to each gallon of renewable fuel that is produced in (or imported into) the United States A "D" code within each RIN represents which of the four certifiable fuel designations is achieved under RFS2. Figure 15 describes how the different fuel designations overlap based on performance threshold. Individual refiners or importers are assigned a different RVO for each D category. Based on the available supply of each fuel type per year and the percentage standard of each category of renewable fuels, some RINs become more valuable than others in given years. Based on percentage standards and fuel category, biomass-based biodiesel fuels generate RINs (D=4) that can be used to meet over 99% of the RVOs. For instance in 2013, only 6 million of the 16.6 billion gallons of mandated renewable fuel volumes (0.04%) were required to be cellulosic biofuels, and thus could not be met by D4 RINs.

The value of RINs provides economic incentive for biofuels. As the price of RINs increase, blenders are incentivized to blend greater volumes of biofuel, benefitting from both the sale of fuel and the separated RINs. (That is assuming that the value of the RINs is not actually passed to the biofuel producers). In the case when biofuels are cost-competitive with petroleum fuels, the value of a RIN is essentially zero. It is when the price of biofuel is higher than nonrenewable fuels that RINs are expected to have value, and this is because mandates from the RFS2 force some quantity of biofuels into the market and the RIN value reflects the point at which a blender (or other firm) will purchase biofuel.

Fuels certification under RFS2, whereby RIN values are generated and assigned to the qualifying fuels produced, is based on the percent reduction in LC-GHG emissions achieved by biofuels compared to their petroleum-based alternatives. Figure 15 and Table 26 describe the LC-GHG emissions arising from AHTL biofuels relative to that of their petroleum counterparts. When the CO_2 used for algae cultivation comes from natural deposits, as in the "extracted CO_2" scenario, the resulting AHTL biofuels have higher LC-GHG emissions than petroleum fuels because they are not eligible for a biogenic carbon credit. Thus, none of the fuels produced under this scenario could qualify under RFS2.

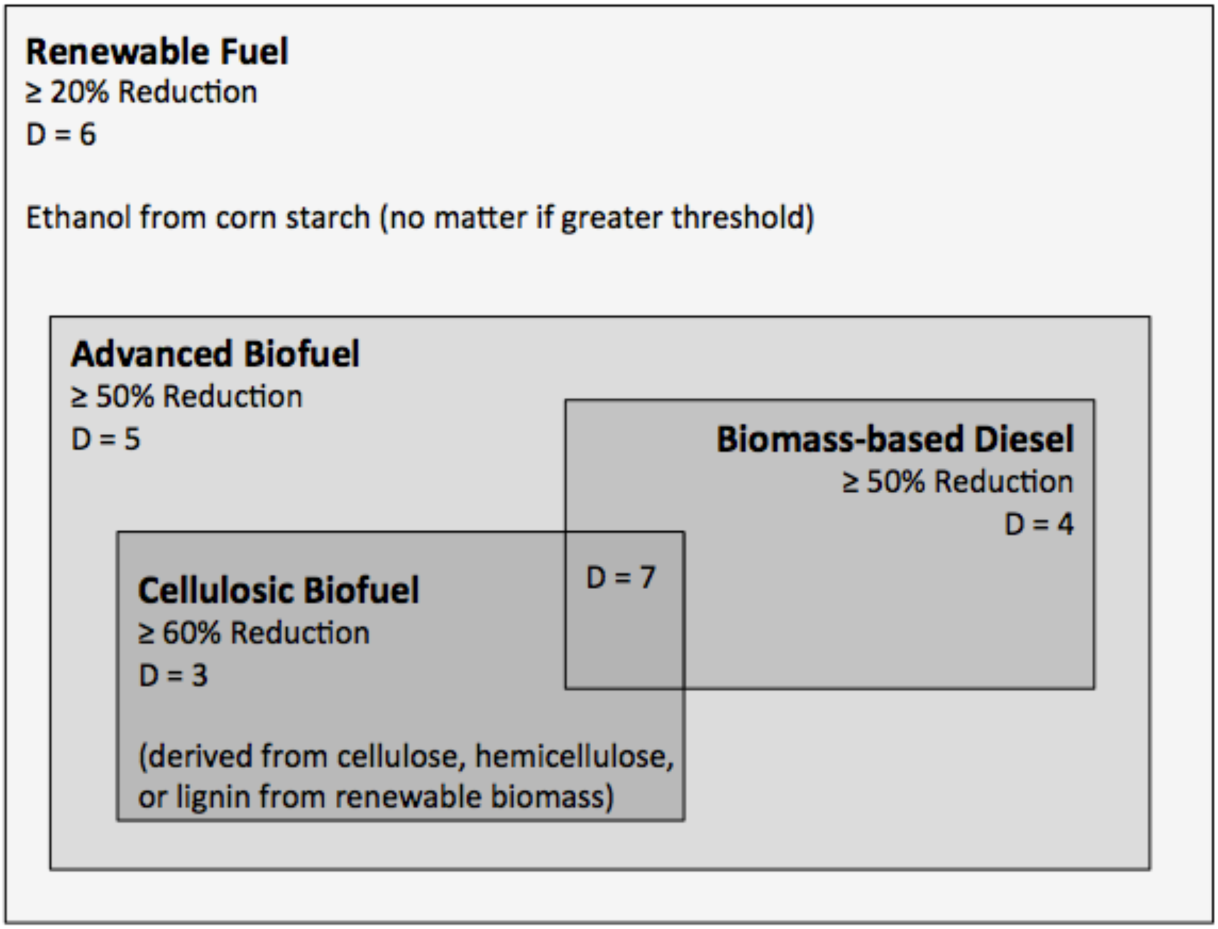

Figure 17 RFS2 categorization of fuels based on LC-GHG emissions reductions compared to 2005 petroleum-equivalents. The "D" designation refers to the fuel code in the RIN, where D=7 means that the RIN can be used to meet either *Cellulosic Biofuel* or *Biomass-based Diesel* volume obligations.

The LC-GHG emissions calculated under the "industrial CO_2" scenario represent a slightly more than 50% reduction in emissions relative to their petroleum counterparts. While CO_2 from ethanol production was used to represent industrial CO_2, Middleton et al. (2014) calculate comparable upstream burdens for industrial CO_2 from ammonia and hydrogen production and natural gas processing. CO_2 as a by-product of power generation could serve as another industrial source, but would increase the LC-GHG emissions by about 60% based on the burdens described reported in Middleton et al. (2014)

RFS2 requires petroleum fuel producers and importers to meet renewable volume obligations as a defined percentage of gasoline and diesel sales. Although jet fuel is not an obligated fuel under RFS2, aviation biofuel is eligible for RIN generation similar to diesel fuels; therefore, it is of interest to anticipate what RIN categorization AHTL aviation biofuel might achieve. Our results indicate that this depends strongly on assumptions related to combustion of the fuel during the use phase, since there is emerging evidence that atmospheric combustion of a bio-based fuel (e.g., as during flight) results in a different emissions profile than terrestrial combustion. This consideration is unique to aviation biofuels. When the non-CO_2 atmospheric impacts are neglected, AHTL jet fuel qualifies as *biomass-based diesel*. In contrast, when the atmospheric combustion multipliers developed by Stratton et al. (2011) are applied to both aviation biofuel and petroleum jet fuel, the AHTL aviation fuel offers a 25% reduction relative to conventional jet fuel. Therefore, if the EPA chose to consider global warming potential (GWP) in place of LC-GHG emissions for jet fuels, AHTL jet fuel would qualify as a *renewable fuel*. From a biofuel producer's viewpoint, this is a less desirable designation than those for AHTL biodiesel (*biomass-based diesel*) or AHTL-derived gasoline (*advanced biofuel*); however, given the rapidly growing demand for domestic, bio-based fuels, it is encouraging that aviation biofuels produced from algae would qualify under the current national regulatory framework.

6.6.2 Sensitivity analysis

In evaluating petitions for certification of renewable fuels under RSF2, the EPA considers the probabilistic uncertainty of LCA results, as characterized using an empirical distribution; rather than just the average or expected value. Respecting this, the distributions of LC-GHG emissions estimates from the AHTL modeling results for each type of fuel were evaluated. Figure 16 is modeled after the EPA "Fuel Pathway Determination under the RFS2" (U.S. Environmental Protection Agency Office of Transportation and Air Quality 2015), showing the results of the sensitivity analysis with respect to AHTL aviation biofuel. Interestingly, all types of fuel share the same general distribution shape when jet fuel calculations exclude atmospheric combustion multipliers. Figure 16a presents the distribution of results for AHTL jet fuel, which is representative of the distributions for other AHTL fuels (see Appendix A for frequency distributions from sensitivity analysis).

Considering the promising baseline results (those calculated with the "baseline" parameter values), with respect to RFS2 qualification, next it is necessary to examine the probability distributions for AHTL fuel produced from industrial CO_2. Eighty-eight percent of the recorded LC-GHG results (i.e., 88% of the simulation output) for AHTL diesel and gasoline fall below the 50% reduction thresholds for their respective petroleum counterparts; therefore, both fuels would likely qualify under RFS2 as *biomass-based diesel* and *advanced biofuel*, respectively. Thus, it was observed that the assumed uncertainty in the parameters does not impact the ability to draw conclusions with respect to the likelihood of certification under RFS2. With more than 80% of the Monte Carlo results indicating that AHTL fuels will be certifiable at the most stringent level under RSF2, the results are encouraging.

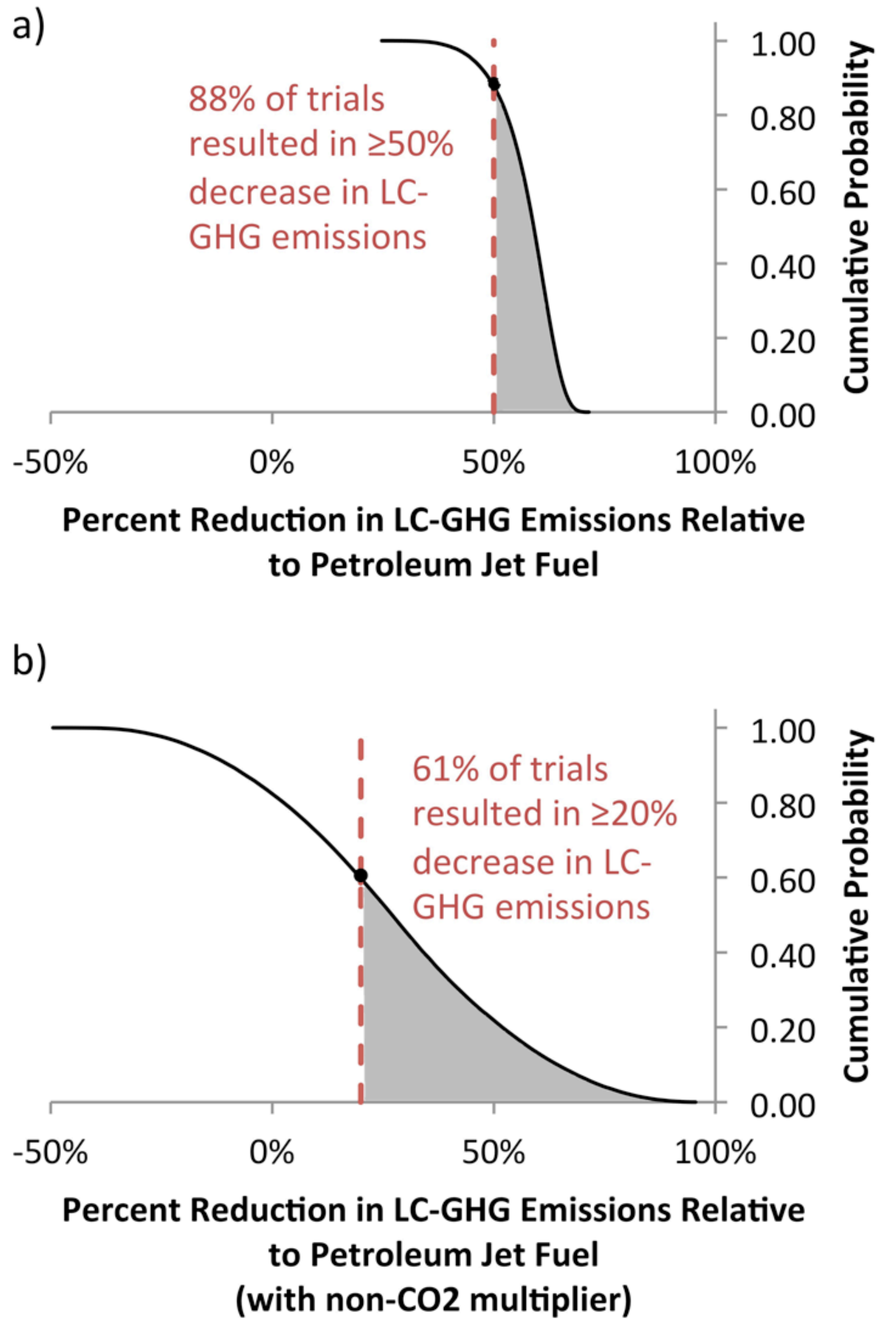

Figure 18. Cumulative probability density distributions of LC-GHG emissions results for AHTL aviation biofuel calculated (a) without and (b) with the non-CO2 atmospheric combustion multiplier

If atmospheric combustion is considered in determining the GWP of aviation biofuels, the qualification petition for AHTL jet fuel would likely be as a *renewable fuel*, since the median LC-GHG emissions are lower than that needed to meet other thresholds (i.e., 25% reduction could only qualify as *renewable fuel*). Based on the sensitivity analysis, about 10% of the forecasted GWP is equal to or greater than petroleum jet fuel, and only 61% of the simulations result in GWP that meet the 20% reduction threshold for *renewable fuels*. Thus, it is unlikely that the EPA would grant approval under RFS2. In this scenario, the use of biofuels in aviation would be discouraged, and the market might be better served by reserving AHTL fuels for ground transportation, using other fuels for aviation. By considering the relative merit of biofuel replacements to petroleum fuels (percentage LC-GHG emissions reductions), RFS2 would encourage the use of petroleum reserves for atmospheric combustion because terrestrial biofuels offer greater global warming abatement. This is an interesting, unexpected conclusion of this analysis, given the growing demand for aviation biofuels to meet commercial and defense demand.

Beyond this, sensitivity analysis reveals what are the most influential parameters on LC-GHG emissions for production of AHTL biofuels. Identifying the most influential variables reveals where reducing uncertainty in parameters can enable LCA to best represent reality. That is to say, if the assumed ranges of values for those parameters shown in Figure 17 do not capture the uncertainty in the field, actual LC-GHG emissions could be significantly impacted. Three of the six most influential parameters are related to the HTL process itself, while the remaining three pertain to nutrient cycling. Regarding the HTL conversion, the most optimistic and pessimistic values for "percent yield of biocrude" (as described in Tables 22 and 23) mediates corresponding changes in LC-GHG emissions of -19% and +46%. Figure 17a shows the level of LC-GHG emissions corresponding to a 50% reduction compared to petroleum jet fuel and reveals that a sufficiently low biocrude yield results in LC-GHG that do not meet this threshold. Similarly, Figure 17b reveals that, when considering the influence of a single parameter, only when the non-CO_2 multiplier is sufficiently low could AHTL jet fuel offer 50% reduction compared to petroleum jet fuel with atmospheric combustion effects included.

Additionally maximum and minimum assumed changes in “nutrient recycle efficiency”, “nitrogen [content] in the biomass”, or “upgraded biocrude yield”, mediate moderate to significant changes (at least 5% change) in overall lifecycle LC-GHG emissions. Additional results from sensitivity analysis can be found in Appendix A. These results are consistent with previously published LCA literature pertaining to algae cultivation, in which it has been repeatedly shown that nutrient recycling and/or nitrogen supply with low upstream burdens is important for reducing the LC-GHG emissions. Still, it is interesting and novel that the cultivation-phase nutrient burdens still tend to dominate the overall lifecycle impacts even when an energy-intensive conversion process, such as HTL, is used to produce fuel from the biomass. Thus, facility designs that use municipal waste water as the nutrient source for algae cultivation could improve the LC-GHG emissions of AHTL biofuels by offering a supply of nitrogen that is less environmentally burdensome than chemical fertilizers.

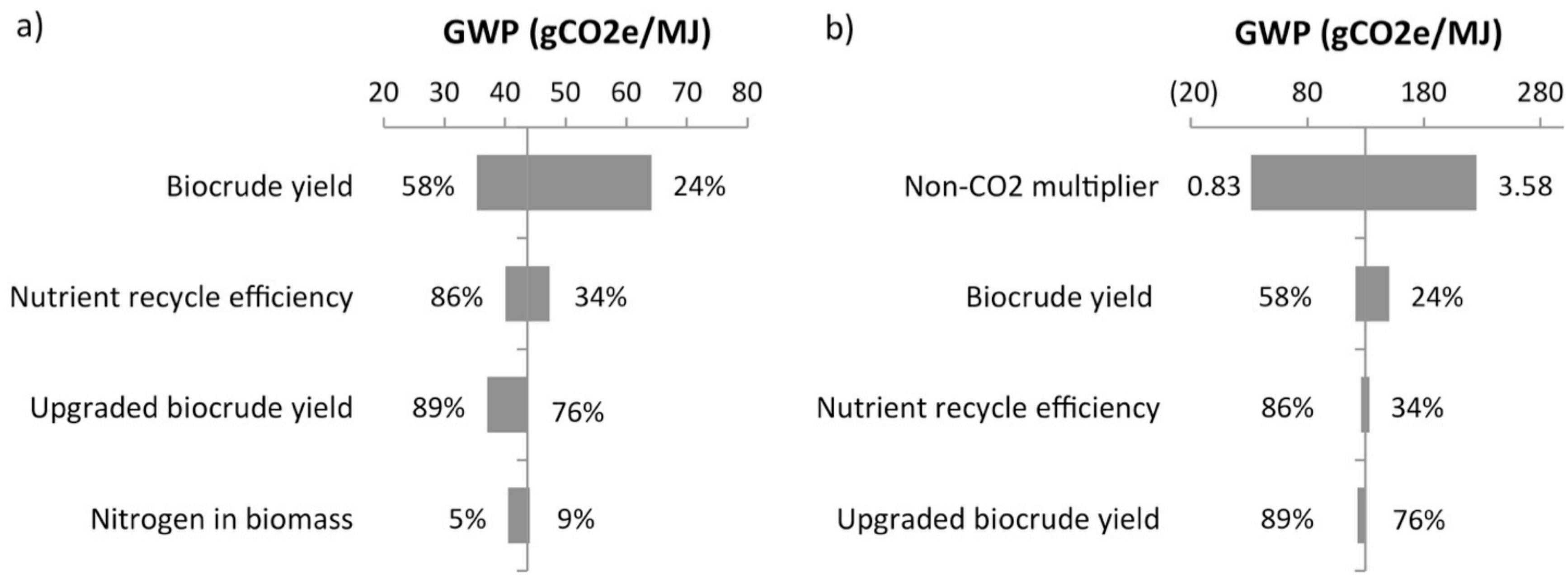

Figure 19. Most influential parameters (those resulting in changes greater than +/- 5% of baseline) to the GWP results of AHTL jet fuel produced using industrially-sourced CO_2 from ethanol production (a) without including non-CO_2 combustion emissions, and (b) with non-CO_2 combustion emissions included

6.7 Chapter Summary

This chapter provided a demonstration of life cycle assessment to determine the energy demand and GWP of an algae hydrothermal liquefaction biofuel pathway. The following chapter will describe how life cycle assessment results such as these can be integrated with decision analysis for designing resilient strategic plans. Chapter 9 will also discuss how information from life cycle assessment, for example the importance of atmospheric combustion, and from sensitivity analysis can inform strategic plans and future research and development.

CHAPTER 7: DEMONSTRATION: INTEGRATING LIFE CYCLE ASSESSMENT

7.1 Overview

This chapter will describe how life cycle assessment and other data are integrated into scenario-based preferences analysis for resilience analytics of aviation biofuel strategic planning. Section 7.2 discusses how criteria for scenario-based preferences modeling can be associated with life cycle impact categories. Gaps in available data can mean that related data must used as proxies for assessing initiative performance with respect to a certain criterion. Section 7.3 describes the feedstock-to-biofuel pathways selected for scenario-based preferences analysis in Chapter 8. Section 7.4 describes how LCA results for GHG emissions, fossil energy demand, water use, and cost are translated into qualitative assessments for the scenario-based preferences modeling.

7.2 Relating Criteria to Life Cycle Impacts

Criteria defined for scenario-based preference analysis address stakeholder objectives with regard to the system being studied. For aviation biofuels, there are a number of objectives related to the life cycle of the alternative systems or pathways. As described in the criteria section of Chapter 5, Section 5.4. and Table 6, life cycle costs and environmental impacts associated with aviation biofuels are of particular concern.

Life cycle analysis, for which we will include life cycle cost analysis, can be used to quantify the various environmental impacts and costs of initiatives or alternatives defined for scenario-based preference analysis. Because performing original life cycle assessments for each initiative is prohibitively time consuming and likely outside the scope of the practitioner's expertise, existing studies are recommended to inform scenario-based preference analysis. As such, there must be a matching that takes place between the initiatives to be analyzed against LCA-based criteria and currently available life cycle assessment results.

One approach is as follows:

(1) Identify initiatives (or systems) to be evaluated

(2) Identify criteria to be measured by life cycle assessment impacts

(3) Search for and compile the available life cycle assessment results for each of the systems in (1) with respect to the criteria in (2); and lastly,

(4) Discard criteria and systems for which there is sufficient data to proceed with scenario-based preference analysis.

With the above approach, step (3) is a directed search where certain impact categories for certain systems are sought. Alternatively, step (2) can be skipped and an attempt can be made to survey all published life cycle assessment data related to the chosen systems. The criteria are then selected from those with sufficient data for the initiatives. This latter method opens up the possibility for otherwise overlooked criteria to be identified, though the method likely requires more effort.

There are numerous viable pathways for producing aviation biofuels, which consist of pairing feedstocks with conversion technologies. There are three broad categories of conversion techniques: thermochemical, hydroprocessing, and biochemical. The Fischer-Tropsch process, ASTM-approved as an alternative aviation fuel pathway, in addition to pyrolysis and hydrothermal liquefaction falls under the category of thermochemical conversion processes. The hydroprocessing of esters and fatty acids (HEFA) process is another ASTM-approved route for converting fats and oils into aviation biofuel. Biochemical processing involves enzymes and other micro-organisms that convert cellulose and hemicellulose to sugars, alcohol, and eventually jet fuel. The recently approved synthesized iso-paraffinic (SIP) fuels are produced by biochemical processing. Alcohol-to-jet (ATJ) is another pathway, making progress for approval by ASTM, which uses fermentation to produce jet fuel from biomass sugars.

Table 27 lists a number of commonly studied feedstocks for aviation, and other, biofuel production (Macfarlane et al. 2011; International Air Transport Association 2013; Kandaramath Hari et al. 2015; Chiaramonti et al. 2014). In the table, these feedstocks are matched with feasible conversion routes. A literature review has been performed to determine the life cycle impacts that have been assessed for each feedstock-to-aviation biofuel pathway.

Table 27. Previously studied life cycle impact categories for various aviation biofuel pathways

Feedstock	Conversion Processes	Life Cycle Impact Categories	Life Cycle Assessment Studies
Agricultural residue	Thermochemical; Biochemical		
Algae	Thermochemical; Hydroprocessing	GHG (gCO2e/MJ); Cost (¢/gal); Land Productivity (L/ha/yr)	Agusdinata et al. (2011); Fortier et al. (2014); Stratton et al. (2010)
Camelina	Hydroprocessing	GHG (gCO2e/MJ); Cost (¢/gal); CED (MJ input/MJ output); Land Productivity (kg/ha/yr)	Han et al. (2013); Agusdinata et al. (2011); Shonnard et al. (2010); Lokesh et al. (2015)
Corn stover	Thermochemical; Biochemical	GHG (gCO2e/MJ); Cost (¢/gal); Land Productivity (L/ha/yr)	Han et al. (2013); Agusdinata et al. (2011); Stratton et al. (2010)
Forest residue	Thermochemical		
Jatropha	Hydroprocessing	GHG (gCO2e/MJ); FED (MJ fossil input/MJ output); Land Productivity (L/ha/yr); Water Use (L water/L fuel)	Han et al. (2013); Trivedi et al. (2015); Stratton et al. (2010); Staples et al. (2013)
Miscanthus	Thermochemical; Biochemical		
Municipal solid waste	Thermochemical; Biochemical		
Palm oil	Hydroprocessing	GHG (gCO2e/MJ); FED (MJ fossil input/MJ output); Land Productivity (L/ha/yr)	Han et al. (2013); Trivedi et al. (2015); Stratton et al. (2010)
Rapeseed	Hydroprocessing	GHG (gCO2e/MJ); FED (MJ fossil input/MJ output); Land Productivity (L/ha/yr); Water Use (L water/L fuel)	Han et al. (2013); Trivedi et al. (2015); Stratton et al. (2010); Staples et al. (2013)
Sorghum	Thermochemical; Biochemical		
Soybean	Hydroprocessing	GHG (gCO2e/MJ); FED (MJ fossil input/MJ output); Land Productivity (L/ha/yr); Cost ($/m3); Water Use (L water/L fuel)	Han et al. (2013); Trivedi et al. (2015); Stratton et al. (2010); Seber et al. (2014); Staples et al. (2013)
Switchgrass	Thermochemical; Biochemical	GHG (gCO2e/MJ); Cost (¢/gal); FED (MJ fossil input/MJ output); Land Productivity (L/ha/yr); Water Use (L water/L fuel)	Agusdinata et al. (2011); Trivedi et al. (2015); Stratton et al. (2010); Staples et al. (2013)
Tallow	Hydroprocessing	GHG (gCO2e/MJ); Cost ($/m3)	Seber et al. (2014)
Wood	Thermochemical	GHG (gCO2e/MJ); Cost (¢/gal)	Agusdinata et al. (2011)
Yellow grease	Hydroprocessing	GHG (gCO2e/MJ); Cost ($/m3)	Seber et al. (2014)

Table 27 reveals that there is a lack of life cycle assessment data on a number of aviation biofuel pathways. LG-GHG emissions are by far the most prevalent life cycle impact category assessed for aviation biofuel pathways. Life cycle cost and energy demand have also been considered by several studies. In addition, Stratton et al. (2010) and Staples et al. (2013) studied the land use and water use requirements, respectively, over the life cycle of several aviation biofuel pathways. Only switchgrass and soybean-based aviation biofuel have been evaluated on all five metrics (i.e., GHG emissions, cost, energy demand, land use, and water use). Rapeseed and jatropha pathways have been assessed for all the metrics except cost.

Currently, neither agricultural residues, forest residues, miscanthus, municipal solid waste, nor sorghum have been studied for life cycle impacts with respect to aviation biofuel production. Renewable diesel has been studied more extensively than aviation biofuel in the life cycle assessment literature. As such, most of the feedstocks have been evaluated with respect to renewable diesel pathways. While the difference in life cycle impacts of producing renewable diesel as opposed to jet fuel can be significant, the use of non-aviation biofuel life cycle assessments can be helpful in determining the relative attractiveness of biofuels with respect to various life cycle impact categories. For example, Dufour and Iribarren (2012) assessed the GHG emissions and energy demand for biodiesel production from a variety of oil-containing feedstocks: waste vegetable oil, beef tallow, poultry fat, sewage sludge, soybean, and rapeseed. Because the processing of bio-oils to diesel and to jet fuel is similar, the relative attractiveness of the biodiesel pathways is likely the same for aviation biofuel.

Regardless of potential difference in renewable diesel and jet fuel produced from the same feedstock, comparative life cycle assessments of renewable diesel and other biofuel pathways can reveal the relative environmental impacts that likely hold for all biofuel products. Table 28 describes the life cycle impact categories that have been studied for feedstocks for biofuel production. The table also indicates for which fuel products (i.e., renewable gasoline [G], renewable diesel [D], or renewable jet fuel [J]) the life cycle assessment was performed. In addition, life cycle assessment has been used to study the impacts of feedstock production, harvest, and transportation, without making assumptions about biofuel conversion pathway. For example, Daystar et al. (2012) analyzed the delivery cost and GHG emissions of six potential biofuel feedstocks: pine, eucalyptus, unmanaged hardwoods, forest residues, switchgrass, and sweet sorghum. Data on the feedstock can also indicate the relative preferability of biofuel pathways based on each feedstock, assuming similar processing would be required to convert each to aviation biofuel. Allowing non-aviation biofuel pathway and feedstock life cycle assessment studies to serve as a proxy for specific aviation biofuel pathways increases the amount of data and the number of metrics with which to compare life cycle impact tradeoffs.

Based on a review of the current life cycle literature for biofuels and biofuel feedstocks, the most common life cycle impacts include GHG emissions, energy demand, water use, land use, and cost. Once specific pathways have been selected for scenario-based preference analysis, the analyst must determine which impacts will be included based on stakeholder preferences and data availability. Selection of biofuel pathways should be based on regional availability of feedstock and suitability of the regional climate and conditions to introduce a new feedstock.

Table 28. Review of LCA impact categories studied for feedstock (F) or biofuel, indicated as renewable gasoline (G), diesel (D), or jet fuel (J)

Feedstock	LCA Impact Category				
	GHG emissions	Energy demand	Water use	Land productivity	Cost
Agricultural residue	D[1], G[1]	G[2]	G[3]		
Algae	J, D, G	J, D, G	D[4]	J, D[4]	J
Camelina	J	J		J	J
Corn stover	J, G[5]	G[5]	G[3]	J, G[6]	J
Forest residue	G[2], F[9]	G[2]			F[9]
Jatropha	J	J	J	J	
Miscanthus	J		G[6]	G[6]	
Municipal solid waste	D[7], G	D			
Palm oil	J	J		J	
Rapeseed	J, D[8]	J, D[8]	J	J	
Sorghum	F[9], G[10]	G[10]	G[10]	G[10]	F[9]
Soybean	J, D[8]	J, D[8]	J, D[3]	J	J
Switchgrass	J, F[9]	J	J, G[6]	J, G[6]	J, F[9]
Tallow	J, D[8]	D[8]			J
Wood	J, D[5], G[5], F[9]	D[5], G[5]	G[11]		J, F[9]
Yellow grease	J, D[8]	D[8]			J

---

[1] Emissions for renewable energy production (including renewable gasoline and diesel) for straw-based feedstocks reported by Weiser et al. (2014)

[2] Emissions and energy for producing ethanol via pyrolysis of straw and forest residue reported by Karlsson et al. (2014)

[3] "Blue" and "green" water use for corn stover ethanol, soybean biodiesel, and wheat straw ethanol reported by Chiu and Wu (2012)

[4] Fresh water use and land requirements for algae biodiesel va lipid extraction and hydrothermal liquefaction reported by Venteris et al. (2014)

[5] Emissions and fossil energy demand for biochemical conversion of corn stover to ethanol, indirect gasification of southern pine to ethanol, and pyrolysis of hybrid poplar to renewable diesel and gasoline reported by Dunn et al. (2013)

[6] Land and water intensity of corn stover, switchgrass, and miscanthus-derived ethanol reported by Zhuang et al. (2013)

[7] Global warming potential and EROI reported for MSW to bioenergy via gasification and FT reported by Pressley et al. (2014)

[8] Emissions and energy demand for biodiesel production from waste vegetable oil, beef and poultry tallow, sewage sludge, soybean, and rapeseed reported by Dufour and Iribarren (2012)

[9] Emissions and cost for the production, harvest, and delivery of pine, eucalyptus, unmanaged hardwoods, forest residue, switchgrass, and sweet sorghum reported by Daystar et al. (2012)

[10] Emissions, energy, water, and land impacts of sorghum-derived ethanol reported by Olukoya et al. (2015)

[11] Blue water use for forest wood biofuel reported by Chiu and Wu (2013)

7.3 Selection of Alternative Pathways for Analysis

Not all possible aviation biofuel pathways need to be evaluated for every location-specific analysis. Of the many feedstocks that can potentially be converted to biofuels, only a subset will be readily available or able to be cultivated in certain geographic regions. Data on feedstock availability by county, state, and/or region has been published for a number of feedstocks, and can be used to narrow the scope of potential biofuel pathways for analysis.

Most data is focused on current availability, such as that reported in the 2011 U.S. Billion Ton Update (BT2) (U.S. Department of Energy 2011). Once a region has been selected for study, the BT2 Data Explorer (U.S. Department of Energy 2013) can be used to quantify the annual projected availability of primary agricultural feedstocks, forest resources, and secondary resources. Using the methodology described by Pate et al. (2011), the potential availability of algae biomass can be calculated using an assumed regional growth rate and pasture land availability from the USDA Census of Agriculture. Columbia University recently estimated the amount of landfilled municipal solid waste (MSW) by state (Themelis and Mussche 2014). The National Renewable Energy Laboratory has estimated the amount of yellow cooking grease produced each year per person, which can be used to estimate the availability in a given region (Wiltsee 1998).

Rapeseed, including the canola varietals, is currently produced in nine states, mainly in the mid- to northwest US (National Agricultural Statistics Service (NASS) 2015). There have, however, been trials to determine the possible yields for cultivating rapeseed as a winter crop in more southern states (Atkinson et al. 2011). Palm oil is not currently produced in the United States, and the ideal growing conditions are found within 10 degrees north and south of the Equator where temperatures are much warmer than those in the U.S., so future production is unlikely (Verheye 2007). Similarly, jatropha cultivation is limited to tropical and subtropical regions (Brittaine and Lutaladio 2010). Although it is unlikely that palm oil or jatropha-based pathways would be pursued for biofuel production in the Commonwealth of Virginia, both are included as initiatives as one means to check the validity of the scenario-based preferences model. That is to say, if current and future resource availability are important factors in the decision on feedstock selection, this should be reflected in the relatively low prioritization of the two feedstocks.

Regional resource assessments are also available for certain areas. The estimated quantity of biomass available in a region can vary depending on feedstock types and definitions in addition to environmental, economic, and technological assumptions. Regardless of differences in estimates, biomass resource assessments can be used to help determine promising feedstocks for scenario-based preferences analysis of biofuel pathways.

7.4 Translating Life Cycle Assessment Results for Initiative-Criterion Assessment

Life cycle assessment results can be used in scenario-based preferences analysis to determine how well initiatives, for example biofuel pathways, address LCA-related criteria (e.g., GHG emissions, energy demand, etc.). If there was no variability in life cycle impacts of each biofuel pathway, then the numerical results could be normalized across all initiatives to provide the quantitative value score x_{ij}, as described in Section 5.6. Because there is variability in life cycle assessment results due to differences in system boundaries, allocation method, process assumptions, and various other factors, it would be inappropriate to simply choose one value (even an average of all reported values) and normalize over all feedstock impacts to get the value scores.

Alternatively, it is suggested that life cycle assessment results are analyzed with a consideration of the full range of values supported in the literature. Further, the ordering of pathways with respect to LCA-based criteria resulting from a single study can be used to help inform about the relative attractiveness of pathways given similar assumptions and systems boundaries. Because there can be conflicting results, the practitioner will ultimately have to decide which pathways receive which categorical initiative-criteria assessment. Sensitivity analysis can be performed to determine the influence of these choices on the resulting prioritization (see Appendix B).

Table 29 describes the baseline or average LC-GHG emissions results for various feedstock-to-biofuel pathways. The minimum and maximum reported values are also included in Appendix B. With four categories (e.g., *strongly addresses, addresses, somewhat addresses, does not* address) describing the relationship between initiatives and criteria in scenario-based preferences modeling, numerical results can be used to systematically define how each is categorized. One approach is to divide the range of results in to four subsets and assign each to a qualitative initiative-criterion assessment category. For example this could be done for LC-GHG emissions in the following manner:

- Category 1 LC-GHG emissions are less than or equal to 17.9 gCO_e/MJ and *strongly address* a global warming criterion;
- Category 2 LC-GHG emissions are above 17.9 and less than or equal to 27 gCO_e/MJ and *address* a global warming criterion;

- Category 3 LC-GHG emissions are greater than 27 and less than or equal to 45 gCO_e/MJ and *somewhat address* a global warming criterion;
- Category 4 LC-GHG emissions are above 45 gCO_e/MJ and *do not address* a global warming criterion.

While this previously described method of translating life cycle assessment results to the categorical initiative-criterion assessment can be applied consistently, this method still might not be suitable. For one, this method does not consider extremes in the positive or negative direction differently from those close to the cut-offs. When the ranges of values for different initiatives vary considerably, the practitioner can instead make the assessment based on minimum, maximum, baseline and/or literature-based preference ordering. When practitioner judgment is used, however, the repeatability of the method is lost. If the practitioner or analyst is going to make the LCA-based assessments using their own judgment as opposed to automating the assessment based on numerical results, it is important that the practitioner is transparent with choices. For the demonstration presented in Chapter 8, average values and analyst judgment are used to make initiative-criterion assessments as indicated in Tables 29-32. Appendix D describes a decision-support tool developed to automate assessments based on input life cycle assessment data, while also allowing the user to modify these assessments.

Table 29. Average LC-GHG emissions of biofuels by feedstock with corresponding categorical assessment for scenario-based preferences analysis in Chapter 8.

Feedstock	Average LC-GHG Emissions (gCO_2e/MJ)	Categorical Assessment for GHG Emissions Criterion
Agricultural residue	18	Strongly addresses
Algae	68	Does not address
Camelina	33	Somewhat addresses
Corn stover	27	Addresses
Forest residue	21	Addresses
Jatropha	28	Somewhat addresses
Miscanthus	10	Strongly addresses
Municipal solid waste	-99	Strongly addresses
Palm oil	31	Somewhat addresses
Rapeseed	54	Does not address
Sorghum	62	Does not address
Soybean	35	Somewhat addresses
Switchgrass	25	Addresses
Tallow	45	Does not address
Wood	23	Addresses
Yellow grease	19	Strongly addresses

Table 30. Average life cycle fossil energy demand of biofuels by feedstock with corresponding categorical assessment for scenario-based preferences analysis in Chapter 8.

Feedstock	Average LC Fossil Energy Demand (MJ in/MJ out)	Categorical Assessment for Energy Demand Criterion
Agricultural residue	0.110	Strongly addresses
Algae	0.802	Does not address
Camelina	0.587	Does not address
Corn stover	0.146	Addresses
Forest residue	-0.127	Strongly addresses
Jatropha	0.679	Does not address
Miscanthus	0.137	Strongly addresses
Municipal solid waste	0.417	Somewhat addresses
Palm oil	0.391	Somewhat addresses
Rapeseed	0.545	Somewhat addresses
Sorghum	0.893	Does not address
Soybean	0.385	Addresses
Switchgrass	0.119	Strongly addresses
Tallow	0.432	Somewhat addresses
Wood	0.300	Addresses
Yellow grease	0.314	Addresses

Table 31. Average life cycle (blue) water demand of biofuels by feedstock with corresponding categorical assessment for scenario-based preferences analysis in Chapter 8. A dash indicates a lack of data.

Feedstock	Average water consumption (L blue water/ L fuel)	Categorical Assessment for Water Use Criterion
Agricultural residue	6	Strongly Addresses
Algae	456	Addresses
Camelina	-	Does Not Address
Corn stover	860	Somewhat Addresses
Forest residue	-	Addresses
Jatropha	8,267	Does Not Address
Miscanthus	745	Addresses
Municipal solid waste	-	Strongly Addresses
Palm oil	-	Does Not Address
Rapeseed	2,505	Does Not Address
Sorghum	1,250	Somewhat Addresses
Soybean	1,724	Somewhat Addresses
Switchgrass	1,065	Somewhat Addresses
Tallow	-	Strongly Addresses
Wood	31	Addresses
Yellow grease	-	Strongly Addresses

Table 32. Average life cycle cost of biofuels by feedstock with corresponding categorical assessment for scenario-based preferences analysis in Chapter 8. A dash indicates a lack of data.

Feedstock	Average Estimated Cost ($/L)	Categorical Assessment for Water Use Criterion
Agricultural residue	0.30	Strongly addresses
Algae	3.19	Somewhat addresses
Camelina	0.90	Strongly addresses
Corn stover	1.06	Addresses
Forest residue	1.42	Somewhat addresses
Jatropha	-	Does not address
Miscanthus	-	Somewhat addresses
Municipal solid waste	0.11	Strongly addresses
Palm oil	-	Does not address
Rapeseed	-	Does not address
Sorghum	-	Does not address
Soybean	0.76	Strongly addresses
Switchgrass	1.05	Addresses
Tallow	1.08-	Addresses
Wood	1.32	Somewhat addresses
Yellow grease	0.93	Addresses

7.5 Chapter Summary

This chapter has described how life cycle data will be incorporated into the following frame of scenario-based preferences analysis of aviation biofuel feedstocks. Based on the availability of life cycle assessment data, sixteen aviation biofuel feedstocks are identified as appropriate for analysis in the following chapter. Further four lifecycle impacts are well-studied in the literature and relate to the environmental and cost criteria to be discussed in Section 8.4. The following chapter will demonstrate scenario-based preferences modeling for analyzing aviation biofuel feedstocks informed by the described LCA data.

CHAPTER 8: DEMONSTRATION: RESILIENCE OF FEEDSTOCK PRIORITY

8.1 Overview

This chapter will present a subsequent frame of scenario-based preferences analysis based on the results from the previous frame described in Chapter 5. Section 8.2 describes the background for this frame of analysis, which includes F2F2 efforts to identify state-specific feedstock opportunities and engagement with biofuel stakeholders throughout the Delaware-Maryland-Virginia (Delmarva) region. Section 8.3 lists the feedstock (representing feedstock-to-biofuel pathways) initiatives for the analysis. Section 8.4 describes the LCA-based and non-LCA based criteria that will be used to evaluate the initiatives. Section 8.5 describes a number of scenarios under which stakeholder preferences shift from the baseline. Section 8.6 describes the calculations and Section 8.7 presents the results of the scenario-based preferences analysis.

8.2 Background

8.2.1 Farm-to-fly 2.0 initiative

In 2010, the United States Department of Agriculture (USDA) joined with Airlines for America (A4A) and the Boeing Company on the "Farm to Fly" initiative with the goal to “accelerate the availability of a commercially viable and sustainable aviation biofuel industry in the United States, increase domestic energy security, establish regional supply chains, and support rural development“(U.S. Department of Agriculture 2012). The public-private partnership was later extended to include the Federal Aviation Administration, the Department of Energy, and CAAFI, among others. The newly termed “Farm to Fly 2.0” (F2F2) initiative explicitly seeks to increase the nation’s supply of alternative jet fuel to 1 billion gallons per year by 2018 (Male 2015).

State initiatives are being pursued to help achieve production goals. There are ongoing efforts supported by F2F2 in Florida, Connecticut, Vermont, New Jersey and South Carolina, among others. While not officially part of the F2F2 initiative, interest in aviation biofuels was first expressed by the Department of Aviation (DOAV) in 2012 with the commissioning a cost-benefit analysis of a future aviation biofuel supply chain, as referenced in Section 4.2 (Clarens et al. 2013). Stimulated in part by a 2014-2015 Airport Cooperative Research Program grant, F2F2 efforts formally began in Virginia when Rich Altman, executive director emeritus of CAAFI, began working with the University of Virginia and the Commonwealth Center for Advanced Logistics Services. As a result of the coordination of these three parties to promote the commercialization of aviation biofuel in Virginia, the team was awarded a 2015-2016 Commonwealth Research Commercialization Fund (CRCF) grant by the Center for Innovative Technology (CIT). Appendix B contains details of the effort and scope of work for the DOAV study, the ACRP award, and the CRCF grant. Evident from the varying topics of these funded efforts, the interest of aviation biofuels in Virginia has evolved from general interest in economic feasibility, to prioritizing future initiatives, to engaging stakeholders to spur commercialization.

The most effective initiatives for developing aviation biofuel supply chains will differ among states due to diversity of factors such as: feedstock supply, local and regional existing markets, available expertise, regional environmental considerations, and others. This purpose of this frame of analysis is to support the commercialization of aviation biofuels specifically in the Commonwealth of Virginia. As a basis, stakeholder elicitation is used to inform multi-criteria decision analysis (MCDA) for prioritizing initiatives across multiple stakeholder objectives (Montibeller and Franco 2010). Incorporating scenario analysis addresses uncertainties and varying stakeholder preferences to study the resilience of priorities (Connelly, Colosi, et al. 2015a)

8.2.2 Stakeholder analysis and engagement

Stakeholders across the aviation biofuel supply chain must be identified and engaged in order to promote the commercialization of aviation biofuels. Traditionally, F2F2 state initiatives have begun with the identification of state leads for the effort, typically a non-profit or other organization as a neutral lead (Rich Altman, personal communication, November 18, 2014). CCALS was selected to be the F2F2 state lead in the Commonwealth of Virginia and began working to engage stakeholders as part of the F2F2 initiative and the CRCF project.

At the beginning of 2015, the CRCF project team began reaching out to government agencies, educational and research institutions, non-profit organizations, and companies with potential interest in or resources for supporting the commercialization of aviation biofuel in the region. Table 33 describes timeline of stakeholder engagement as well as the types of communication. Email communications and communications solely with CAAFI are not included in the table.

Table 33. Sample of stakeholder engagement for the Virginia F2F2 initiative, with type of communication indicated. This list does not include engagement with CAAFI.

Date	Stakeholder group	Hours	Type of communication
11/18/14	FAA	2	Conference call
01/27/15	FAA; Virginia USDA Rural Development and Natural Resource Conservation Service	4	On-site meeting
03/02/15	Virginia Cooperative Extension	1	Conference call
03/03/15	Agricultural Research Station, Virginia Commonwealth University	1	Conference call
03/04/15	Chesapeake Bay Foundation	1	Conference call
03/27/15	Virginia Foundation for Agriculture, Innovation and Rural Sustainability	1	Conference call
03/31/15	Delaware/Maryland USDA Rural Development and Natural Resource Conservation Service	4	On-site meeting
03/31/15	Airlines for America	2	On-site meeting
04/07/15	Synagro	1	Conference call
04/16/15	Greener Solutions	1	Conference call
04/20/15	Fiberight/Quviant	1	Conference call
05/20/15	Advanced Biofuels USA	1	Conference call
06/01/15	Aviation Sustainability Center, FAA	2	Telephone call
06/02/15	Virginia Foundation for Agriculture, Innovation and Rural Sustainability	1	Conference call
06/10/15	Virginia Poultry Federation	2	On-site meeting
06/24/15	USDA; DOE; FAA; Agri-Tech Producers; Advanced Biofuels USA and Maryland Clean Energy Center Advisory Council	4	On-site meeting
06/26/15	Genera Energy	1	Telephone call
07/01/15	USDA Rural Development	1	Conference call
07/08/15	USDA Rural Development	1	Conference call
08/31/15	Aviation Sustainability Center, FAA	1	Conference call
09/21/15	Virginia House Appropriations Committee	3	On-site meeting
10/02/15	PSU Aviation Sustainability Center	4	On-site meeting

8.3 Initiatives

The set $S_x=\{x_1,\ldots,x_n\}$ represents the set of *n* feedstock initiatives being considered for enhancing the aviation biofuel industry. Table 34 summarizes the initiatives that are being considered in the analysis. The initiatives relate to various feedstocks that have previously been studied in the context of aviation and other biofuels. These feedstocks include established dedicated energy crops, waste products from current agricultural, forestry, and other human activities, and innovative, less established feedstocks. This list is by no means exhaustive and can be extended into the future as more feedstocks are identified to support the development of an aviation biofuel industry. The list is based on current research papers and reports from academic researchers, interest groups, and government agencies, among others, as indicated in the last column of the table. The current list of feedstocks differentiates corn stover from other agricultural residues, which could be further disaggregated in future iterations of analysis.

Table 34. Frame 2 initiatives of feedstocks to support aviation biofuel production. The second column lists a sample of references that have previously considered each feedstock for aviation biofuel.

Feedstock Initiative	Sample of References
x_{01}: Agricultural residue	Macfarlane et al. (2011); MASBI (2013); Andrew et al. (2011)
x_{02}: Algae	Bauen et al. (2009); Nair and Paulose (2014); Hari et al. (2015); Hendricks et al. (2011)
x_{03}: Camelina	Bauen et al. (2009); Hendricks et al. (2011); Hari et al. (2015); Macfarlane et al. (2011); Novelli (2011); MASBI (2013)
x_{04}: Corn stover	Hari et al. (2015); Macfarlane et al. (2011); MASBI (2013); International Air Transport Association (2013)
x_{05}: Forest residue	Macfarlane et al. (2011); MASBI (2013); Guell et al. (2012); Bauen et al. (2009)
x_{06}: Jatropha	Kinder and Rahmes (2009); Bauen et al. (2009); Hendricks, et al. (2011); Hari et al. (2015); Liu et al. (2013); Novelli (2011)
x_{07}: Miscanthus	Bauen et al. (2009); Macfarlane et al. (2011); Novelli (2011); MASBI (2013)
x_{08}: Municipal solid waste	Bauen et al. (2009); Hari et al. (2015); MASBI (2013); Macfarlane et al. (2011); Guell et al. (2012)
x_{09}: Palm oil	Bauen et al. (2009); Hari et al. (2015); Hendricks et al. (2011); Macfarlane et al. (2011); Novelli (2011); MASBI (2013)
x_{10}: Rapeseed	Bauen et al. (2009); Hari et al. (2015); Macfarlane et al. (2011); Novelli (2011); MASBI (2013)
x_{11}: Sorghum	Macfarlane et al. (2011); MASBI (2013); International Air Transport Association (2013)
x_{12}: Soybean	Bauen et al. (2009); Macfarlane et al. (2011); MASBI (2013); Rosillo-Calle et al. (2012)
x_{13}: Switchgrass	Bauen et al. (2009); Köhler et al. (2014); Macfarlane et al. (2011); Novelli (2011)
x_{14}: Tallow	Bauen et al. (2009); Hari et al. (2015); Chiaramonti et al. (2014); Macfarlane et al. (2011); MASBI 2013; Rosillo-Calle et al. (2012); Hileman et al. (2009)
x_{15}: Wood	Bauen et al. (2009); Hari et al. (2015); Andrew et al. (2011); Macfarlane et al. (2011); Novelli (2011); MASBI (2013)
x_{16}: Yellow grease	Macfarlane et al. (2011); International Air Transport Association (2013)

8.4 Criteria

The set $S_c=\{c_1,\ldots,c_m\}$ is defined as the set of *m* criteria chosen to evaluate aviation biofuel feedstocks. These criteria span economic, environmental, and social considerations. The cost of the feedstock is the focus of the economic considerations. While job creation and economic growth could also constitute worthwhile economic criteria for feedstock selection, cost estimates are more readily available to as data to inform the evaluation.

Environmental considerations were aggregated in the Frame 1 analysis presented in Chapter 4. For this frame of analysis, environmental considerations are broken down into impact categories that have been studied through environmental life cycle assessment. The environmental criteria for this frame of analysis include: (i) life cycle greenhouse gas emissions; (ii) life cycle fossil energy demand for feedstock-to-biofuel pathway; (iii) feedstock freshwater demand.

Current and potential biomass availability address the near- and far-term ability to domestically produce aviation biofuel. Current availability of biomass feedstock is particularly important for meeting near term production goals, such as the Farm to Fly 2.0 goal of one billion gallons per year by 2018. Potential biomass availability captures the feasible future availability, as it relates to feedstock productivity and land resources, as well as projected population growth.

8.5 Scenarios

The set $S_s=\{s_1,\ldots,s_q\}$ is defined to represent scenarios of emergent conditions that could impact preferences for biofuel feedstocks. Tables 35-39 describe five scenarios considered in this frame of analysis. These scenarios were constructed specifically to address stakeholder concerns.

For example, scenario s_{04} *Low fossil fuel costs* directly addresses concerns brought up at the Virginia House Appropriations Committee Meeting in September of 2015 (see Table 33 for a complete list of stakeholder engagement). Government officials and other stakeholders worry about the appeal of biofuels when petroleum fuel costs are low, but this concern ignores or devalues the competing objectives that biofuels address. In response to stakeholder concerns about low fossil fuel costs, the Executive Director Emeritus of CAAFI has stressed the importance of environmental benefits aviation biofuels offer (Altman, 2015).

To address stakeholder concerns about climate change and environmental sustainability, the following scenarios were constructed: s_{01} *Emissions reductions;* s_{03} *Water scarcity;* s_{05} *Fossil fuel independence.* Under each of these scenarios, at least one of the environmental criteria increases in importance. Scenario s_{02} *Domestic production* addresses F2F2 goals for aviation biofuel production as well as national security concerns for aviation fuel. The matrix in Equation 9 in the following section describes the final weights for each criterion under the five constructed scenarios.

Table 35. Description of Frame 2 emissions reductions scenario s_{01}.

Scenario

s_{01}: Emissions Reductions

Description

In order to address climate change concerns, there are a number of rules and regulations that attempt to limit emissions by means of some market-based mechanism, whereby emissions, typically over some limit, incurs a cost. The European Union Emissions Trading System (EU ETS) is a cap-and-trade system meant to limit the emissions, and over time reduce, for certain industries. As a result, emissions allowances over the limit are bought at auction. Legislation adopted in 2008 dictated that beginning in 2012 aviation emissions from flights to, from, or within the EU member states, and others, are to be included under the EU ETS. The requirement was suspended for 2012-2016 for flights in and out of non-EU countries to allow negotiations for global market-based measures for aviation emissions. International Civil Aviation Organization (ICAO) has agreed to develop such a mechanism by 2016 and apply it by 2020 (European Union 2013). Thus, in the foreseeable future (at least) flights from the US to Europe are expected to be subject to emissions reductions or face heavy fines. In addition, the US Renewable Fuel Standard (RFS2), while not directly applying to aviation fuel, allows renewable jet fuel to qualify for Renewable Identification Numbers (RINs). For such market-based measures, aviation biofuels benefit from minimizing life-cycle GHG emissions by producing credits that can be sold, effectively reducing the cost of fuel production.

Preference changes

- GHG emissions criterion increases in importance
- Cost criterion decreases somewhat in importance

Table 36. Description of Frame 2 domestic production of aviation biofuel scenario s_{02}.

Scenario

s_{02}: Domestic Production

Description

One of the major reasons cited for the importance of biofuel production in the United States is to reduce dependence on foreign oil. Domestic production of fuels is considered to enhance national security. Seventy-three percent of the armed services fuel purchases are for jet fuel, with the U.S. Air Force consuming about 2.5 billion gallons per year (Macfarlane, Mazza, and Allan 2011). In the event of a national security crisis, domestically available aviation fuel could be critical. Thus the current and potential supply of feedstock would increase in importance. In particular, with the Navy and Defense Logistics Agency ties to Virginia, this scenario could put pressure on the Commonwealth to provide aviation biofuel.

Preference changes

- Current availability criterion increases in importance
- Potential availability criterion increases somewhat in importance
- Cost criterion decreases somewhat in importance

Table 37. Description of Frame 2 water scarcity scenario s_{03}.

Scenario

s_{03}: Water Scarcity

Description

Demand for freshwater resources is a common concern about increased biofuel production (Hendricks, Bushnell, and Shouse 2011). Freshwater shortages are expected to continue into the future, with local shortages expected within Virginia during the next 10 years (United States Government Accountability Office 2014). A study by the U.S. Army Corps finds Virginia military installations vulnerable to water sustainability issues (Jenicek et al. 2009). With expected population growth and the possibility of climate change, water sustainability and conservation become important issues.

Preference changes

- Water use criterion increases in importance

Table 38. Description of Frame 2 low fossil fuel costs scenario s_{04}.

Scenario

s_{04}: Low Fossil Fuel Costs

Description

According to the U.S. Energy Information Administration, there was a drastic decrease (45%) in the price of jet fuel between August 2014 and January 2015. When fossil fuel prices are low, renewable fuels with the lowest cost stand the best chance to penetrate the market. Thus, the relative cost of aviation biofuels will increase in importance. With low fossil fuel costs, the fossil energy demand will decrease somewhat in importance, in a scenario where costs and not the environment are the focus.

Preference changes

- Cost criterion increases in importance
- Energy demand criterion decreases somewhat in importance

Table 39. Description of Frame 2 fossil fuel independence scenario s_{05}.

Scenario

s_{05}: Fossil Fuel Independence

Description

Various environmentalist and other groups have begun to campaign for divestment in fossil fuels. Specifically, the Carbon Tracker Initiative has estimated that the current amount of proven coal and oil and gas reserves, if burned, would release five times the amount of carbon (2,795 gigatons versus 565 gigatons) that would be associated with a 2 degree Celsius change in global temperature (Carrington 2013). This scenario considers a case where support for fossil fuel independence continues to grow. As the contribution of renewables to the electricity grid continues to grow, the energy demand of producing aviation biofuel would decrease in importance, because it would rely on renewable fuel as opposed to fossil. Lifecycle GHG emissions will increase in importance when preferences change such that climate change mitigation is at the forefront of energy decision-making. This environmentalist mindset is considered to place somewhat less importance on costs.

Preference changes

- Energy demand criterion decreases in importance
- GHG emissions criterion increases somewhat in importance
- Cost criterion decreases somewhat in importance

8.6 Calculations

The qualitative ratings of how well each feedstock initiative addresses each criterion are given in Table 34. The ratings, unlike those in Frame 1, are the result of data analysis, including life cycle assessment results, biomass availability surveys, among other data. Rating choices for the initiatives consist of a *strongly addresses*, *addresses, somewhat addresses*, and *does not address* each criterion. For example, initiative *x_{02}: Algae*, is rated as *strongly addressing* criteria *c_{06}: Potential availability*, *addressing* criteria *c_{03}: Water use*, *somewhat addressing* criterion *c_{04}: Cost*, and *not addressing* criteria *c_{01}: GHG emissions, c_{02}: Energy demand* and *c_{05}: Current availability*.

These qualitative ratings are translated to a quantitative assessment matrix. Table 24, Section 4.6, describes how the qualitative rating corresponds to quantitative value score x_{ij} that are used to evaluate how each initiative x_i addresses each criterion c_j. The current frame of analysis, Frame 2, maintains the same value scores used in Frame 1 analysis, though the quantitative scores are changeable as long as the value associated with *strongly addresses* is greater than *addresses,* which is greater than *somewhat addresses,* and *does not address* is assigned a value of 0. These scores are used to populate the 6x16 matrix *A* (Figure 17) as is described in Section 4.2.

Table 40. Fulfillment of Frame 2 criteria for each initiative, with ● indicating the initiative *strongly addresses* the criterion, ⦿ indicating the initiative *addresses* the criterion, ○ indicating the initiative *somewhat addresses* the criterion, and omission indicating that the initiative *does not address* the criteria.

	c_{01}: GHG emissions	c_{02}: Energy demand	c_{03}: Water use	c_{04}: Cost	c_{05}: Current availability	c_{06}: Potential availability
x_{01}: Agricultural residue	●	●	●	●	⦿	⦿
x_{02}: Algae			⦿	○		●
x_{03}: Camelina	○			●		
x_{04}: Corn stover	⦿	⦿	○	⦿	⦿	○
x_{05}: Forest residue	⦿	●	⦿	○	●	●
x_{06}: Jatropha	○					
x_{07}: Miscanthus	●	●	⦿	○		⦿
x_{08}: Municipal solid waste	●	○	●	●	●	●
x_{09}: Palm oil	○	○				
x_{10}: Rapeseed		○				○
x_{11}: Sorghum			○		○	○
x_{12}: Soybean	○	⦿	○	●	⦿	⦿
x_{13}: Switchgrass	⦿	●	○	⦿	⦿	⦿
x_{14}: Tallow		○	●	⦿	○	○
x_{15}: Wood	⦿	⦿	⦿	○	●	●
x_{16}: Yellow grease	●	⦿	●	⦿	○	○

$$
A = \begin{bmatrix}
1.0 & & 0.3 & 0.7 & 0.7 & 0.3 & 1.0 & 1.0 & 0.3 & & & 0.3 & 0.7 & 0.7 & & 0.7 & 1.0 \\
1.0 & & & 0.7 & 1.0 & & 1.0 & 0.3 & 0.3 & 0.3 & & 0.7 & & 1.0 & 0.3 & 0.7 & 0.7 \\
1.0 & 0.7 & & 0.3 & 0.7 & & 0.7 & 1.0 & & & 0.3 & 0.3 & & 0.3 & 1.0 & 0.7 & 1.0 \\
1.0 & 0.3 & 1.0 & 0.7 & 0.3 & & 0.3 & 1.0 & & & & 1.0 & & 0.7 & 0.7 & 0.3 & 0.7 \\
0.7 & & & 0.7 & 1.0 & & & 1.0 & & & 0.3 & 0.7 & & 0.7 & 0.3 & 1.0 & 0.3 \\
0.7 & 1.0 & & 0.3 & 1.0 & & 0.7 & 1.0 & & 0.3 & 0.3 & 0.7 & & 0.7 & 0.3 & 1.0 & 0.3
\end{bmatrix}
$$

Figure 20. Frame 2 assessment matrix *A* where entry j,i represents the degree to which initiative x_i addresses criterion c_j using the translated ratings described in Table 13. Numbers are rounded for visibility in the figure, but not for the calculations, and only non-zero entries are shown.

Each criterion is weighted to determine the relative influence of the criteria. The relative influence of each criterion may change during each of the five scenarios introduced in Tables 35-39. For the baseline scenario s_{00}, each criterion is considered to have equal influence. Thus, for the baseline, each criterion is assigned a weight of approximately $w_i^{0'}$=0.167 $\forall i$. Identifying whether the influence of the criteria *increases, increases somewhat, stays the same, decreases somewhat,* or *decreases*, under other scenarios, the weight of the criteria is adjusted according to Equation 8.

$$w_i^k = \begin{cases} 8{w_i}^{0\prime}, & \text{for } \mathit{increase} \text{ in influence} \\ 6{w_i}^{0\prime}, & \text{for } \mathit{somewhat\ increase} \text{ in influence} \\ {w_i}^{0\prime}, & \text{for } \mathit{no\ change} \text{ in influence} \\ \frac{1}{6}{w_i}^{0\prime}, & \text{for } \mathit{somewhat\ decrease} \text{ in influence} \\ \frac{1}{8}{w_i}^{0\prime}, & \text{for } \mathit{decrease} \text{ in influence} \end{cases} \tag{8}$$

After applying Equation 8, the weights w_i^k under each scenario k are normalized to $w_i^{k\prime}$ such that $\sum_{i=1}^{m} w_i^{k\prime} = 1$. Reassessing the weights under each scenario results in the 6x6 matrix W. The first column of W represents the weights in the baseline scenario. The other columns represent the reconsidered weights under scenarios 1, 2, 3, 4, and 5 respectively.

$$W = \begin{bmatrix} 0.167 & 0.658 & 0.058 & 0.077 & 0.082 & 0.645 \\ 0.167 & 0.082 & 0.058 & 0.077 & 0.014 & 0.014 \\ 0.167 & 0.082 & 0.058 & 0.615 & 0.082 & 0.108 \\ 0.167 & 0.014 & 0.010 & 0.077 & 0.658 & 0.018 \\ 0.167 & 0.082 & 0.466 & 0.077 & 0.082 & 0.108 \\ 0.167 & 0.082 & 0.340 & 0.077 & 0.082 & 0.108 \end{bmatrix} \tag{9}$$

The value score matrix is computed by multiplying the transpose of the weight matrix W^T by the assessment matrix *A,* as demonstrated in Table 41*.*

Table 41. Performance scores of the Frame 2 aviation biofuel feedstock initiatives under each scenario. Scores are out of 100, with 100 representing the best performing initiative.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}
s_{00}	89	33	22	56	78	6	61	89	11	11	17	61	67	44	72	67
s_{01}	95	14	23	61	74	22	85	95	25	5	8	42	67	17	72	86
s_{02}	73	39	3	53	95	2	39	96	4	14	29	63	67	36	94	43
s_{03}	95	51	10	44	72	3	64	95	5	5	26	46	49	74	69	85
s_{04}	95	36	68	61	51	3	42	99	3	3	8	83	64	58	50	67
s_{05}	93	19	23	59	74	22	81	99	22	4	11	42	64	20	73	85
Median	94	35	23	59	74	3	63	96	7	5	12	50	65	38	72	80
Mean	90	32	25	56	74	9	62	95	12	7	16	56	63	42	72	72

8.7 Results

Table 42 illustrates the rank order of initiatives based on the value scores of each initiative for the five scenarios and the baseline scenario. Figure 19 demonstrates the range of rankings that each initiative is assigned under the scenarios. The following two initiatives were ranked highest under at least one scenario: (i) x_{01}*: Agricultural residue* and (ii) $x_{08:}$*: Municipal solid waste*. Although x_{01}*: Agricultural residue* was the highest ranked in the baseline scenario, the value score (see Table 41) was nearly equivalent to that of $x_{08:}$*: Municipal solid waste.* Initiative $x_{08:}$*: Municipal solid waste* also ranked first in four of the five alternative scenarios considered in this frame of analysis.

Further $x_{08:}$*: Municipal solid waste* was also the most robust initiative, only changing in rank by one place, as second under the baseline scenario and scenario s_3*: Water scarcity*. Figure 20 illustrates the robustness of initiatives for the initiatives with a median rank higher than 8, representing the top 50th percentile. Initiatives x_{01}*: Agricultural residue,* x_{10}*: Rapeseed*, and x_{11}*: Sorghum* are also fairly robust feedstock initiatives, each changing rank order by most four positions across all scenarios considered in this analysis, as shown in Figure 19.

Table 43 illustrates the absolute value of the change in prioritization of initiatives caused by the scenarios relative to the baseline scenario. In terms of average change in rank of initiative, scenario s_{04}*: Low fossil fuel costs* is the most disruptive to priorities. And, it also accounted for the largest change in rank, causing initiative x_{03}*: Camelina* to be the least robust initiative increasing from rank 12 under the baseline scenario to rank 4 under scenario s_{04}*: Low fossil fuel costs.* The largest decreases in rankings under the baseline scenario are also due to scenario s_{04}*: Low fossil fuel costs*, experienced by initiatives x_{05}*:*

Forest residue and *x_{15}: Wood.* Scenario *s_{02}: Domestic production*, on the other hand, is the least disruptive scenario in terms of the prioritization of aviation biofuel feedstock initiatives.

Table 42. Performance rank of Frame 2 aviation biofuel feedstock initiatives. The highest scoring initiative for each scenario is highlighted in gray.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}
s_0	1	11	12	9	3	16	7	2	14	14	13	8	5	10	4	5
s_1	1	14	11	8	5	12	4	1	10	16	15	9	7	13	6	3
s_2	4	9	15	7	2	16	9	1	14	13	12	6	5	11	3	8
s_3	1	8	13	11	5	16	7	2	14	14	12	10	9	4	6	3
s_4	2	12	4	7	9	16	11	1	14	14	13	3	6	8	10	5
s_5	2	14	10	8	5	12	4	1	11	16	15	9	7	13	6	3
Median	1.5	11.5	11.5	8	5	16	7	1	14	14	13	8.5	6.5	10.5	6	4

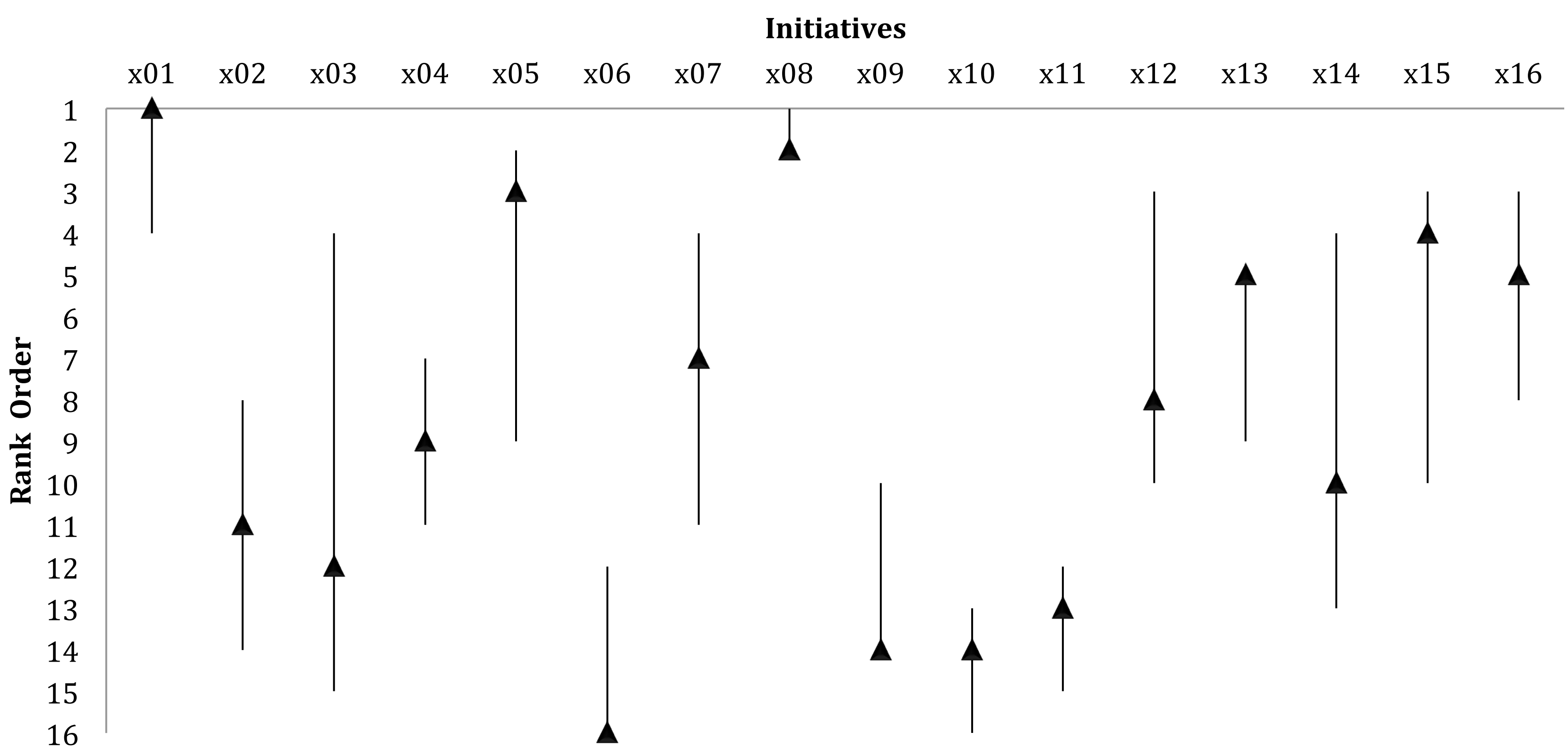

Figure 21. Comparison of rank order of Frame 2 aviation biofuel feedstock initiatives and robustness to changes in rank. The triangle marks the baseline scenario rank, with the high-low lines indicating the rank of rank orders under the set of scenarios.

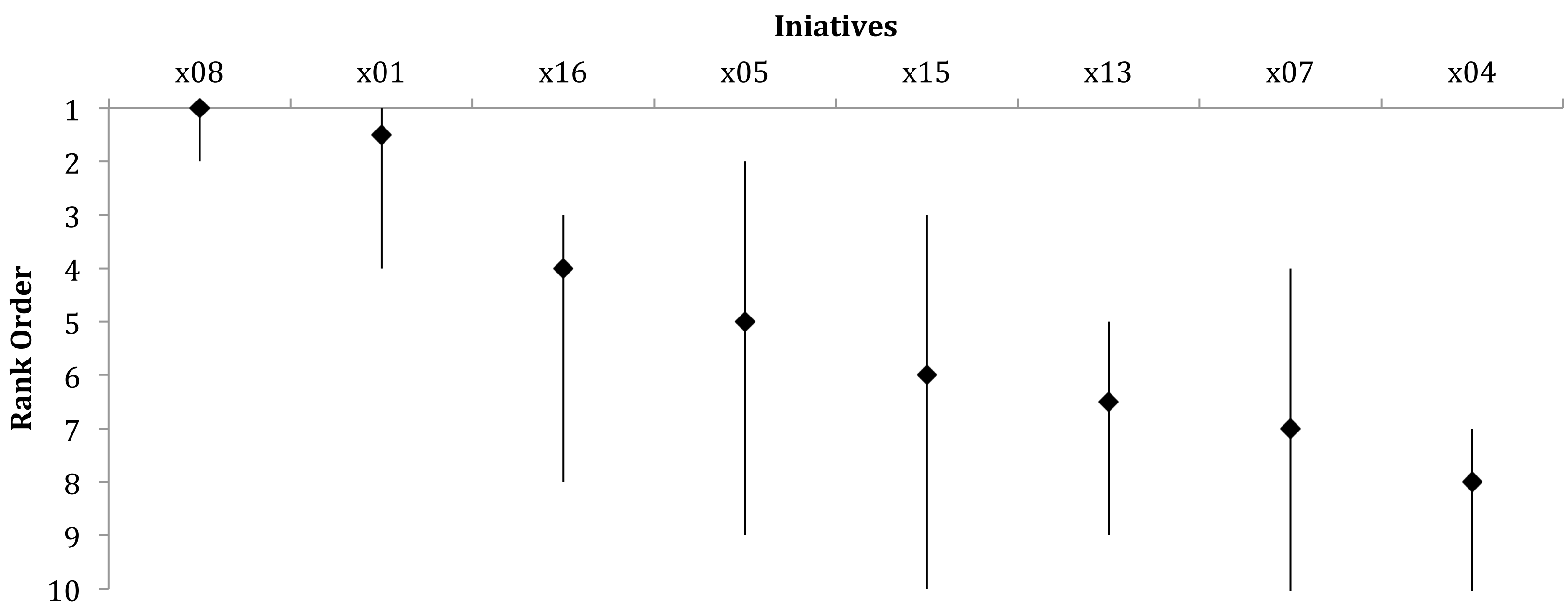

Figure 22. Comparison of Frame 2 aviation biofuel feedstock initiatives with median rank (represented by the diamond) of 8 or better.

Table 43. Changes in rank (in absolute terms) of the Frame 2 aviation biofuel feedstock initiatives in response to the set of scenarios s_{01}-s_{05} as compared to the baseline scenario. The values in the last column are the Spearman rank correlation coefficient, where lower values of $\phi(s_k)$ correspond to more disruptive scenarios.

	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}	x_{14}	x_{15}	x_{16}	$\phi(s_k)$
s_1: Emissions reductions	0	9	1	1	4	16	9	1	16	4	4	1	4	9	4	4	0.872
s_2: Domestic production	9	4	9	4	1	0	4	1	0	1	1	4	0	1	1	9	0.927
s_3: Water scarcity	0	9	1	4	4	0	0	0	0	0	1	4	16	36	4	4	0.877
s_4: Low fossil fuel costs	1	1	64	4	36	0	16	1	0	0	0	25	1	4	36	0	0.722
s_5: Fossil fuel independence	1	9	4	1	4	16	9	1	9	4	4	1	4	9	4	4	0.876

Table 44 provides a summary of the LCA-informed scenario-based preference analysis results. As scenario s_{04}*: Low fossil fuel costs* is the most disruptive scenario across all initiatives relative to the baseline scenario, the results suggest future research should be performed to understand the future prices and regulations related to petroleum and other fossil fuel prices. As technology improves, the cost of feedstocks and processing into biofuels will decrease and could prove competitive even when fossil fuel prices remain low.

The two highest ranking feedstock initiatives (x_{01}*: Agricultural residue* and x_{08}*:: Municipal solid waste*) performed well relative to other feedstocks by their ability to address all criteria to some degree. Specifically, both were considered to *strongly address* the following three criteria: (i) c_{01}*: GHG emissions*; (ii) c_{03}*: Water use*; and (iii) c_{04}*: Cost*. Because these are waste products from other activities, it is assumed that their margin burdens in terms of GHG emissions and water use are minimal. As waste products, their assumed costs are also relatively low. For these feedstocks to remain attractive into the future, it is important to keep in mind potential market competition and other factors that could affect availability and cost. For example, recycling and re-use programs could result in the amount of MSW decreasing in the future. In addition, the production of electricity from these feedstocks could prove more profitable than aviation biofuel conversion, in which case low price feedstock availability might also become a concern. These results, along with insights from LCA, stakeholder analysis, and previous frames of scenario-based preference analysis will be used to inform R&D efforts for a Virginia aviation biofuel industry.

Table 44. Summary of results from Frame 2 analysis of Virginia aviation biofuel feedstock initiatives.

Highest ranked initiatives	$x_{08:}$: Municipal solid waste x_{01}: Agricultural residue
Lowest ranked initiatives	x_{06}: Jatropha x_{10}: Rapeseed
Greatest increase in rank relative to baseline scenario	x_{03}: Camelina
Greatest decrease in rank relative to baseline scenario	x_{05}: Forest residue x_{15}: Wood
Most disruptive scenario across all initiatives relative to baseline scenario	s_{04}: Low fossil fuel costs
Least disruptive scenario across all initiatives relative to baseline scenario	s_{02}: Domestic production

8.8 Chapter Summary

This chapter demonstrated a subsequent problem framing of scenario-based preferences analysis of aviation biofuel production. Using the data described in Chapter 7, LCA and other analytical results were used to inform the analysis. In particular, these results have been useful in planning F2F2 strategies for the Commonwealth of Virginia. The next chapter will describe how these results, combined with those from the first frame of analysis in Chapter 5 and other analytics, support the general design of resilient strategic plans to promote aviation biofuel production.

CHAPTER 9: DEMONSTRATION: R&D RECOMMENDATIONS

9.1 Overview

This chapter will describe how the first (Chapter 5) and second (Chapter 8) frame of scenario-based preferences analysis for aviation biofuels, as well as LCA (Chapter 6) and other data can be used for resilience analytics of research and development strategies. Section 9.2 describes the results of each problem frame, and relates them to each other. Particular attention is paid to disruptions to priorities from changes in preferences as well as which initiatives are robust across scenarios. Section 9.3 describes how supplementary analyses such as life cycle assessment, sensitivity analysis, and stakeholder analysis can inform strategic decision making for aviation biofuel R&D. Section 9.4 summarizes recommendation for future R&D for aviation biofuel industry development in general and lists initiatives helpful for regional industry development.

9.2 Comparison of Problem Frame Results

9.2.1 Scenario disruptiveness

The first problem frame explored in this dissertation (see Chapter 5) investigated strategic supply chain initiatives and investments for aviation biofuels, prioritizing and analyzing the numerous investment decisions needed to develop the fuels. The initiatives spanned the supply chain including feedstock research and development, feedstock collection infrastructure and transportation logistics, biorefining technologies, siting of biorefinery and blending units, and storage at airports. The results of this frame indicate that of the constructed scenarios, s_{04}*: Green preferences* is the most disruptive to priorities. Under this scenario, the importance of c_{02} *production quality* and c_{03} *environmental quality* increased, c_{01} *production quantity* and c_{07} *safety and security* increased somewhat, and c_{05} *life cycle costs* decreased somewhat. The described changes in preferences result in the following initiatives decreasing significantly in priority: x_{20} *Develop market for co-products*; x_{23} *Provide tax credits for biofuels*; x_{34} *Convert petroleum pipeline to biofuel pipeline for biofuel distribution*; x_{37} *Establish coalitions encompassing all parts of the supply chain*. The decrease in priority of these initiatives under scenario s_{04} *Green preferences* can be explained in part by the fact that these initiatives were not considered strongly address production or environmental quality of aviation biofuels.

The subsequent frame of analysis (see Chapter 7) also addressed environmental quality of aviation biofuels, considering the life cycle impacts related to greenhouse gas emissions, fossil fuel use, and fresh water demand. With evidence from Chapter 4 revealing that increasing preferences towards environmental quality can be disruptive to priorities, it will be important for future research to examine how not only feedstocks but other supply chain decisions address a variety of environmental impacts through the use of life cycle assessment. Almost as disruptive as s_{04} *Green preferences* in the preliminary frame of analysis was scenario s_{01}*: Expected regulations*, which was similar in the increasing of importance of environmental quality. In the subsequent frame of analysis, a similar scenario was considered, s_{01}: *Emissions Reductions,* which focused exclusively on the importance of GHG emissions as opposed to environmental quality in general. Scenario s_{01}: *Emissions Reductions* also proved to be disruptive to feedstock prioritization. These results reaffirm that life cycle assessment research on the GHG emissions and other environmental impacts of initiatives should be on the aviation biofuel R&D agenda.

The feedstock problem frame revealed scenario s_{04} *Low fossil fuel costs* to be the most disruptive to priorities. This scenario corresponded to a somewhat decrease in the importance of energy use and an increase in the importance of feedstock cost. Although cost is not the only, or necessarily the most important, criterion for choosing aviation biofuel pathways, reducing costs is generally preferred when all else remains the same.

9.2.2 Initiative robustness

Initiatives that are found to be robust to scenario-based preference changes could represent appealing investments even if they are not highly ranked. The least robust initiatives, however, offer suggestions for where future research could reduce variability and uncertainty in priorities. Table 45 describes the least and most robust initiatives found under both problem frames described in this dissertation.

In the first frame of analysis I^1 initiatives intended to reduce the costs or financial liabilities for biofuel producers were found to be some of the least robust. Policies related to future tax credits for biofuel production are uncertain and vary by state. The market for various biofuel co-products is also difficult to predict but could encourage the development of certain feedstocks and conversion technologies over others.

Under frame I^2, initiative x_{03} *Camelina* was found to be the least robust, and the variability in rank increased when maximum values for water use were considered (see sensitivity results in Appendix B). The priority of x_{03} *Camelina* becomes significantly more robust to scenario-based preference changes when minimum life cycle cost estimates are used for assessing initiatives. Further investigation into life cycle costs for camelina-based biofuel production, as well as for other feedstocks, could better inform strategic investments for aviation biofuels. The initiative x_{14} *Tallow* becomes more robust and more highly ranked when minimum LC-GHG emissions are used to assess feedstocks. For both tallow and municipal solid waste, collection logistics would need optimization to decrease environmental impacts and costs. Future competition for these two "waste" feedstocks also warrants further investigation.

Table 45. Most and least robust initiatives from I^1 and I^2 problem frames

	Frame I^1 (supply chain initiatives)	**Frame I^2 (feedstock initiatives)**
Most robust initiatives	x_{01} Invest in R&D of more productive feedstocks x_{04} Cultivate halophyte feedstocks x_{05} Cultivate algae as feedstock	x_{01} Agricultural residue x_{08} Municipal solid waste x_{10} Rapeseed x_{11} Sorghum
Least robust initiatives	x_{20} Develop market for co-products x_{23} Provide tax credits for biofuels x_{28} Locate bio-refinery in proximity of pipeline access x_{34} Convert petroleum pipeline to biofuel pipeline for biofuel distribution x_{37} Establish coalitions encompassing all parts of the supply chain	x_{03} Camelina x_{14} Tallow

9.3 Insights from Supplementary Analyses

9.3.1 Life cycle assessment

The life cycle assessment described in Chapter 5 highlights the importance of accounting for upstream and downstream burdens in biofuel production. With current, and likely future, regulations relying on LCA, it is important to be able to project the life cycle impacts of alternative biofuel pathways. Particularly for aviation biofuels, future research should be performed to better understand the climate change impacts of atmospheric combustion of biofuels.

Table 46 summarizes the conclusions of life cycle assessment results, and in some cases sensitivity analysis results, from the current literature on aviation biofuel pathways. There are several conclusions made from multiple studies such as: (i) feedstock cultivation is a major source of LC-GHG emissions, especially due to the impact of fertilizer use; (ii) direct and indirect land-use change present significant uncertainty in the LC-GHG emissions of aviation biofuel; (iii) biofuel production can be a significant source of LC-GHG emissions, particularly due to H_2, heat and power, and solvent requirements; (iv) allocation method and system boundaries significantly influence LCA results. Results of sensitivity analysis to changes in parameter values can also reveal areas in which further research should be focused in order to reduce likely life cycle impacts. As such, LCA results and conclusions can also be incorporated into developing a research and development roadmap for innovations in sustainability.

Table 46. Summary of conclusions and sensitivity analysis results of aviation biofuel LCA and LCC studies

Study	Conclusions
Agusdinata et al. (2011)	➢ Feedstock cultivation is largely responsible for LC-GHG emissions ➢ Soil organic carbon sequestration is a considerable source of LC-GHG emissions and uncertainty ➢ Biofuel yield tends to be the most important factor influencing LC-GHG emissions and costs ➢ Efficiency of fertilizer use is also an important factor for LC-GHG emissions ➢ Refinery co-products have a significant influence on lowering productions costs ➢ Oil price and land availability are two critical factors for feedstock viability ➢ Recommended that development of feedstocks for growth on marginal lands
Fortier et al. (2014)	➢ LC-GHG emissions of AHTL are primarily sensitive to heat recycle efficiency ➢ There are a number of sensitive parameters related to process efficiency causing LC-GHG emissions of AHTL to be uncertain in terms of sustainability ➢ Further study of the relationship between microalgal macromolecular and elemental composition and the HTL biocrude yield is recommended ➢ Operating conditions for AHTL should be optimized beyond baseline conditions to ensure a decrease in LC-GHG emissions compared to conventional jet fuel
Han et al. (2013)	➢ For pyrolysis jet fuels, the use of biochar as soil amendment reduces LC-GHG emissions to a greater extent than when used for power generation from combustion ➢ H_2 and natural gas, required in the production stage, constitute a significant portion of the LC-GHG emissions ➢ Fertilizer and fertilizer N_2O are also significant sources of LC-GHG emissions ➢ Co-product handling methods and allocation boundary selection approach impact LCA results ➢ Land-use change emissions for oil-seed crops remain highly uncertain
Lokesh et al. (2015)	➢ Development of hardware specifications that are biofuel compatible would allow a higher percentage (>50%) of low-aromatic biofuels be used in commercial flights ➢ Fertilizer requirements cause feedstock production to be one of the most LC-GHG intensive stages
Seber et al. (2014)	➢ The primary contributor to LC-GHG emissions is from fuel production ➢ Maximizing jet fuel production increases the cost of produced biofuel due to additional hydrogen required

	➢ Price support is needed to make waste oil or tallow-based fuels competitive with petroleum fuels ➢ Climate change mitigation for waste oils and tallow-based fuels is limited by current availability and future scalability
Shonnard et al. (2010)	➢ Feedstock production followed by biofuel production are the two most significant stages with respect to LC-GHG emissions ➢ H_2 generation, heat and power, and solvents for biofuel production dominate the biofuel production emissions ➢ Soil emission of N_2O is important and highly uncertain ➢ Allocation method can have significant effect on LCA results
Staples et al. (2013)	➢ Blue water consumption of irrigated crops is several magnitudes of order higher than for conventional crude ➢ Water consumption is dependent on geographic location, which determines climate, soil conditions and productivity of biomass cultivation, and indirect water use for electricity production
Stratton et al. (2010)	➢ Land use change contributes significantly to the variability in LC-GHG emissions ➢ Current/short-term feedstock production can provide essential learning for the long-term commercial viability of aviation biofuels ➢ The major challenge for aviation biofuels is developing and commercializing large scale production of sustainable biomass feedstocks
Trivedi et al. (2015)	➢ Generally, aviation biofuel produced from the HEFA process and advanced fermentation are more energy intensive than FT biofuels or conventional jet fuel

9.3.2 Sensitivity analysis

Section 5.6.2 describes sensitivity analysis performed for life cycle assessment. The results of which indicate key parameters that have the greatest influence on results. Conclusions from published LCA sensitivity analyses are summarized in Table 46 in the previous section.

Sensitivity analysis can also be performed on scenario-based preferences modeling. Appendix B describes sensitivity analysis performed on Frame I^2 results. The sensitivity analysis explores the impact of using minimum and maximum reported values for the life cycle impacts and costs used to assess feedstock initiative agreement with criteria.

The results from this sensitivity analysis indicate the changes in life cycle initiative-criterion assessments do not have a significant impact on the frame I^2 results described in Chapter 7. In most cases, scenario *s_{04}: Low fossil fuel costs* remained the most disruptive scenario. In one case (e.g., using minimum values for life cycle costs) scenario *s_{01} Emissions reductions* became the most disruptive. Generally, however, changing the values used for the assessment did not significantly increase the disruptiveness of scenarios. That is to say, none of the scenarios considered became significantly more disruptive to priorities do to using minimum or maximum LCA values to inform initiative-criterion assessments. Changing assessments related to fossil energy demand appear to have the greatest impact on the degree of scenario disruptiveness of scenarios. On the other hand, changing assessments related to GHG emissions resulted in the most changes in initiative rankings. Although changing the LCA values used for assessment in the frame I^2 analysis was not significantly disruptive to priorities, combinations of such changes could be. Further sensitivity analysis could be used to reveal which areas should be the targets for future LCA investigations to reduce the variability in LCA impact results.

9.3.3 Stakeholder analysis

Continuous stakeholder engagement can be advantageous in performing resilience and scenario-based preferences analysis. Such engagement provides a means to being attuned to industry developments such as new knowledge and information, changes in preferences, and other emergent conditions. With respect to aviation biofuels, stakeholders can provide insights on what has and has not worked to promote industry development in other regions. Further, ongoing communications with stakeholder groups like CAAFI or subscribing to biofuel newsletters (e.g., Advanced Biofuels USA) enables updates on U.S. policies, regulations, funding opportunities, etc. for aviation biofuels.

Stakeholder groups in the Midwest and Pacific Northwest have published guides on aviation biofuel development for their respective regions. Reviewing such reports can provide guidance on how Virginia and the Southeast could approach commercializing aviation biofuels. Efforts in the Northwest highlight the importance of working with government agencies to provide funding for pilot plants and feasibility studies to explore non-traditional feedstocks such as algae (Macfarlane, Mazza, and Allan 2011). Policies and regulations can have a significant impact on the economic attractiveness of biofuel production and, as such, research on the impact of different incentive mechanisms should be undertaken to strengthen lobbying efforts for aviation biofuels. Stakeholders from the Northwest have indicated the need for long-term contracts (at least 15 years) to attract investment in the production of aviation biofuels (Macfarlane, Mazza, and Allan 2011).

In the Midwest efforts have begun to identify idle cropland suitable for use for feedstock production, but stakeholders cite the need for agricultural innovation to improve feedstock production capacity (e.g., cross-breeding, crop rotations, etc.) (MASBI 2013). Stakeholders in the Midwest also recognize the need for financing mechanisms that reduce risks to early adopters. Another major hurtle recognized by the Midwest aviation biofuel stakeholders is the need for policies and other means to level the playing field between the biofuels and fossil fuels industries. The 2013 report on the Midwest Aviation Sustainable Biofuels Initiative (MASBI 2013) concludes with the recommendation to ensure the sustainability of biofuel supply chains and incorporating sustainability criteria and standards into aviation biofuel initiatives.

Stakeholders engaged in the Commonwealth of Virginia and surrounding states (i.e., Maryland, Delaware, Pennsylvania) have also highlighted the importance of coupling aviation biofuel production with other sustainability practices, specifically water pollution mitigation for the Chesapeake Bay (Richard et al. 2015; James et al. 2015). For example, using cover crops as aviation biofuel feedstocks would exploit funding opportunities for nutrient trading and similar initiatives as a way to support the production of aviation biofuels. In June 2015, the USDA Rural Development announced support for regional projects through Section 6025 of the 2014 Farm Bill (United States Department of Agriculture 2015).

9.4 Recommendations for Strategic Priorities

The results of resilience analytics should be considered for developing recommendations for resilient research and development strategies. Specifically decision makers should focus on disruptive emergent conditions. The results of scenario-based preferences analysis reveal which scenarios are most disruptive to priorities. Supplementary analytics that provide inputs to scenario-based preferences modeling must also be considered. Sensitivity analysis is particularly well suited to identifying which uncertain parameters have the greatest impact on results under certain conditions. Decision makers should keep in mind the sensitivity of parameters when planning for future research and development. The remainder of this section demonstrates how resilience analysis can inform the development of an R&D roadmap specifically for aviation biofuel development.

Strategic planning based on resilience analytics should begin by considering disruptive scenarios. From the first frame of analysis, we find that the greatest disruption to priorities occurs when environmental quality increases in importance. This result highlights the importance of environmental life cycle assessment in informing the strategic selection of aviation biofuel initiatives. Thus, it is suggested that future R&D put LCA at the forefront.

The LCA of algal aviation biofuel demonstrated in Chapter 6 and Connelly et al. (2015b) provides insights on environmental impacts for aviation biofuels, beyond just those that are related to algal biofuels. Specifically, there is evidence, though sparse, that indicates atmospheric combustion of biofuels could have greater climate change implications than conventional jet fuel. Further R&D should be performed to better understand the effects of atmospheric combustion on radiative forcing. With better information some aviation biofuels, with slightly different chemical profiles, could perform much better in terms of environmental impacts, specifically GWP.

Based on sensitivity analysis of life cycle assessment results for aviation and other biofuels, land use change is consistently cited as a source of uncertainty and variability. In particular, the extent and impacts of indirect land use change is not fully understood. Fertilizer use is another uncertain and variable contributor to the environmental impact of biofuel and warrants further investigation into low-impact alternatives and improved efficiencies in application. LCA sensitivity data also show that maximizing yield through technological and efficiency improvements can significantly reduce environmental impacts, both in terms of GHG emissions, energy demand, and water use.

In the second frame of analysis, focusing on aviation biofuel feedstocks, presented in Chapter 8, the scenario formed around low fossil fuel costs is the most disruptive. In this scenario the importance of feedstock cost increases in importance. Thus, future research should investigate which feedstocks have the most potential for cost reductions. While innovative feedstocks such as algae may exhibit higher upfront costs, there could also be the greatest opportunity for cost saving measures later on. Understanding where the most significant opportunities exist should be an R&D priority for strategic planning.

Stakeholder analysis and engagement is also important for strategic decision-making. For example, stakeholders indicated the importance of feedstock selection on the additional supply chain investments that must be made to produce aviation biofuel and lead to the problem framing demonstrated in Chapter 8. The CAAFI R&D Team published a letter about the critical challenges for aviation biofuel production, noting the need for research and development related to feedstocks and the economics of biomass resources with competing markets (Commercial Aviation Alternative Fuels Initative Research and Development Team 2013). A major approach of the CAAFI-led F2F2 state initiatives has focused on the initial step of identifying promising feedstock(s) and as one of the most active stakeholders in the aviation biofuel industry, strategic plans should take into consideration lessons from their efforts.

In addition to feedstock development, there are also R&D efforts required to address the entire supply chain in order to promote the production of aviation biofuels. There are a number of roadmaps for aviation biofuel, with scopes ranging from international to regional (Novelli 2011; Andrew et al. 2011; Macfarlane, Mazza, and Allan 2011; MASBI 2013). These roadmaps tend to make long-term recommendations, and typically targeted at government investment. Some additional high-level recommendations based on the results of the resilience analytics presented in the dissertation are further investigation into the following areas: (i) innovative feedstocks, such as algae; (ii) long-term contracts and other risk-mitigating financial mechanisms; (iii) technological and biological innovation for improving feedstock yields.

For state-based roadmaps for aviation biofuel, however, the magnitude of the efforts must be scaled down and focused on identifying the opportunities and relative strengths and weaknesses of the state in terms of producing aviation biofuels. While some states might have a clear choice of feedstock, others can benefit from the use of resilience analysis and other techniques to identify the best opportunities.

Engaging experts and stakeholders with a variety of experience and interests is a key early step to begin establishing an aviation biofuel supply chains. In the United States, introductions to key stakeholders can come from a variety of sources, but in particular the CAAFI is dedicated to supporting state F2F2 initiatives. In addition, conferences on biofuel and bioenergy provide a venue that promotes networking within the industry. Through stakeholder engagement, feedstock opportunities can be identified, funding mechanisms, suggested, technological challenges revealed, and relationships established.

Table 47 describes initiatives recommended in (Connelly and Lambert 2016b) that can help to promote aviation biofuel supply chain establishment at the state-level. The recommendations are based on prior work on F2F2 initiatives in the U.S. as well as higher-level aviation biofuel roadmaps. The initiatives are organized in two groups, with "Phase 1" representing initiatives that should likely occur in the nearest term with "Phase 2" initiatives following, though all are near-to-mid-term recommendations for action. On one hand, resilience analytics can be used to carryout certain initiatives, while on the other hand resilience analysis can identify further research and development needs.

Table 47. Roadmap for state and regional promotion of aviation biofuel production (Connelly and Lambert 2016b). "Phase 1" refers near-term initiatives whereas "Phase 2" refers to actions necessary in a longer time horizon.

"Phase 1" Initiatives	"Phase 2" Initiatives
Initiate Farm-to-Fly effort and identify lead	Determine most appropriate or suitable conversion technology
Engage stakeholders from government, academia, industry, and non-profit organizations	Perform economic and/or technical feasibility studies to analyze the selected feedstock-to-fuel supply chain
Assess feedstock availability	Perform analysis to identify optimal site(s) for biorefining facilities
Evaluate and identify most promising, resilient, and sustainable feedstock options	Develop supply chain contracts and/or other means for risk sharing
Identify applicable funding opportunities	Investigate optimal product portfolio for biorefinery
Identify R&D needs	Study and develop logistics and management of aviation biofuel at airports
Investigate ongoing biofuel activities	Investigate and promote supportive policies and financial incentives
Form partnerships or collaborations between stakeholders throughout the identified feedstock-to-fuel supply chain	
Publicize progress and experiences	

9.5 Chapter Summary

This chapter provides a summary of the resilience analytics demonstrated for the promotion of an aviation biofuel industry and provides recommendations for research and development strategies. Specifically, the disruptive scenarios and robust initiatives from Frame 1 and Frame 2 scenario-based preferences analyses should be considered in the design of strategic R&D plans. Supplementary analytics also support the design of resilient strategic plans. Specifically, the results of life cycle assessment, sensitivity analysis, and stakeholder analysis are important for decision makers to consider when developing R&D strategies. High-level recommendations to support the resilience of an aviation biofuel industry include:

- Refinement of LCA of aviation biofuel pathways through: (i) exploring the impact of atmospheric combustion emissions on global warming potential; (ii) investigating the extent and implications of direct and indirect land use change; (iii) increasing fertilizer efficiencies and yield related to feedstock production;
- Exploring innovative feedstock options (such as algae) and identifying those with the greatest opportunities for cost reductions/cost parity with conventional fuels;
- Identifying and creating risk-mitigating financial mechanisms, contracts, and partnerships to engage stakeholders across the supply chain.

The following chapter will discuss the usefulness of these methods for application to aviation biofuels as well as generally for strategic planning.

CHAPTER 10: DISCUSSION

10.1 Overview

This chapter provides a discussion on the methods of resilience analysis demonstrated in Chapters 5-9. Section 10.2 discusses validation of the methodology based on the approach described by Pedersen et al. (2000). Section 10.3 acknowledges limitations to the described methodology for resilience analytics, including variability in life cycle assessment inputs, cognitive biases of stakeholders, and extensive stakeholder engagement.

10.2 Validation of Methods

Validation is an important step for establishing credibility of models and designs. Validation of systems models can be difficult, especial for those used in multi-criteria analysis because there are many parameters and inputs which are based on preferences of stakeholders (Qureshi, Harrison, and Wegener 1999), meaning repeatability is diminished. Conventional model validation examines how well model outputs match reality (Gass 1983).

Schilling, Oeser, and Schaub (2007) acknowledge the difficulty of proven the long-term value created by decision analyses. The quality of the decision process can be evaluated by three metrics: process effectiveness, output effectiveness, and outcome effectiveness (Schilling, Oeser, and Schaub 2007). The degree of mission achievement or desired outcome achievement are commonly suggested as metrics for validating decision analytics (Goodman and Pennings 1977; Rainey and Steinbauer 1999; Ellis and Mitchell 2002). For the applications of resilience analysis presented in this dissertation, it is impossible to yet judge the long-term outcome. It has been suggested that applying the methods to a similar, historical case study could provide confidence that application of the model would improve outcome. It is however difficult to objectively judge how well the model would perform with respect to an historical case study. Because scenario-based preferences hinges on constructing future scenarios, validating the model would entail considering scenarios that are known to have either occurred or not occurred. This confounds the validation because it is not clear whether disruptive emergent conditions would have been predicted without this "clairvoyance."

For example, consider the ethanol industry in the United States. One controversy surrounding the commercial-scale production of corn ethanol is the indication that more energy is consumed in producing ethanol that is contained in the ethanol (i.e., EROI<1). Integrating life cycle assessment into multi-criteria analysis of fuels clearly reveals this tradeoff, and thus it could be argued that the methods presented in this dissertation would have revealed this information prior strategic decisions being made. Further, life cycle assessment and systems analysis can address another controversial issue of land use change for corn production. Today, the food versus fuel debate is a common consideration for biofuel development, but when ethanol production was first being incentivized by U.S. policies in 1978, this concern was not as widespread. Further, although life cycle assessment of transportation fuels began in the 1980s, the environmental impacts of associated with land use change remain one of the largest uncertainties in LCA (Unnasch et al. 2011). Applying resilience analysis at the early stages of the ethanol industry development likely would have revealed issues, particularly related to life cycle impacts, but it is unclear how decision-makers would have used this information and thus how the outcome would have been improved. Stakeholder comments described in Appendix C specifically mention that past and ongoing problems with an establishing an ethanol facility in Hopewell, VA would have benefited from resilience analysis of strategic plans.

Because it is often difficult to establish outcome effectiveness, it is commonly suggested that validation focus on evaluating the decision process (Von Winterfeldt and Edwards 1986; Dean and Sharfman 1993; McCartt and Rohrbaugh 1989). (Matheson and Matheson (2001) measure decision quality of an organization on the following elements: identification of value-centered objectives creating alternatives, continual learning, addressing uncertainty, considering multiple perspectives, and incorporating systems thinking. The resilience analytics presented in this dissertation was designed to incorporate all of these aspects.

Output effectiveness is often gauged through the collection of stakeholder satisfaction surveys (Schilling, Oeser, and Schaub 2007; Finlay and Forghani 1998; Timmermans and Vlek 1996). Appendix C contains stakeholder response to questions about the value of resilience analytics for application to aviation biofuel industry promotion. The output of resilience analysis is dependent on the stakeholder input. As such, the effectiveness of the output also depends on stakeholder engagement and is one of the arguments for iterative problem framing that includes refinement of scenarios to identify disruptive emergent conditions.

Pedersen et al. (2000) describe an approach to validating design methods and research. They term the approach the “Validation Square” which consists of three steps for structural validation and three for performance validation. Structural validation consists of:

i) Accepting the construct’s validity based on literature supporting the model constructs;
ii) Accepting method (internal) consistency based on information flow;
iii) Accepting the example problems through comparison with accepted applications, example problem representativeness of real need, and appropriateness of data to support a conclusion.

Performance validation consists of:

i) Accepting usefulness of method for example problems;
ii) Accepting that usefulness is linked to the application of the method;
iii) Accepting usefulness of method extends beyond example problems.

10.2.1 Structural validity of resilience analysis for strategic priorities

Pedersen et al. (2000) recommend using the literature as a means to build confidence in the individual constructs of a methodological approach to be validated. The principle individual constructs constituting the presented method of resilience analysis for strategic planning are: (i) multi-criteria decision analysis; (ii) scenario-based preference analysis; and (iii) life cycle assessment. The use of multi-criteria decision analysis for assessing the tradeoffs for strategic planning has been well documented in the literature

(Montibeller and Franco 2010) and has previously been applied to sustainability and alternative energy decision making (Troldborg, Heslop, and Hough 2014; Perimenis et al. 2011; Scott, Ho, and Dey 2012; De Meyer et al. 2014; Pohekar and Ramachandran 2004; Espen 2007; Tsoutsos et al. 2009). Scenario analysis is recommended in the literature as a means of exploring the potential impact of uncertain emergent conditions (Heijden 1996; Schoemaker 1991; Goodwin and Wright 2001; Swart, Raskin, and Robinson 2004). The integration of scenario analysis and multi-criteria decision analysis has also been previously explored to account for the impact of preference changes on priorities (Montibeller, Gummer, and Tumidei 2006; Karvetski, Lambert, and Linkov 2011; Karvetski, Lambert, and Linkov 2009b; Martinez, Lambert, and Karvetski 2011; Karvetski and Lambert 2012; Comes, Hiete, and Schultmann 2013). The concept of life cycle assessment was introduced in the 1970s as a way to compare products' environmental impacts, based on systems analysis of the product from "cradle to grave" (Guinee et al. 2011). Since then, LCA has been used to study a number of alternative energy pathways (Iribarren, Peters, and Dufour 2012; Dufour and Iribarren 2012; Cherubini and Strømman 2011; Tonini and Astrup 2012; Fortier et al. 2014; Agusdinata et al. 2011; Stratton, Wong, and Hileman 2010; Elgowainy et al. 2012; Ou et al. 2013). LCA results have also recently been used in the literature to inform MCDA (Myllyviita et al. 2012; Troldborg, Heslop, and Hough 2014; Oltean-Dumbrava, Watts, and Miah 2015; Linkov and Seager 2011). The above references are provided to support the construct's validity.

A flow-chart representation is the recommended method for validating the way the model constructs are put together (Pedersen et al. 2000). The diagram of the proposed approach for resilience analysis in Figure 5 generally describes the information flow.

Figure 21 describes the information flow for the application to aviation biofuels presented in this dissertation. Stakeholder engagement and analysis is used to identify criteria, initiatives, scenarios, and criteria weights for the scenario-based preferences modeling as well as for criterion-initiative assessments in the first frame of analysis. In the second frame of analysis, life cycle assessment, life cycle cost analysis, and resource assessment were used to make the criterion-initiative assessments. The results (e.g., most disruptive scenarios, most robust initiatives, initiative rankings, etc.) of each frame of analysis are reported back to stakeholders, who over time will revise their inputs and can relate this knowledge to the creation of a resilient research and development strategies. Sensitivity analysis of scenario-based preferences analysis, as well as of the supplementary analytics, is able to information for resilience of strategic plans.

To build confidence in the appropriateness of the application, first the example problem must be shown to be similar to problems in which the constructs are generally accepted (Pedersen et al. 2000). References have been given earlier in this section that use MCDA for analyzing the tradeoffs of alternative energy pathways, using scenarios to explore changes in preferences, and using life cycle assessment to study the environmental impacts of energy systems and using that information to inform MCDA. Further, these methods have all been used for strategic planning. The method is intended to inform decision makers and other stakeholders about the opportunities and risks surrounding the establishment of an aviation biofuel industry, to allow them to make resilient strategic plans. The example problem in Frame 1 explores real supply chain initiatives that support aviation biofuel commercialization. The initiatives in Frame 2 represent feedstocks that have been proven as technically feasible for aviation biofuel conversion. The tradeoffs between the initiatives should be explored to support strategic planning. Scenarios constructed from stakeholder analysis are used for risk and resilience analysis at the time of problem frame analysis. The problem frames are intended to analyze investment decisions necessary across and at the beginning of the aviation biofuel supply chain. Based on the problem statements discussed by other stakeholder groups in the US and around the world (Novelli 2011; MASBI 2013; Macfarlane, Mazza, and Allan 2011; Boeing/Embraer/ FAPESP and UNICAMP 2013; Andrew et al. 2011), taking both a supply chain as well as feedstock view of the problem seems appropriate.

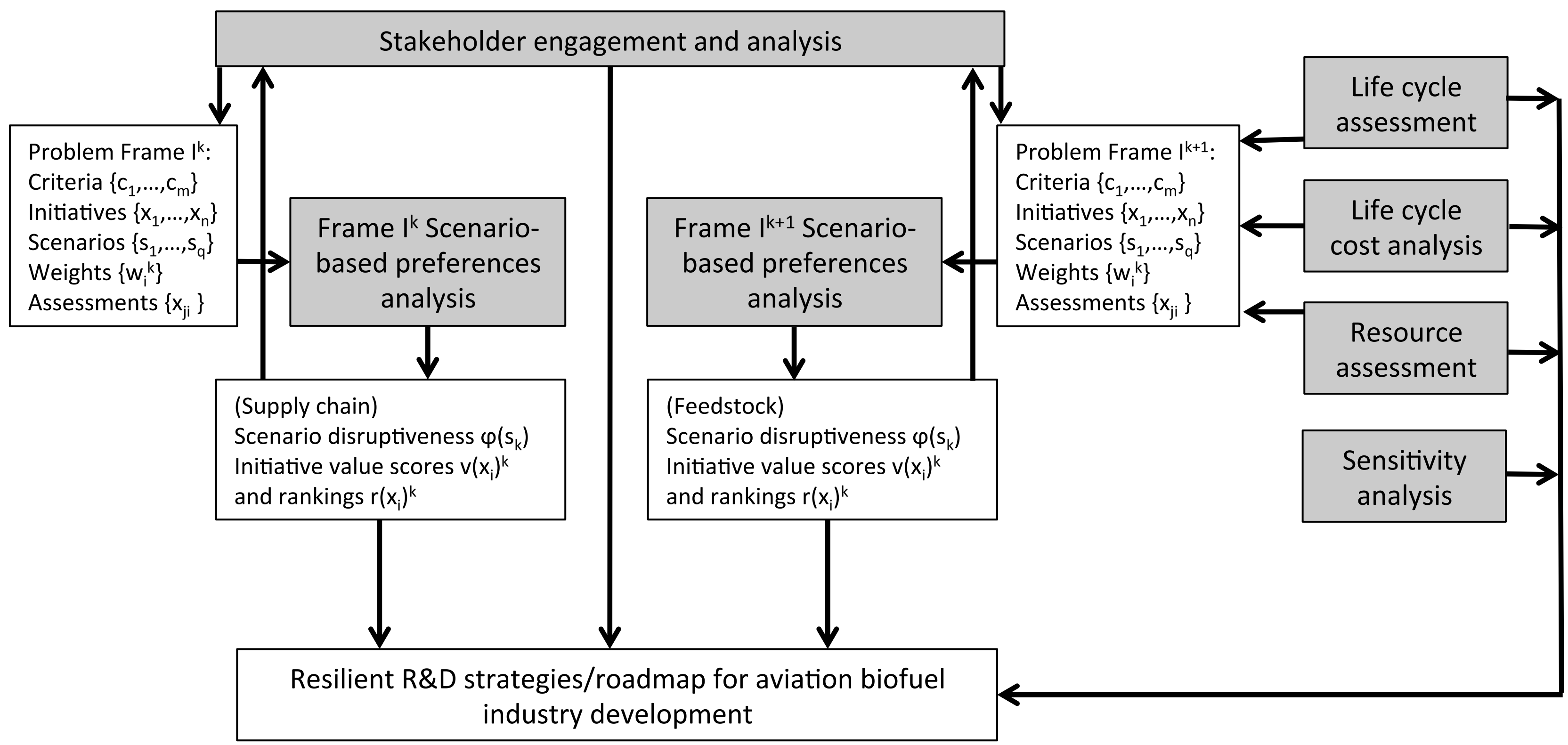

Figure 23. Information flows diagram for resilience analytics for R&D strategies to promote aviation biofuel industry development.

10.2.2 Performance validity of resilience analysis for strategic priorities

The first of three elements for performance validation suggested by Pedersen et al. (2000) is accepting the usefulness of the method with respect to an example problem. Chapters 5-9 of this dissertation describe the application of the method to a case study of aviation biofuels. For this case study, the purpose of applying resilience analytics was to support the development of R&D strategies with consideration for disruptive events or conditions. Chapter 9 summarizes the recommendations resulting from the resilience analytics. A key stakeholder group involved in the case study is the Commonwealth Center for Advanced Logistics Services (CCALS). When questioned about the usefulness of these methods they responded with the following comments: *"We are already seeing the direct interest in and the value of these methods with respect to a research grant from the Center for Innovative Technology (CIT) to evaluate the tradeoffs for aviation drop-in biofuels feedstock pathways in Virginia. Sufficient production and transportation capabilities are critical but there is also significant political emphasis on Chesapeake Bay environmental quality and a Delmarva Peninsula region life cycle assessment (LCA). These methods support, sustain and guide our R&D tradeoff strategy for this award."*

The above comments also support the second element of performance validation: accepting that the usefulness is linked to applying the method. Stakeholders appreciate that multi-criteria analysis with life cycle assessment is able to analyze environmental and non-environmental tradeoffs between aviation biofuel pathways. In addition, Tom Polmateer, a Logistics Research Systems Analyst for CCALS, acknowledged that previous efforts to establish a biofuels industry in Virginia have failed because of a lack of consideration and planning for "*disruptive emergent market conditions and the significance of the feedstock* *supply-chain."* Scenario analysis, including scenario-based preferences modeling, is able to explore the disruptiveness of uncertain emergent conditions to priorities for establishing supply chain and feedstock logistics. Appendix C describes stakeholder input that confirms the usefulness of MCDA, scenario analysis, life cycle assessment and other supplementary analytics, and the iterative problem framing for this application. The methods of resilience analytics demonstrated in this dissertation directly address potential disruptions to strategic plans.

As suggested by Pedersen et al. (2000), attempt to prove the acceptance of the usefulness of the method beyond the example problem will proceed with the following points:

- In Section 10.2.1 it is demonstrated through literature review that the individual model constructs (e.g., MCDA, scenario analysis, scenario-based preferences modeling, LCA, etc.) are generally accepted for application to strategic planning.
- Figure 21 depicts how the constructs are put together in the method in an internally consistent way. Specifically, stakeholder analysis is used frame the problem and provide the inputs to scenario-based preferences modeling. Life cycle assessment and other analytics are used to identify other inputs, particularly the criterion-initiative assessments. Results from the scenario-based preferences analysis and the other analytics are used to inform strategic planning with particular attention paid to disruptions to and sensitivities of the model.

- Section 10.2.1 and Chapter 2 also describe how the constructs application for the case study of aviation biofuels is consistent with the accepted application of these methods. Specifically, MDCA and LCA have been applied extensively in the literature for studying alternative energy systems. Scenario-based preferences have been studied with respect to energy research and development (Hamilton et al. 2013). Stakeholder analysis and engagement, especially with scenario planning, are commonly used in multi-stakeholder strategic planning settings.
- Previously in this section the usefulness of these methods has been demonstrated with respect to the aviation biofuel case study, which is within the appropriate application areas of the method constructs.
- This section and the responses in Appendix C demonstrate that the usefulness achieved is due to the application of the method of resilience analytics.

Based on the above points, Pedersen et al. (2000) suggest that generality of the method can be claimed. It is important, however, to note that validation relies on "faith" in the method. Future application of the methods will provide further evidence to support the validation of the method.

10.3 Issues and Limitations

10.3.1 Variability in life cycle assessment and other data inputs

Integrating life cycle assessment results and other data into scenario-based preferences analysis is done principally as a way to assess how well initiatives address environmental and other related criteria. This works well when there is one data source evaluating each of the initiatives or alternatives using the same assumptions and system boundaries. This often, however, will not be the case. When different sources are used to evaluate the various initiatives with respect to the same criterion, differences in allocation technique, system boundaries, and other assumptions (see Table 2 in Section 4.3). These issues have commonly been cited for life cycle assessment (Reap et al. 2008b; Reap et al. 2008a), but can apply to many other supplementary analytics whose results are used to inform MCDA and scenario-based preferences analysis.

Without standardization of life cycle assessment and other analytics, practitioners must devote time to sifting through the literature and deciding which studies are similar enough to use in the analysis. In particular, land use change presents a significant source of uncertainty in life cycle assessment and can cause variability in results as different studies use different land use change assumptions. In this dissertation, data was compiled on GHG emissions, fossil energy demand, water use, cost, and resource availability when system boundaries and definitions were similar among data sources. The average of reported values for each was used to inform the baseline model presented in Chapter 8. Sensitivity analysis was performed to assess how priorities changed if minimum and maximum values were used instead (see Appendix B), as discussed in Section 9.3.2. Regardless, the relative life cycle impacts of the initiatives could be different from those considered in this dissertation and would impact the results of this analysis and ultimately could impact research and development strategies. Plevin et al. (2014) argue, however, that with acknowledgement of the limitations of life cycle assessment, results can still be useful in guiding decision- and policy-makers.

10.3.2 Biases in scenario-based preferences analysis

A common bias in decision analysis is anchoring. This can occur such that stakeholders under adjust preferences from the baseline preference scheme (Von Winterfeldt and Edwards 1986). When preferences are not sufficiently shifted from the baseline, the disruptiveness of scenarios will likely be under estimated. The Pearson correlation coefficient used in this dissertation to measure disruptiveness is calculated based on changes in rank resulting from a change to baseline preferences. Because relative disruptiveness of scenarios is considered over the value of the Pearson correlation coefficient, the R&D strategies devised to address the most disruptive scenarios should remain the same. Further, multi-criteria decisions have been found to be robust in several practical situations even when small errors from anchoring have been introduced (Stewart 1996).

Anchoring can also be introduced such that the initiatives, criteria, and scenarios identified in Frame I^t influence the introduction of new and innovative inputs for Frame I^{t+1}. Keeney (1992) suggests focusing on one criterion at a time in order to identify initiatives that are attractive with respect to that single attribute. Along these lines, anchoring could be avoided by explicitly suggesting that stakeholders consider a single scenario at a time and identify current or new initiatives that would be desirable under those specific conditions. Hamilton (2014) also suggests reconsidering previously discarded initiatives in subsequent frames to help prevent anchoring from amplifying through iterations.

10.3.3 Reliance on stakeholder engagement

The method of resilience analytics presented in this dissertation relies on elicitation from and engagement of stakeholders to inform the identification of criteria, preference weights, initiatives, and scenarios. If some subset of stakeholders has political motives, their gaming behavior can jeopardize the integrity of the analysis and resulting R&D strategies. Beierle (2002) investigates the value of stakeholder-intensive decision-making and finds that in 70% of cases there are joint-stakeholder benefits, whereby all stakeholders involved are better off. Only in 6% of cases are there stakeholders who become worse off from the solutions resulting from collaborative decision-making.

Further, the implementation of these methods requires multiple periods of stakeholder engagement. Ideally, a wide variety of stakeholder groups should be involved in the process, for which coordination is difficult. If stakeholders do not see value in the process, they are likely to have less desire to be engaged and provide quality information. Involvement with the F2F2 initiative and the CAAFI enables greater access to willing stakeholders. Activities in the Commonwealth of Virginia have revealed feedstock producers to be one of the most hesitant stakeholder groups.

10.4 Chapter Summary

This chapter discussed the validity and limitations of the described approach for resilience analytics. One issue is in the quality of life cycle assessment and other supplementary data used to inform criterion-initiative assessments. Limitations of the model usefulness also come from the biases of the stakeholders who provide valuable inputs into the model and the extent to which these stakeholders are willing to dedicate sufficient time for iterating over multiple problem framings. The following chapter will discuss how the methodological approach to resilience analysis and application to aviation biofuels have contributed to systems engineering and strategic planning practices.

CHAPTER 11: SUMMARY AND CONCLUSIONS

11.1 Overview

This chapter will summarize and conclude the work presented in this dissertation. Section 11.2 reviews the purpose and scope. Section 11.3 describes the theoretical, methodological, and application contributions of this work. Section 11.4 describes potential areas for future work. Section 11.5 concludes the dissertation.

11.2 Review of Purpose and Scope

The purpose of this dissertation is to describe methods for resilience analytics to support research and development roadmapping, especially for sustainability innovations. The concept of resilience is generalized so that it can be applied to strategic decision-making across a variety of fields and applications. Resilience analytics in this dissertation is meant to support decision-making through the identification of disruptive emergent conditions. The methods are demonstrated for aviation biofuels, specifically intended to support commercialization in the Commonwealth of Virginia. Two problem frames are considered – one investigating supply chain initiatives and one identifying feedstock opportunities in Virginia. The results from two frames of scenario-based preferences analysis, in addition to life cycle assessment, sensitivity analysis, and stakeholder analysis, are used to guide strategic planning for aviation biofuel development generally and state-level initiatives.

Chapter 1 provided the background and problem motivation for developing resilient strategies to support aviation biofuel commercialization. Chapter 2 describes the evolution of multi-criteria decision analysis and scenario analysis into iterative scenario-based preference analysis. Chapter 3 describes historical definitions of resilience and identifies gaps in the literature. Chapter 4 details the proposed approach for resilience analytics which incorporates MCDA, scenario analysis, and LCA through multiple problem framings. Chapter 5 demonstrates scenario-based preferences analysis for aviation biofuel supply chain initiatives. Chapter 6 demonstrates life cycle assessment for algal aviation biofuel. Chapter 7 describes how LCA results from the literature can be incorporated into scenario-based preferences analysis. Chapter 8 demonstrates a subsequent frame of scenario-based preferences analysis, which incorporates data from LCA, LCC, and other analyses to study aviation biofuel feedstocks in the Commonwealth of Virginia. Chapter 9 describes how the demonstrated resilience analytics can be used to identify strategies for future R&D.

Figure 22 depicts how the chapters of this dissertation relate to the research contributions in the form of journal articles and conference proceedings, which are described in the following section.

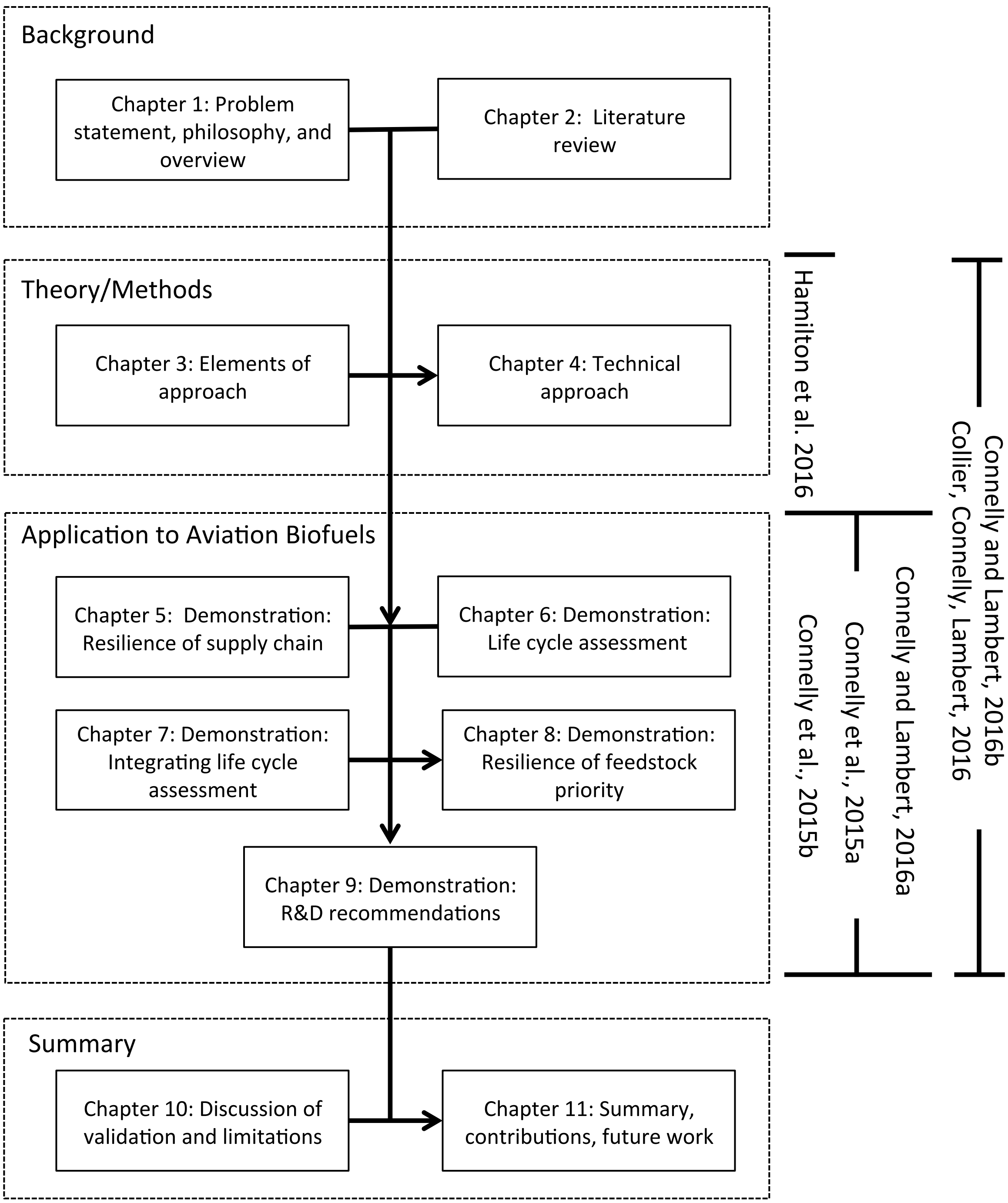

Figure 24.Diagram of dissertation with related journal and conference papers.

11.3 Research Contributions

There are a number of theoretical, methodological, and application contributions of this research as follows:

The **first** contribution of this dissertation is the conceptualization of resilience analytics as the identifications of emergent conditions disruptive to priorities (Connelly and Lambert 2016a; Connelly and Lambert 2016b). Recent literature has cited the need for a concept of resilience that can be used across a wide range of application areas. The approach to resilience analytics presented in this dissertation generally serves to enhance strategic decision making, regardless of the domain.

The **second** contribution is the integration of life cycle assessment and scenario-based preferences analysis. While LCA is a widely accepted technique for assessing environmental impacts, the MCDA community had yet to offer a formal method of integrating LCA data with MCDA. The results of LCA and other supplementary analytics can provide insights for designing resilient R&D strategies to support environmental sustainability.

The **third** contribution is the demonstration of the use of resilience analysis for aviation biofuel supply chains (Connelly, Colosi, et al. 2015a). The results reveal risks in the form of disruptive emergent conditions and support the resilience of strategic plans

The **fourth** contribution is the life cycle assessment of an innovative algal biofuel pathway. The work reveals the importance of considering upstream and downstream factors in a system life cycle (Connelly, Colosi, et al. 2015b). The work also demonstrated how sensitivity analysis of LCA results can provide information pertinent to R&D strategies.

The **fifth** contribution is the demonstration of resilience analysis integrated with LCA to prioritize potential feedstocks for aviation biofuel production in the Commonwealth of Virginia. The results also reveal which feedstocks are robust and which scenarios are most disruptive to priorities.

The **sixth** contribution is the development of strategic state-level initiatives to support the development of an aviation biofuel supply chain (Connelly and Lambert 2016b). These recommendations support the F2F2 initiative and were developed in coordination with the CAAFI.

Figure 3 in Chapter 1 describes the timeline of contributions and effort associated with this dissertation. This work has culminated with the publication of five journal articles (Connelly, Colosi, et al. 2015a; Connelly, Colosi, et al. 2015b; You et al. 2014; Connelly, Lambert, and Thekdi 2015; Connelly, Thorisson, et al. 2016), an additional manuscript submitted with revisions (Hamilton et al. 2016), the submission of three conference papers (Connelly and Lambert 2016b; Connelly and Lambert 2016a; Collier, Connelly, and Lambert 2016), and submission of a book chapter from a NATO workshop (Connelly, Akanji, et al. 2016). Figure 23 describes the evolution of life cycle assessment and MCDA for strategic decision making, and shows how the work described above has expanded the literature integrating lifecycle analysis with scenario-based preferences. Figure 25 similarly describes how the above work has contributed to the literature on resilience analysis.

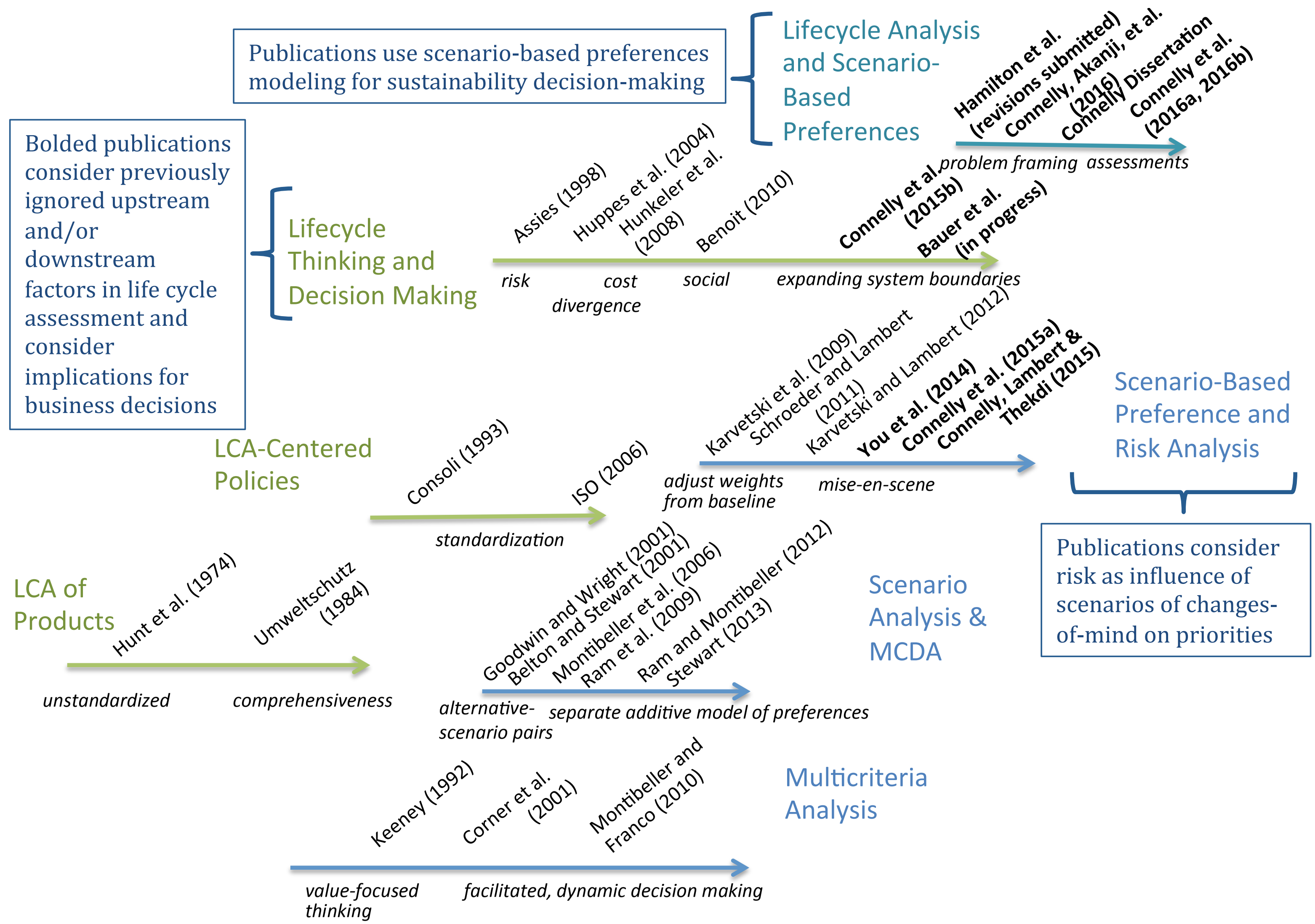

Figure 25. Description of publications related to lifecycle analysis and scenario-based preferences for strategic priorities.

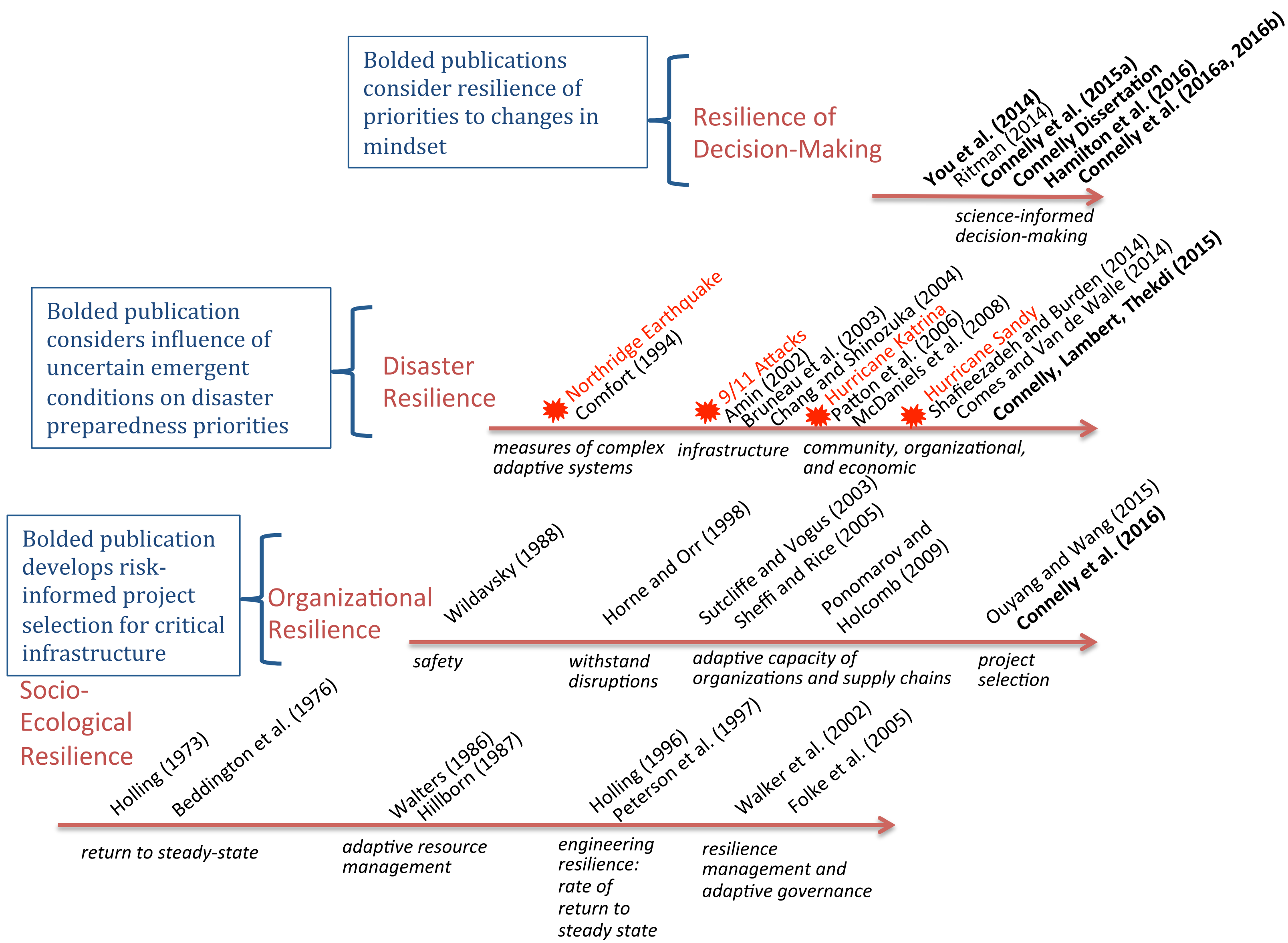

Figure 26. Description of publications related to resilience analysis.

Aspects of this work have been presented in poster format at a clean energy conference, an engineering conference, and a VA General Assembly meeting. A total of ten oral presentations have been given on these methods and applications at domestic and international risk analysis conferences, operations research conferences, systems engineering conferences, and a workshop on natural disasters. There are future plans to present the method of resilience analytics for strategic planning at the Transportation Research Board annual meeting and the 2016 IEEE Systems Engineering Conference. The direction of this work has and will continue to be shaped by input from stakeholders and experts from diverse fields that have been engaged through the dissemination of this research.

11.4 Future Work

This section describes opportunities for future work. Prominently, future research can explore the application of these methods to sustainability research and development. To support strategic decision making for sustainability technologies, further work is required to integrate LCA data with the scenario-based preferences model. In addition, the life cycle data being used for resilience analytics and strategic planning should reflect the specific geographic area under consideration.

A prototype of a scenario-based preferences model with a life cycle assessment module is shown Appendix D. In this dissertation, life cycle assessment data was collected and averages were considered for the qualitative initiative-criterion assessments. As described in Chapter 8, a practitioner makes the final assessment. Future work, such as that exemplified in the prototype, could automate the assessment, in theory making it more objective. There are difficulties associated with such an automation, however. If impacts are normalized and used to assign a quantitative assessment score, this could in essence put overconfidence in the point-value accuracy, ignoring variability in results. Also, a practitioner's judgment is likely better at selecting which number of initiatives should receive a certain qualitative assessment rather than partitioning the initiatives without regard for how close life cycle impacts are to each other. For example, as in the demonstration in Chapter 8, there are sixteen feedstock initiatives and four qualitative assessment categories, so a model might choose to automatically select four initiatives for each category. If the difference in life cycle impact between those with the fourth and fifth greatest impact is small, then it is more representative to assign both the same assessment. It will be difficult for an integrated model to employ the same logic as a practitioner. The prototype allows the practitioner, or stakeholder, to choose to override the LCA-based assessment. Future work on the interactive, Excel-based tool could also include integration with @Risk or Crystal Ball for sensitivity analysis.

In order to reduce time resources spent on compiling life cycle assessemnt data as inputs to the resilience analysis methods, future work could also focus on pulling information from online databases. This will require significant progress in open source LCA data however. One option specifically for biofuels, or transportation options, would be the integration of the Argonne GREET model with scenario-based preferences modeling. Again, automated uploading of data would be difficult as each GREET update is accompanied with differences in the data structure. As the prototype currently exists, the analyst must manually enter the life cycle assessment data for each initiative. Using a single source, like GREET, for all the data would at least address problems with differences in systems boundaries, functional units, etc.

Over time, life cycle data will improve in accuracy. A common assumption of many current life cycle models is national (or regional) average impacts, such as for electricity production. Location-specific life cycle assessment data will be helpful into the future to guide regional decision-making, where certain opportunities might become more attractive because local impacts are significantly lower than average. Integrating life cycle assessment with geographic information systems (GIS) is an area that will likely be able to provide higher quality data for local or state strategic, sustainability decision making.

11.5 Conclusions

This dissertation contributes a conceptualization of resilience as the identification of disruptive emergent conditions in order to guide strategic decision-making. This concept of risk is widely applicable to diverse fields and domains. This dissertation proposes a methodology for resilience analytics that incorporates: (i) multiple, sometimes competing, stakeholder values via multi-criteria decision analysis; (ii) deep uncertainties via scenario analysis; (iii) potential shifts in stakeholder values via scenario-based preferences analysis; (iv) objective life cycle data inputs on alternative systems via supplementary analytics including environmental life cycle assessment and life cycle cost analysis; (v) an acknowledgment of the transient nature of knowledge and problem statement via iterative problem framing to support the adaptability of strategic plans. These methods serve to inform strategic planning and research and development roadmapping, specifically by recognizing sources of disruption to priorities. A case study of aviation biofuels is presented as a demonstration of the methods, which are particularly useful for R&D roadmapping for innovative technologies in sustainability.

In summary, this dissertation represents the theory, methodology, and application of research that has been disseminated in the literature (Connelly, Lambert, and Thekdi 2015; Connelly, Colosi, et al. 2015a; You et al. 2014; Connelly, Colosi, et al. 2015b; Connelly, Thorisson, et al. 2016; Hamilton et al. 2016) and in conference presentations (Connelly et al. 2013; Connelly et al. 2014a; Connelly et al. 2014b; Connelly 2014; Connelly et al. 2014c; Connelly et al. 2014d; Connelly and Lambert 2015; Connelly, Colosi, et al. 2015c; Connelly, Lambert, et al. 2015a; Connelly, Lambert, et al. 2015b).

REFERENCES

Agusdinata, Datu B, Fu Zhao, Klein Ileleji, and Dan DeLaurentis. 2011. “Life Cycle Assessment of Potential Biojet Fuel Production in the United States.” *Environmental Science & Technology* 45 (21): 9133–43. doi:10.1021/es202148g.

Air Transport Action Group. 2011a. *Powering the Future of Flight: The Six Easy Steps to Growing a Viable Aviation Biofuels Industry*. Geneva, Switzerland.

———. 2011b. “Beginner’s Guide to Aviation Biofuels.”

Alba, Laura Garcia, Cristian Torri, Chiara Samorì, Jaapjan van der Spek, Daniele Fabbri, Sascha R. a. Kersten, and Derk W. F. (Wim) Brilman. 2012. “Hydrothermal Treatment (HTT) of Microalgae: Evaluation of the Process As Conversion Method in an Algae Biorefinery Concept.” *Energy & Fuels* 26 (1): 642–57. doi:10.1021/ef201415s.

Altman, Rich. “PSU/CCALS/UVA Meeting.” Charlottesville, VA.

———. 2014. “Personal Communication.”

Amin, Massoud. 2002. “Toward Secure and Resilient Interdependent Infrastructures.” *Journal of Infrastructure Systems* 8 (September): 67–75. doi:10.1061/(ASCE)1076-

0342(2002)8:3(67).

Andrew, Matthew, Peter Birt, Heather Brodie, Peter Broschofsky, Grant Crenfeldt, Andrew Drysdale, Andrew Dudgeon, et al. 2011. *Flight Path to Sustainable Aviation*. Newcastle, NSW.

Atkinson, A.D., B.A. Rich, K.D. Tungate, K.S. Creamer, J.T. Green, and A.D. Moore. 2011. *North Carolina Canola Production*. *Castanea*. Vol. 76. doi:10.2179/11-019.1.

Aven, Terje. 2011. "On Some Recent Definitions and Analysis Frameworks for Risk, Vulnerability, and Resilience." *Risk Analysis* 31 (4): 515–22. doi:10.1111/j.1539-6924.2010.01528.x.

Baral, Anil, and Chris Malins. 2014. *Assessing the Climate Mitigation Potential of Biofuels Derived From Residues and Wastes in the European Context*.

Bauen, A, J Howes, L Bertuccioli, and C Chudziak. 2009. *Review of the Potential for Biofuels in Aviation*.

Beddington, J R, C a Free, and J H Lawton. 1976. "Concepts of Stability and Resilience in Predator-Prey Models." *Journal of Animal Ecology* 45 (3): 791–816. doi:10.2307/3581.

Beierle, Thomas C. 2002. "The Quality of Stakeholder-Based Decisions." *Risk Analysis* 22 (4).

Ben-Haim, Yakov. 2001. *Information-Gap Decision Theory: Decisions under Severe Uncertainty*. Academic Press.

Benoît, Catherine. 2010. *Guidelines for Social Life Cycle Assessment of Products*. UNEP/Earthprint.

Benoit, Valérie, and Patrick Rousseaux. 2003. "Aid for Aggregating the Impacts in Life Cycle

Assessment." *The International Journal of Life Cycle Assessment* 8 (2): 74–82. doi:10.1007/BF02978430.

Bhamra, Ran, Samir Dani, and Kevin Burnard. 2011. "Resilience: The Concept, a Literature Review and Future Directions." *International Journal of Production Research* 49 (18): 5375–93. doi:10.1080/00207543.2011.563826.

Boeing/Embraer/ FAPESP and UNICAMP. 2013. *Flightpath to Aviation BioFuels in Brazil: Action Plan*. http://www.fapesp.br/publicacoes/flightpath-to-aviation-biofuels-in-brazil-action-plan.pdf.

Brittaine, Richard, and N. Lutaladio. 2010. "Jatropha Cultivation." In *Jatropha: A Smallholder Bioenergy Crop*, 8:27–54. Food and Agriculture Organization of the United Nations (FAO).

Brown, Duncan, Andrew Rowe, and Peter Wild. 2014. "Techno-Economic Comparisons of Hydrogen and Synthetic Fuel Production Using Forest Residue Feedstock." *International Journal of Hydrogen Energy* 39 (24): 12551–62. doi:10.1016/j.ijhydene.2014.06.100.

Bruneau, Michel, Stephanie E Chang, Ronald T Eguchi, George C Lee, Thomas D O'Rourke, Andrei M Reinhorn, Masanobu Shinozuka, Kathleen Tierney, William A Wallace, and Detlof von Winterfeldt. 2003. "A Framework to Quantitatively Assess and Enhance the Seismic Resilience of Communities." *Earthquake Spectra* 19 (4): 733–52.

Bryant, Benjamin P, and Robert J Lempert. 2010. "Thinking inside the Box: A Participatory, Computer-Assisted Approach to Scenario Discovery." *Technological Forecasting and Social Change* 77 (1). Elsevier: 34–49.

Buede, Dennis M. 2011. *The Engineering Design of Systems: Models and Methods*. Vol. 55. John Wiley & Sons.

Carrington, Damian. 2013. "Carbon Bubble Will Plunge the World into Another Financial Crisis- Report." *The Guardian*, April 18.

Carter, NA. 2012. "Environmental and Economic Assessment of Microalgae-Derived Jet Fuel," no. June. http://dspace.mit.edu/handle/1721.1/76099.

Carter, Nicholas, Russell Stratton, Michael Bredehoeft, and James Hileman. 2011. "Energy and Environmental Viability of Select Alternative Jet Fuel Pathways." In *47th AIAA/ASME/SAU/ASEE Joint Propulsion Conference & Exhibit*. San Diego, California. http://stuff.mit.edu:8001/afs/athena.mit.edu/dept/aeroastro/partner/reports/proj28/altfuelpathways.pdf.

Castellacci, Fulvio. 2015. "Institutional Voids or Organizational Resilience? Business Groups, Innovation, and Market Development in Latin America." *World Development* 70 (June): 43–58. doi:10.1016/j.worlddev.2014.12.014.

Chang, Stephanie E, and Masanobu Shinozuka. 2004. "Measuring Improvements in the Disaster Resilience of Communities." *Earthquake Spectra* 20 (3): 739–55.

Cherubini, Francesco, and Anders Hammer Strømman. 2011. "Life Cycle Assessment of Bioenergy Systems: State of the Art and Future Challenges." *Bioresource Technology* 102 (2). Elsevier Ltd: 437–51. doi:10.1016/j.biortech.2010.08.010.

Chiaramonti, David, Matteo Prussi, Marco Buffi, and Daniela Tacconi. 2014. "Sustainable Bio Kerosene: Process Routes and Industrial Demonstration Activities in Aviation Biofuels."

Applied Energy 136 (December): 767–74. doi:10.1016/j.apenergy.2014.08.065.

Chiu, Yi Wen, and May Wu. 2012. "Assessing County-Level Water Footprints of Different Cellulosic-Biofuel Feedstock Pathways." *Environmental Science and Technology* 46 (16): 9155–62. doi:10.1021/es3002162.

Chiu, Yi-Wen, and May Wu. 2013. "The Water Footprint of Biofuel Produced from Forest Wood Residue via a Mixed Alcohol Gasification Process." *Environmental Research Letters* 8.

Chok, Nian Shong. 2010. "Pearson's Versus Spearman's and Kendall's Correlation Coefficients for Continuous Data." University of Pittsburgh. http://d-scholarship.pitt.edu/8056/\nhttp://d-scholarship.pitt.edu/8056/1/Chokns_etd2010.pdf.

Clarens, Andres F, Lisa M Colosi, James H Lambert, and Elizabeth B Connelly. 2013. *Systems Analysis of Future Biojet Fuel Industry in Virginia*. http://www.washingtonairports.com/boardexec/exec/2013/november/uvaexecsummary.pdf.

Clarens, Andres F, Eleazer P Resurreccion, Mark A White, and Lisa M Colosi. 2010. "Environmental Life Cycle Comparison of Algae to Other Bioenergy Feedstocks." *Environmental Science & Technology* 44 (5): 1813–19. doi:10.1021/es902838n.

Collier, Zachary A., Elizabeth B. Connelly, and James H. Lambert. 2016. "Creating a Sustainable Supply Chain from the Bottom-Up: Life Cycle and Resilience Assessments for Aviation Biofuels." In *International Symposium on Sustainable Systems and Technology*. Phoenix, AZ.

Comes, T.A., and B. Van De Walle. 2014. "Measuring Disaster Resilience: The Impact of Hurricane Sandy on Critical Infrastructure Systems." *ISCRAM 2014 Conference Proceedings - 11th International Conference on Information Systems for Crisis Response and Management*, no. November 2013: 195–204. http://www.scopus.com/inward/record.url?eid=2-s2.0-84905859939&partnerID=40&md5=f1b8e89c92933af5a66610e729642533.

Comes, Tina, and Michael Hiete. 2009. "Integrating Scenario-Based Reasoning into Multi-Criteria Decision Analysis." In *Proceedings of the 6th International ISCRAM Conference*.

Comes, Tina, Michael Hiete, and Frank Schultmann. 2013. "An Approach to Multi-Criteria Decision Problems Under Severe Uncertainty." *Journal of Multicriteria Decision Analysis* 48 (November 2012): 29–48. doi:10.1002/mcda.

Comfort, Louise K. 1994. "Risk and Resilience: Inter-Organizational Learning Following the Northridge Earthquake of 17 January 1994." *Journal of Contingencies and Crisis Management*. doi:10.1111/j.1468-5973.1994.tb00038.x.

Commercial Aviation Alternative Fuels Initative Research and Development Team. 2013. "Research and Development Investment Position Paper." http://www.caafi.org/information/pdf/CAAFI_Research_and_Development_Team_Position_Paper_updated_FINAL_2013_06_05.pdf.

Connelly, Elizabeth B. 2013. "Case Studies Identifying Scenarios of Influence to Priority-Setting: Rio de Janeiro Disaster Management and Commonwealth of Virginia Biojet Fuels." University of Virginia.

———. 2014. "Managing Risks from Emergent and Future Scenarios in Supply Chain

Logistics." In *MORS and SARMA Co-Sponsored Workshop: How Risk Assessments Inform National Security Decision Making*. Alexandria, VA.

Connelly, Elizabeth B., J. Akanji, Michael E. Goodsite, Mark D. Kodack, Kasper D. Mikkelsen, Kate M. Stoughton, and James H. Lambert. 2016. "Recent Advances in the Net-Zero Paradigm and Resilience of Net-Zero Strategic Plans for Water Systems." In *Triple Net Zero Energy, Water and Waste Models Applications*. Springer.

Connelly, Elizabeth B., Lisa M. Colosi, Andres F. Clarens, and James H. Lambert. 2014a. "Investigating Investment Priorities for Biofuel Production and the Influence of Regulations, Policies, and Emergent Conditions." In *SEDC Systems Engineering Conference*. Chantilly, VA.

———. 2014b. "Identifying Disruptive Scenarios for Supply Chains with Application to Emergency Management and Aviation Biofuels." In *23rd Annual Meeting of the Society for Risk Analysis Europe*. Istanbul, Turkey.

———. 2014c. "R&D Roadmap for Aviation Biofuels: New Use for Decision Analysis Methods." In *2014 Annual Meeting of the Institute for Operations Research Adn Management Sciences*. San Francisco, CA.

———. 2014d. "Risk Analysis Methods as Roadmap for Engineering Innovations." In *2014 Annual Meeting of the Society for Risk Analysis*. Denver, CO.

———. 2015a. "Risk Analysis of Biofuels Industry for Aviation with Scenario-Based Expert Elicitation." *Systems Engineering*. doi:10.1002/sys.21298.

———. 2015b. "Life Cycle Assessment of Biofuels from Algae Hydrothermal Liquefaction:

The Upstream and Downstream Factors Affecting Regulatory Compliance." *Energy & Fuels*, 150215103039003. doi:10.1021/ef502100f.

———. 2015c. "Combining Risk Analysis Methods with Life Cycle Assessment to Prioritize R&D Initiatives for Innovative Energy Technologies." In *2015 Annual Meeting of the Society for Risk Analysis Europe*. Maastricht, The Netherlands.

Connelly, Elizabeth B., and James H. Lambert. 2015. "Multicriteria Decision Analytics to Inform Emergency Management and Planning Subject to Uncertain Disaster Scenarios." In *Mathematics of Planet Earth 2013+*. Atlanta, GA.

———. 2016a. "Resilience Analytics in Systems Engineering with Application to Aviation Biofuels." In *10th Annual IEEE International Systems Conference*. Orlando, FL.

———. 2016b. "Resilience Analytics of a Future Supply Chain for Aviation Biofuels." In *Transportation Research Board 95th Annual Meeting*. Washington, D.C.

Connelly, Elizabeth B., James H. Lambert, Lisa M. Colosi, and Andres F. Clarens. 2015a. "Sustainability Roadmap with Changing Societal Preference as Extension to Lifecycle Analysis." In *23rd International Conference on Multiple Criteria Decision Making MCDM 2015*. Hamburg, Germany.

———. 2015b. "Risk-Based Technology Roadmap for Alternative Fuels." In *2015 Annual Meeting of the Society for Risk Analysis*. Arlington, VA.

Connelly, Elizabeth B., James H. Lambert, J.O. Gomes, and Shital A. Thekdi. 2013. "Robust Supply Chain Investments for Disaster Preparedness and Community Resilience: An Application to Rio de Janeiro, Brazil." In *2013 Annual Meeting of the Society for Risk*

Analysis. Baltimore, MD.

Connelly, Elizabeth B., James H. Lambert, and Shital A. Thekdi. 2015. "Robust Investments in Humanitarian Logistics and Supply Chains for Disaster Resilience and Sustainable Communities." *Natural Hazards Review*, 1–11. doi:10.1061/(ASCE)NH.1527-6996.0000187.

Connelly, Elizabeth B., Heimir Thorisson, L. James Valverde Jr., and James H. Lambert. 2016. "Asset Risk Management and Resilience for Flood Control, Hydropower, and Waterways." *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering*.

Contreras, Francisco, Keisuke Hanaki, Toshiya Aramaki, and Stephen Connors. 2008. "Application of Analytical Hierarchy Process to Analyze Stakeholders Preferences for Municipal Solid Waste Management Plans, Boston, USA." *Resources, Conservation and Recycling* 52 (7): 979–91. doi:10.1016/j.resconrec.2008.03.003.

Cooper, Joyce Smith, and James A Fava. 2006. "Life-Cycle Assessment Practitioner Survey: Summary of Results" 10 (4): 12–14.

Cox, Louis Anthony Tony. 2012. "Confronting Deep Uncertainties in Risk Analysis." *Risk Analysis* 32 (10): 1607–29. doi:10.1111/j.1539-6924.2012.01792.x.

Dahmann, J, G Rebovich, and G Turner. 2014. "An Actionable Framework for System of Systems and Mission Area Security Engineering." In *Systems Conference (SysCon), 2014 8th Annual IEEE*.

Davis, Ryan E, Daniel B Fishman, Edward D Frank, Michael C Johnson, Susanne B Jones, Christopher M Kinchin, Richard L Skaggs, Erik R Venteris, and Mark S Wigmosta. 2014. “Integrated Evaluation of Cost, Emissions, and Resource Potential for Algal Biofuels at the National Scale.” *Environmental Science & Technology* 48 (10): 6035–42. doi:10.1021/es4055719.

Daystar, Jesse, Ronalds Gonzalez, Carter Reeb, Richard Venditti, Trevor Treasure, Robert Abt, and Steve Kelley. 2014. “Economics, Environmental Impacts, and Supply Chain Analysis of Cellulosic Biomass for Biofuels in the Southern US: Pine, Eucalyptus, Unmanaged Hardwoods, Forest Residues, Switchgrass, and Sweet Sorghum.” *BioResources* 9 (1): 393–444.

De Meyer, Annelies, Dirk Cattrysse, Jussi Rasinmäki, and Jos Van Orshoven. 2014. “Methods to Optimise the Design and Management of Biomass-for-Bioenergy Supply Chains: A Review.” *Renewable and Sustainable Energy Reviews* 31 (March): 657–70. doi:10.1016/j.rser.2013.12.036.

de Miguel Mercader, F., M.J. Groeneveld, S.R.a. Kersten, N.W.J. Way, C.J. Schaverien, and J.a. Hogendoorn. 2010. “Production of Advanced Biofuels: Co-Processing of Upgraded Pyrolysis Oil in Standard Refinery Units.” *Applied Catalysis B: Environmental* 96 (1-2): 57–66. doi:10.1016/j.apcatb.2010.01.033.

Dean, James W, and Mark P Sharfman. 1993. “PROCEDURAL RATIONALITY IN THE STRATEGIC DECISION-MAKING PROCESS*.” *Journal of Management Studies* 30 (4). Wiley Online Library: 587–610.

Delrue, F., Y. Li-Beisson, P-a. Setier, C. Sahut, A. Roubaud, A-K. Froment, and G. Peltier. 2013. “Comparison of Various Microalgae Liquid Biofuel Production Pathways Based on

Energetic, Economic and Environmental Criteria." *Bioresource Technology*, March. doi:10.1016/j.biortech.2013.02.091.

dos Santos, Fernando Teigão, and Maria Rosário Partidário. 2011. "SPARK: Strategic Planning Approach for Resilience Keeping." *European Planning Studies* 19 (8): 1517–36. doi:10.1080/09654313.2011.533515.

Dovers, Stephen R., and John W. Handmer. 1992. "Uncertainty, Sustainability and Change." *Global Environmental Change* 2 (4): 262–76. doi:10.1016/0959-3780(92)90044-8.

Dufour, Javier, and Diego Iribarren. 2012. "Life Cycle Assessment of Biodiesel Production from Free Fatty Acid-Rich Wastes." *Renewable Energy* 38 (1): 155–62. doi:10.1016/j.renene.2011.07.016.

Duijnhoven, Hanneke, and Martijn Neef. 2014. "Framing Resilience. From a Model-Based Approach to a Management Process." *Procedia Economics and Finance* 18: 425–30. doi:10.1016/S2212-5671(14)00959-9.

Dunn, Jennifer B., Michael Johnson, Zhichao Wang, Michael Wang, Kara Cafferty, Jake Jacobson, Erin Searcy, et al. 2013. *Supply Chain Sustainability Analysis of Three Biofuel Pathways*. Argonne, Illinois.

Durbach, Ian N, and Theodor J Stewart. 2012. "A Comparison of Simplified Value Function Approaches for Treating Uncertainty in Multi-Criteria Decision Analysis." *Omega* 40 (4). Elsevier: 456–64.

Dyer, James S., Peter C. Fishburn, Ralph E. Steuer, Jyrki Wallenius, and Stanley Zionts. 1992. "Multiple Criteria Decision Making, Multiattribute Utility Theory: The Next Ten Years."

Management Science 38 (5): 645–54. doi:10.1287/mnsc.38.5.645.

Elgowainy, A, J Han, M Wang, N Carter, R Stratton, J Hileman, A Malwitz, and S Balasubramanian. 2012. *Life-Cycle Analysis of Alternative Aviation Fuels in GREET*. Argonne, Illinois.

Elliott, Douglas C., Todd R. Hart, Andrew J. Schmidt, Gary G. Neuenschwander, Leslie J. Rotness, Mariefel V. Olarte, Alan H. Zacher, Karl O. Albrecht, Richard T. Hallen, and Johnathan E. Holladay. 2013. "Process Development for Hydrothermal Liquefaction of Algae Feedstocks in a Continuous-Flow Reactor." *Algal Research* 2 (4). Elsevier B.V.: 445–54. doi:10.1016/j.algal.2013.08.005.

Ellis, Kevin, and Stephen Mitchell. 2002. "Outcome-Focused Management in the United Kingdom." *OECD Journal on Budgeting* 1 (4): 7–34. doi:10.1787/budget-v1-art20-en.

Espen, Loken. 2007. "Use of Multicriteria Decision Analysis Methods for Energy Planning Problems." *Renewable and Sustainable Energy Reviews* 11 (7): 1584–95. doi:10.1016/j.rser.2005.11.005.

European Parliament and Council Directive 94/62/EC of 20 December 1994 on Packaging and Packaging Waste. 1994. http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31994L0062&from=EN.

European Union. 2013. *The EU Emissions Trading System (EU ETS)*. doi:10.2834/55480.

Fath, Brian D, Carly A Dean, and Harald Katzmair. 2015. "Navigating the Adaptive Cycle: An Approach to Managing the Resilience of Social Systems." *Ecology and Society* 20 (2). doi:10.5751/ES-07467-200224.

Federal Aviation Administration. 2011. *Destination 2025*. *E. Nz Magazine: The Magazine of Technical ….* http://search.informit.com.au/documentSummary;dn=884532445936506;res=IELENG.

Fiksel, Joseph. 2003. "Designing Resilient, Sustainable Systems." *Environmental Science and Technology* 37 (23): 5330–39. doi:10.1021/es0344819.

———. 2006. "Sustainability and Resilience: Toward a Systems Approach." *Sustainability: Science Practice and Policy* 2 (2): 14–21.

Fiksel, Joseph, Keely L Croxton, and Timothy J Pettit. 2015. "From Risk to Resilience: Learning to Deal With Disruption." *MIT Sloan Management Review* 56 (2): 79–86.

Finlay, Paul N., and Morteza Forghani. 1998. "A Classification of Success Factors for Decision Support Systems." *The Journal of Strategic Information Systems* 7 (1): 53–70. doi:10.1016/S0963-8687(98)00013-4.

Folke, Carl. 2006. "Resilience: The Emergence of a Perspective for Social–ecological Systems Analyses." *Global Environmental Change* 16 (3): 253–67. doi:10.1016/j.gloenvcha.2006.04.002.

Folke, Carl, Stephen R. Carpenter, Brian Walker, Marten Scheffer, Terry Chapin, and Johan Rockström. 2010. "Resilience Thinking: Integrating Resilience, Adaptability and Transformability." *Ecology and Society* 15 (4): 62–68. doi:10.1038/nnano.2011.191.

Fortier, Marie-Odile P., Griffin W. Roberts, Susan M. Stagg-Williams, and Belinda S.M. Sturm. 2014. "Life Cycle Assessment of Bio-Jet Fuel from Hydrothermal Liquefaction of

Microalgae." *Applied Energy* 122 (July 2011). Elsevier Ltd: 73–82. doi:10.1016/j.apenergy.2014.01.077.

Frank, ED, J Han, I Palou-Rivera, A. Elgowainy, and M. Q. Wang. 2011. *Life-Cycle Analysis of Algal Lipid Fuels with the GREET Model*. *Center for Transportation …*. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Life-Cycle+Analysis+of+Algal+Lipid+Fuels+with+the+GREET+Model#0.

Frank, Edward D., Amgad Elgowainy, Jeongwoo Han, and Zhichao Wang. 2013. "Life Cycle Comparison of Hydrothermal Liquefaction and Lipid Extraction Pathways to Renewable Diesel from Algae." *Mitigation and Adaptation Strategies for Global Change* 18 (1): 137–58. doi:10.1007/s11027-012-9395-1.

Gass, S. I. 1983. "Decision-Aiding Models: Validation, Assessment, and Related Issues for Policy Analysis." *Operations Research* 31 (4): 603–31. doi:10.1287/opre.31.4.603.

Gerbens-Leens, P. W., L. Xu, G. J. de Vries, and A. Y. Hoekstra. 2014. "The Blue Water Footprint and Land Use of Biofuels from Algae." *Water Resources Research* 5: 8549–63. doi:10.1002/2014WR015710.Received.

Gerber, S., K. Meurlin, L. Schefer, and B. Miller. 2013. "Fiberight Meeting Notes."

Gibson, John E, William T Scherer, and William F Gibson. 2007. *How to Do Systems Analysis*. Vol. 47. John Wiley & Sons.

Giezen, Mendel, Willem Salet, and Luca Bertolini. 2015. "Adding Value to the Decision-Making Process of Mega Projects: Fostering Strategic Ambiguity, Redundancy, and Resilience." *Transport Policy* 44 (November): 169–78.

doi:10.1016/j.tranpol.2015.08.006.

Glisic, Sandra B., and Aleksandar M. Orlović. 2014. “Review of Biodiesel Synthesis from Waste Oil under Elevated Pressure and Temperature: Phase Equilibrium, Reaction Kinetics, Process Design and Techno-Economic Study.” *Renewable and Sustainable Energy Reviews* 31 (March): 708–25. doi:10.1016/j.rser.2013.12.003.

Gloria, Thomas P., Barbara C. Lippiatt, and Jennifer Cooper. 2007. “Life Cycle Impact Assessment Weights to Support Environmentally Preferable Purchasing in the United States.” *Environmental Science and Technology* 41 (21): 7551–57. doi:10.1021/es070750+.

Goodman, Paul S, and Johannes M Pennings. 1977. *New Perspectives on Organizational Effectiveness*. Jossey-Bass San Francisco.

Goodwin, Paul, and G Wright. 2001. “Enhancing Strategy Evaluation in Scenario Planning: A Role for Decision Analysis.” *Journal of Management Studies*, no. January. http://onlinelibrary.wiley.com/doi/10.1111/1467-6486.00225/abstract.

Groves, David G, and Robert J Lempert. 2007. “A New Analytic Method for Finding Policy-Relevant Scenarios.” *Global Environmental Change* 17 (1). Elsevier: 73–85.

Guell, Berta Matas, Mette Bugge, Rajesh S. Kempegowda, Anthe George, and Scott M Paap. 2012. *Report Benchmark of Conversion and Production Technologies for Synthetic Biofuels for Aviation*. Norway.

Guilford, Megan C., Charles a S Hall, Pete O'Connor, and Cutler J. Cleveland. 2011. “A New Long Term Assessment of Energy Return on Investment (EROI) for U.S. Oil and

Gas Discovery and Production.” *Sustainability* 3 (10): 1866–87. doi:10.3390/su3101866.

Guinée, Jeroen B, ed. 2002a. *Handbook on Life Cycle Assessment*. Volume 7. Dorderecht: Kluwer Academic Publishers.

———. 2002b. “Handbook on Life Cycle Assessment Operational Guide to the ISO Standards.” *The International Journal of Life Cycle Assessment* 7 (5). Springer: 311–13.

Guinee, Jeroen B, Reinout Heijungs, Gjalt Huppes, Alessandra Zamagni, Paolo Masoni, Roberto Buonamici, Tomas Ekval, and Tomas Rydber. 2011. “Life Cycle Assessment: Past, Present, and Future.” *Environmental Science & Technology* 45 (1): 90–96.

Gutierrez, A, ME Domine, and Y Solantausta. 2007. “CO-PROCESSING OF UPGRADED BIO-LIQUIDS IN STANDARD REFINERY UNITS - FUNDAMENTALS.” In *Proceeding of the 15th …*. Berlin. http://www.biocoup.com/uploads/media/Berlin_2007_Solantausta_Biocoup_final2.pdf.

Haddad, MAM. 2011. “Towards Greener Aviation: A Comparative Study on the Substitution of Standard Jet Fuel with Algal Based Second Generation Biofuels.” http://digitalcommons.ryerson.ca/dissertations/702/.

Haddad, Mona, and Zouheir Fawaz. 2012. “Evaluation of Microalgal Alternative Jet Fuel Using the AHP Method with an Emphasis on the Environmental and Economic Criteria.” *Environmental Progress & Sustainable Energy* 0000 (0000): 1–13. doi:10.1002/ep.

Haimes, Yacov. 2009. *Risk Modeling, Assessment, and Management*. Edited by Andrew Sage.

3rd ed. Wiley.

Haimes, Yacov Y, Stan Kaplan, and James H Lambert. 2002. “Risk Filtering, Ranking, and Management Framework Using Hierarchical Holographic Modeling.” *Risk Analysis : An Official Publication of the Society for Risk Analysis* 22 (2): 383–97. http://www.ncbi.nlm.nih.gov/pubmed/12022684.

Haimes, Yacov Y. 2009a. “On the Complex Definition of Risk: A Systems-Based Approach.” *Risk Analysis* 29 (12): 1647–54. doi:10.1111/j.1539-6924.2009.01310.x.

———. 2009b. “On the Definition of Resilience in Systems.” *Risk Analysis* 29 (4): 498–501. doi:10.1111/j.1539-6924.2009.01216.x.

Hamel, Gary, and Liisa Välikangas. 2003. “The Quest for Resilience.” *Harvard Business Review* 81 (9): 52–65. doi:10.1225/R0309C.

Hamilton, Michelle C, James H Lambert, Jeffrey M Keisler, Franklin H Holcomb, and Igor Linkov. 2013. “Research and Development Priorities for Energy Islanding of Military and Industrial Installations” 19 (3): 297–305. doi:10.1061/(ASCE)IS.1943-555X.0000133.

Hamilton, Michelle C, James H Lambert, and L James Valverde. 2015. “Climate and Related Uncertainties Influencing Research and Development Priorities.” *Journal of Risk Uncertainty in Engineering Systems* 1 (2). doi:10.1061/AJRUA6.0000814.

Hamilton, Michelle C. 2014. “Scenario-Based Preferences in Risk Analysis and Systems Engineering: Evolution through Time Frames.” University of Virginia.

Hamilton, Michelle C., James H. Lambert, Elizabeth B. Connelly, and Kash A. Barker. 2016.

"Resilience Analytics with Disruption of Preferences and Lifecycle Cost Analysis for Energy Microgrids." *Reliability Engineering & System Safety*.

Hamilton, Michelle C., Shital a. Thekdi, Elisabeth M. Jenicek, Russell S. Harmon, Michael E. Goodsite, Michael P. Case, Christopher W. Karvetski, and James H. Lambert. 2013. "Case Studies of Scenario Analysis for Adaptive Management of Natural Resource and Infrastructure Systems." *Environment Systems & Decisions* 33 (December): 89–103. doi:10.1007/s10669-012-9424-3.

Hammel, Debbie. 2013. *Aviation Biofuel Sustainability Survey*.

Han, Jeongwoo, Amgad Elgowainy, Hao Cai, and Michael Q Wang. 2013. "Life-Cycle Analysis of Bio-Based Aviation Fuels." *Bioresource Technology* 150 (December). Elsevier Ltd: 447–56. doi:10.1016/j.biortech.2013.07.153.

Heijden, Kees van der. 1996. *Scenarios: The Art of Strategic Conversation*. West Sussex: John Wiley & Sons. doi:10.1007/s13398-014-0173-7.2.

Hendricks, Robert C., Dennis M. Bushnell, and Dale T. Shouse. 2011. "Aviation Fueling: A Cleaner, Greener Approach." *International Journal of Rotating Machinery* 2011: 1–13. doi:10.1155/2011/782969.

Hermann, B.G., C. Kroeze, and W. Jawjit. 2007. "Assessing Environmental Performance by Combining Life Cycle Assessment, Multi-Criteria Analysis and Environmental Performance Indicators." *Journal of Cleaner Production* 15 (18): 1787–96. doi:10.1016/j.jclepro.2006.04.004.

Hileman, James I., Pearl E. Donohoo, and Russell W. Stratton. 2010. "Energy Content and

Alternative Jet Fuel Viability." *Journal of Propulsion and Power* 26 (6): 1184–96. doi:10.2514/1.46232.

Hileman, JI, DS Ortiz, JT Bartis, and HM Wong. 2009. "Near-Term Feasibility of Alternative Jet Fuels." http://stuff.mit.edu:8001/afs/athena.mit.edu/dept/aeroastro/partner/reports/proj17/altfuelfeasrpt.pdf.

Holling, C S. 1973. "Resilience and Stability of Ecological Systems." *Annual Review of Ecology and Systematics* 4 (1). Annual Reviews: 1–23. doi:10.1146/annurev.es.04.110173.000245.

Holling, C.S. 1996. "Surprise for Science, Resilience for Ecosystems, and Incentives for People." *Ecological Applications* 6 (3): 733–35.

Holma, Anne, Kati Koponen, Riina Antikainen, Laurent Lardon, Pekka Leskinen, and Philippe Roux. 2013. "Current Limits of Life Cycle Assessment Framework in Evaluating Environmental Sustainability – Case of Two Evolving Biofuel Technologies." *Journal of Cleaner Production* 54 (September): 215–28. doi:10.1016/j.jclepro.2013.04.032.

Holtzapple, M T, R R Davison, M K Ross, S Albrett-Lee, M Nagwani, C M Lee, C Lee, et al. 1999. "Biomass Conversion to Mixed Alcohol Fuels Using the MixAlco Process." *Applied Biochemistry and Biotechnology* 77-79: 609–31. doi:10.1385/ABAB:79:1-3:609.

Horne, John F., and John E. Orr. 1998. "Assessing Behaviors That Create Resilient Organizations." *Employment Relations Today*, 29–39.

Hosseini, Seyedmohsen, Kash Barker, and Jose E. Ramirez-Marquez. 2015. "A Review of Definitions and Measures of System Resilience." *Reliability Engineering & System Safety* 145 (August): 47–61. doi:10.1016/j.ress.2015.08.006.

Huber, G W, S Iborra, and A Corma. 2006. "Synthesis of Transportation Fuels from Biomass: Chemistry, Catalysts, and Engineering." *Chemical Reviews*, no. 106: 4044.

Hughes, Larry, and Darren Shupe. 2010. "Creating Energy Security Indexes with Decision Matrices and Quantitative Criteria." In *World Energy Council's 2010 Conference*.

Hunkeler, David, Kerstin Lichtenvort, and Gerald Rebitzer. 2008. *Environmental Life Cycle Costing*. CRC Press.

International Air Transport Association. 2013. *IATA 2013 Report on Alternative Fuels*. 8th Editio. Montreal-Geneva.

International Air Transport Association (IATA). 2013. "Fact Sheet: Alternative Fuels." http://www.iata.org/pressroom/facts_figures/fact_sheets/pages/alt-fuels.aspx.

Iribarren, Diego, Jens F. Peters, and Javier Dufour. 2012. "Life Cycle Assessment of Transportation Fuels from Biomass Pyrolysis." *Fuel* 97 (July). Elsevier Ltd: 812–21. doi:10.1016/j.fuel.2012.02.053.

ISO. 2009. "31000–Risk management–Principles and Guidelines." *International Organization for Standardization*.

James, Joe, James Lambert, Rich Altman, and Elizabeth Connelly. "DOE Bioenergy Conference Meeting." Washington, D.C.

Jardine, CN. 2005. *Part 1: Calculating the Environmental Impact of Aviation Emissions*.

Environment Change Institute, University of Oxford, …. Oxford. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Part+1:+Calculating+the+Environmental+Impact+of+Aviation+Emissions#3.

Jena, Umakanta, and KC Das. 2011. "Comparative Evaluation of Thermochemical Liquefaction and Pyrolysis for Bio-Oil Production from Microalgae." *Energy & Fuels* 25 (11): 5472–82. doi:10.1021/ef201373m.

Jenicek, E.M., N.R.D. Meyers, D.F. Fournier, K. Miller, M. Hessel, R. Carroll, and R. Holmes. 2009. *Army Installations Water Sustainability Assessment*.

Jeswani, Harish Kumar, Adisa Azapagic, Philipp Schepelmann, and Michael Ritthoff. 2010. "Options for Broadening and Deepening the LCA Approaches." *Journal of Cleaner Production* 18 (2): 120–27. doi:10.1016/j.jclepro.2009.09.023.

Jones, S., Y. Zhu, D. Anderson, R. Hallen, D. Elliott, A. Schmidt, K. Albrecht, et al. 2014. *Process Design and Economics for the Conversion of Algal Biomass to Hydrocarbons: Whole Algae Hydrothermal Liquefaction and Upgrading*.

Kandaramath Hari, Thushara, Zahira Yaakob, and Narayanan N. Binitha. 2015. "Aviation Biofuel from Renewable Resources: Routes, Opportunities and Challenges." *Renewable and Sustainable Energy Reviews* 42 (February): 1234–44. doi:10.1016/j.rser.2014.10.095.

Kaplan, S, Y Y Haimes, and B J Garrick. 2001. "Fitting Hierarchical Holographic Modeling into the Theory of Scenario Structuring and a Resulting Refinement to the Quantitative Definition of Risk." *Risk Analysis : An Official Publication of the Society for Risk Analysis* 21 (5): 807–19. http://www.ncbi.nlm.nih.gov/pubmed/11798118.

Kaplan, Stanley, and B. John Garrick. 1981. “On The Quantitative Definition of Risk.” *Risk Analysis* 1 (1): 11–27. doi:10.1111/j.1539-6924.1981.tb01350.x.

Karlsson, Hanna, Pål Börjesson, Per-Anders Hansson, and Serina Ahlgren. 2014. “Ethanol Production in Biorefineries Using Lignocellulosic Feedstock – GHG Performance, Energy Balance and Implications of Life Cycle Calculation Methodology.” *Journal of Cleaner Production* 83 (November): 420–27. doi:10.1016/j.jclepro.2014.07.029.

Karvetski, C.W., J.H. Lambert, J.M. Keisler, and I. Linkov. 2011. “Integration of Decision Analysis and Scenario Planning for Coastal Engineering and Climate Change.” *Systems, Man and Cybernetics, Part A: Systems and Humans, IEEE Transactions on* 41 (1): 63–73.

Karvetski, C.W., J.H. Lambert, J.M. Keisler, B. Sexauer, and I. Linkov. 2011. “Climate Change Scenarios: Risk and Impact Analysis for Alaska Coastal Infrastructure.” *International Journal of Risk Assessment and Management* 15 (2-3): 258–74.

Karvetski, C.W., J.H. Lambert, and I. Linkov. 2009a. “Emergent Conditions and Multiple Criteria Analysis in Infrastructure Prioritization for Developing Countries.” *Journal of Multicriteria Decision Analysis* 16 (5-6): 125–37. doi:10.1002/mcda.

———. 2009b. “Emergent Conditions and Multiple Criteria Analysis in Infrastructure Prioritization for Developing Countries.” *Journal of Multicriteria Decision Analysis* 16: 125–37. doi:10.1002/mcda.

———. 2011. “Scenario and Multiple Criteria Decision Analysis for Energy and Environmental Security of Military and Industrial Installations.” *Integrated Environmental Assessment and Management* 7 (2): 228–36.

Karvetski, Christopher W, and James H Lambert. 2012. "Evaluating Deep Uncertainties in Strategic Priority-Setting with an Application to Facility Energy Investments." *Systems Engineering* 15: 483–93. doi:10.1002/sys.

Karvetski, Christopher W, James H Lambert, and Igor Linkov. 2011. "Scenario and Multiple Criteria Decision Analysis for Energy and Environmental Security of Military and Industrial Installations." *Integrated Environmental Assessment and Management* 7 (2): 228–36. doi:10.1002/ieam.137.

Keeney, R L. 1992. "Value-Focused Thinking: A Path to Creative Decision Analysis." Harvard University Press, Cambridge.

Kendall, M G, and B Babington Smith. 1939. "The Problem of M Rankings." *The Annals of Mathematical Statistics* 10 (3). Institute of Mathematical Statistics: 275–87. http://www.jstor.org/stable/2235668.

Kincaid, I, M Tretheway, S Gros, and D Lewis. 2012. *ACRP Report 76: Addressing Uncertainty about Future Airport Activity Levels in Airport Decision Making*. Washington, D.C. http://books.google.com/books?hl=en&lr=&id=WfuCze8okqQC&oi=fnd&pg=PP1&dq=Addressing+Uncertainty+about+Future+Airport+Activity+Levels+in+Airport+Decision+Making&ots=qgY2dmomhf&sig=_4MYm_Ik4e1o5b5Q_m23To0d7ds.

Kinder, James, and Timothy Rahmes. 2009. *Evaluation of Bio-Derived Synthetic Paraffinic Kerosenes (Bio-SPK)*.

Kleinmuntz, Don N. 2007. "20 Resource Allocation Decisions." *Advances in Decision Analysis: From Foundations to Applications*. Cambridge University Press, 400.

Köhler, Jonathan, Rainer Walz, Frank Marscheder-Weidemann, and Benjamin Thedieck. 2014. “Lead Markets in 2nd Generation Biofuels for Aviation: A Comparison of Germany, Brazil and the USA.” *Environmental Innovation and Societal Transitions* 10 (March): 59–76. doi:10.1016/j.eist.2013.10.003.

Korteling, Brett, Suraje Dessai, and Zoran Kapelan. 2013. “Using Information-Gap Decision Theory for Water Resources Planning Under Severe Uncertainty.” *Water Resources Management* 27 (4): 1149–72. doi:10.1007/s11269-012-0164-4.

Lambert, J.H., C.W. Karvetski, D.K. Spencer, B.J. Sotirin, D.M. Liberi, H.H. Zaghloul, J.B. Koogler, et al. 2012. “Prioritizing Infrastructure Investments in Afghanistan with Multiagency Stakeholders and Deep Uncertainty of Emergent Conditions.” *ASCE Journal of Infrastructure Systems* 18 (2): 155–66. doi:10.1061/(ASCE)IS.1943-555X.0000078.

Lambert, James H, Yao-jan Wu, Haowen You, Andres Clarens, and Brian Smith. 2013. “Climate Change Influence on Priority Setting for Transportation Infrastructure Assets.” *Journal of Infrastructure Systems* 19: 36–46. doi:10.1061/(ASCE)IS.1943-555X.0000094.

Laser, Mark, Eric Larson, Bruce Dale, Michael Wang, Nathanael Greene, and Lee R. Lynd. 2009. “Comparative Analysis of Effi Ciency, Environmental Impact, and Process Economics for Mature Biomass Refi Ning Scenarios.” *Biofuels, Bioproducts and Biorefining*, no. 3: 247–70. doi:10.1002/bbb.136.

Laurencelle, L. 2009. “Le Tau et Le Tau-B de Kendall Pour La Corrélation de Variables Ordinales Simples Ou Catégorielles.” *Psychology* 5 (2): 51–58.

Lee, Changyong, Bomi Song, and Yongtae Park. 2014. “An Instrument for Scenario-Based Technology Roadmapping: How to Assess the Impacts of Future Changes on Organisational Plans.” *Technological Forecasting and Social Change*, January. doi:10.1016/j.techfore.2013.12.020.

Lempert, Robert J. 2003. *Shaping the next One Hundred Years: New Methods for Quantitative, Long-Term Policy Analysis*. Rand Corporation.

Lempert, Robert J., David G. Groves, Steven W. Popper, and Steve C. Bankes. 2006. “A General , Analytic Method for Generating Robust Strategies and Narrative Scenarios.” *Management Science* 52 (4): 514–28. doi:10.1287/mnsc.l.

Li, Boyan, Longwen Ou, Qi Dang, Pimphan Meyer, Susanne Jones, Robert Brown, and Mark Wright. 2015. “Techno-Economic and Uncertainty Analysis of in Situ and Ex Situ Fast Pyrolysis for Biofuel Production.” *Bioresource Technology* 196 (July): 49–56. doi:10.1016/j.biortech.2015.07.073.

Linkov, Igor, Daniel A Eisenberg, Matthew E Bates, Derek Chang, Matteo Convertino, Julia H Allen, Stephen E Flynn, and Thomas P Seager. 2013. “Measurable Resilience for Actionable Policy.” *Environmental Science and Technology* 47 (ii): 10108–10. doi:10.1021/es403443n.

Linkov, Igor, and Thomas P Seager. 2011. “Coupling Multi-Criteria Decision Analysis, Life-Cycle Assessment, and Risk Assessment for Emerging Threats.” *Environmental Science & Technology* 45 (12): 5068–74. doi:10.1021/es100959q.

Liu, Guangrui, Beibei Yan, and Guanyi Chen. 2013. “Technical Review on Jet Fuel Production.” *Renewable and Sustainable Energy Reviews* 25 (September). Elsevier: 59–

70. doi:10.1016/j.rser.2013.03.025.

Liu, Xiaowei, Benjamin Saydah, Pragnya Eranki, Lisa M Colosi, Greg B Mitchell, James Rhodes, and Andres F Clarens. 2013. "Pilot-Scale Data Provide Enhanced Estimates of the Life Cycle Energy and Emissions Profile of Algae Biofuels Produced via Hydrothermal Liquefaction." *Bioresource Technology* 148 (November). Elsevier Ltd: 163–71. doi:10.1016/j.biortech.2013.08.112.

Lokesh, Kadambari, Vishal Sethi, Theoklis Nikolaidis, Eric Goodger, and Devaiah Nalianda. 2015. "Life Cycle Greenhouse Gas Analysis of Biojet Fuels with a Technical Investigation into Their Impact on Jet Engine Performance." *Biomass and Bioenergy* 77 (June): 26–44. doi:10.1016/j.biombioe.2015.03.005.

Longstaff, Patricia H, Thomas G Koslowski, and Will Geoghegan. 2013. "Translating Resilience : A Framework to Enhance Communication and Implementation." In *5th International Symposium on Resilience Engineering*.

Lowrance, William W. 1976. *Of Acceptable Risk: Science and the Determination of Safety*.

Macfarlane, Ross, Patrick Mazza, and Jeannette Allan. 2011. *Sustainable Aviation Fuels Northwest: Powering the next Generation of Flight*.

Madni, Azad M., and Scott Jackson. 2009. "Towards a Conceptual Framework for Resilience Engineering." *IEEE Systems Journal* 3 (2): 181–91. doi:10.1109/JSYST.2009.2017397.

Male, Jonathan. 2015. "Farm to Fly 2.0: Energy Department Joins Initiative to Bring Biofuels to the Skies." *Energy.Gov*. Accessed May 4. http://www.energy.gov/eere/bioenergy/articles/farm-fly-20-energy-department-joins-initiative-bring-biofuels-skies.

Martinez, L.J., J.H. Lambert, and C.W. Karvetski. 2011. "Scenario-Informed Multiple Criteria Analysis for Prioritizing Investments in Electricity Capacity Expansion." *Reliability Engineering & System Safety* 96 (8). Elsevier: 883–91. doi:10.1016/j.ress.2011.03.007.

MASBI. 2013. *Fueling a Sustainable Future for Aviation*.

Matheson, David, and James E Matheson. 2001. "Smart Organizations Perform Better." *Research-Technology Management* 44 (4). Industrial Research Institute, Inc: 49–54.

Matin, Nilufar, and Richard Taylor. 2015. "Emergence of Human Resilience in Coastal Ecosystems under Environmental Change." *Ecology and Society* 20 (2): art43. doi:10.5751/ES-07321-200243.

McCartt, Anne T, and John Rohrbaugh. 1989. "Evaluating Group Decision Support System Effectiveness: A Performance Study of Decision Conferencing." *Decision Support Systems* 5 (2). Elsevier: 243–53.

McDaniels, Timothy, Tamsin Mills, Robin Gregory, and Dan Ohlson. 2012. "Using Expert Judgments to Explore Robust Alternatives for Forest Management under Climate Change." *Risk Analysis* 32 (12): 2098–2112. doi:10.1111/j.1539-6924.2012.01822.x.

Melin, Kristian, and Markku Hurme. 2011. "Lignocellulosic Biorefinery Economic Evaluation." *Cellulose Chemistry and Technology* 45: 443–54. http://www.cellulosechemtechnol.ro/pdf/CCT45,7-8(2011)/p.443-454.pdf.

Mendes, Pietro A S, Allan Kardec Barros, Luiz Antonio D'Avila, and Adelaide M Antunes. 2012. "Multicriteria Mapping of Stakeholder Preferences for the Sustainability of the

Brazilian Program for Biodiesel Production and Use." *Environmental Progress & Sustainable Energy* 00 (00): 1–9. doi:10.1002/ep.

Middleton, Richard S, Andres F Clarens, Xiaowei Liu, Jeffrey M Bielicki, and Jonathan S Levine. 2014. "CO2 Deserts: Implications of Existing CO2 Supply Limitations for Carbon Management." *Environmental Science & Technology*, August. doi:10.1021/es5022685.

Miettinen, Pauli, and Raimo P. Hämäläinen. 1997. "How to Benefit from Decision Analysis in Environmental Life Cycle Assessment (LCA)." *European Journal of Operational Research* 102 (2): 279–94. doi:10.1016/S0377-2217(97)00109-4.

Miller, B., D. Johnson, P. Jones, T. Thompson, M. Johnson, M. Hunt, D. Schenk, et al. 2013. *ACRP Report 83: Assessing Opportunities for Alternative Fuel Distribution Programs*. Washington, D.C.

Miller, B., T. Thompson, M. Johnson, M. Brand, A. McDonald, D. Schenk, J. Driver, et al. 2012. *ACRP Report 60: Guidelines for Integrating Alternative Jet Fuel Into the Airport Setting*. National Academy of Sciences. http://books.google.com/books?hl=en&lr=&id=QyM58KcmiaoC&oi=fnd&pg=PP1&dq=Guidelines+for+Integrating+Alternative+Jet+Fuel+Into+the+Airport+Setting&ots=UZCY_4-3IK&sig=8Y4VqaA5ByhXch8SQ2myqYo5TqE.

Montibeller, Gilberto, and Alberto Franco. 2010. "Multi-Criteria Decision Analysis for Strategic Decision Making." In *Handbook of Multicriteria Analysis*, edited by C. Zopounidis and P.M. Pardalos, Applied Op, 25–49. Springer-Verlag Berlin Heidelberg. doi:10.1007/978-3-540-92828-7.

Montibeller, Gilberto, Haidee Gummer, and Danielle Tumidei. 2006. "Combining Scenario Planning and Multi-Criteria Decision Analysis in Practice." *Journal of Multi-Criteria Decision Analysis* 14: 5–20. doi:10.1002/mcda.403.

Motuzienė, Violeta, Artur Rogoža, Vilūnė Lapinskienė, and Tatjana Vilutienė. 2015. "Construction Solutions for Energy Efficient Single-Family House Based on Its Life Cycle Multi-Criteria Analysis: A Case Study." *Journal of Cleaner Production*, September. doi:10.1016/j.jclepro.2015.08.103.

Myllyviita, Tanja, Anne Holma, Riina Antikainen, Katja Lähtinen, and Pekka Leskinen. 2012. "Assessing Environmental Impacts of Biomass Production Chains – Application of Life Cycle Assessment (LCA) and Multi-Criteria Decision Analysis (MCDA)." *Journal of Cleaner Production* 29-30 (July): 238–45. doi:10.1016/j.jclepro.2012.01.019.

Nair, Sujith, and Hanna Paulose. 2014. "Emergence of Green Business Models: The Case of Algae Biofuel for Aviation." *Energy Policy* 65 (February): 175–84. doi:10.1016/j.enpol.2013.10.034.

National Agricultural Statistics Service (NASS). 2015. *Acreage*.

Novelli, Philippe. 2011. *Sustainable Way for Alternative Fuels and Energy in Aviation Final Report*.

Oltean-Dumbrava, Crina, Greg Watts, and Abdul Miah. 2015. "Towards a More Sustainable Surface Transport Infrastructure: A Case Study of Applying Multi Criteria Analysis Techniques to Assess the Sustainability of Transport Noise Reducing Devices." *Journal of Cleaner Production*, October. doi:10.1016/j.jclepro.2015.09.096.

Olukoya, Ife A., Danielle Bellmer, James R. Whiteley, and Clint P. Aichele. 2015. "Evaluation of the Environmental Impacts of Ethanol Production from Sweet Sorghum." *Energy for Sustainable Development* 24 (February): 1–8. doi:10.1016/j.esd.2014.10.004.

Ou, Xunmin, Xiaoyu Yan, Xu Zhang, and Xiliang Zhang. 2013. "Life-Cycle Energy Use and Greenhouse Gas Emissions Analysis for Bio-Liquid Jet Fuel from Open Pond-Based Micro-Algae under China Conditions." *Energies* 6 (9): 4897–4923. doi:10.3390/en6094897.

Ouyang, Min, and Zhenghua Wang. 2015. "Resilience Assessment of Interdependent Infrastructure Systems: With a Focus on Joint Restoration Modeling and Analysis." *Reliability Engineering & System Safety* 141 (September): 74–82. doi:10.1016/j.ress.2015.03.011.

Parlak, Ayse I., James H. Lambert, Thomas M. Guterbock, and Janet L. Clements. 2012. "Population Behavioral Scenarios Influencing Radiological Disaster Preparedness and Planning." *Accident; Analysis and Prevention* 48 (September): 353–62. doi:10.1016/j.aap.2012.02.007.

Parnell, Gregory S., Jack A. Jackson, Roger C. Burk, Lee J. Lehmkuhl, and Joseph A. Engelbrecht. 1999. "R&D Concept Decision Analysis: Using Alternate Futures for Sensitivity Analysis." *Journal of Multi-Criteria Decision Analysis* 8 (3): 119–27.

Pate, Ron, Geoff Klise, and Ben Wu. 2011. "Resource Demand Implications for US Algae Biofuels Production Scale-Up." *Applied Energy* 88 (10): 3377–88. doi:10.1016/j.apenergy.2011.04.023.

Pearlson, Matthew. 2011. "A Techno-Economic and Environmental Assessment of

Hydroprocessed Renewable Distillate Fuels." Massachusetts Institute of Technology. http://dspace.mit.edu/handle/1721.1/65508.

Pearlson, Matthew, Christoph Wollersheim, and James Hileman. 2013. "A Techno-Economic Review of Hydroprocessed Renewable Esters and Fatty Acids for Jet Fuel Production." *Biofuels, Bioproducts and Biorefining*, 89–96. doi:10.1002/bbb.

Pedersen, Kjartan, Jan Emblemsvag, Reid Bailey, Janet K Allen, and Farrokh Mistree. 2000. "Validating Design Methods and Research: The Validation Square." In *ASME DETC, Design Theory and Methodology Conference*, DETC00-145:1–12.

Pellegrino, Joan, Sabine Brueske, Tracy Carole, and Howard Andres. 2007. *Energy and Environmental Profile of the U.S. Petroleum Refining Industry*. Columbia, Maryland.

Pena, Naomi, Dorian Frieden, and David Neil Bird. 2013. "Accounting for Algae." *GCB Bioenergy* 5 (3): 243–56. doi:10.1111/j.1757-1707.2012.01194.x.

Penner, Joyce E., David H. Lister, David J. Griggs, David J. Dokken, and Mack McFarland. 2001. *Aviation and the Global Atmosphere*. http://www.grida.no/publications/other/ipcc_sr/?src=/climate/ipcc/aviation/.

Perimenis, Anastasios, Hartley Walimwipi, Sergey Zinoviev, Franziska Müller-Langer, and Stanislav Miertus. 2011. "Development of a Decision Support Tool for the Assessment of Biofuels." *Energy Policy* 39 (3): 1782–93. doi:10.1016/j.enpol.2011.01.011.

Peterson, Garry, Craig R. Allen, and C. S. Holling. 1997. "Ecological Resilience, Biodiversity, and Scale." *Ecosystems* 1 (1): 6–18. doi:10.1007/s100219900002.

Peterson, Garry D., Graeme S. Cumming, and Stephen R. Carpenter. 2003. "Scenario

Planning: A Tool for Conservation in an Uncertain World." *Conservation Biology* 17 (2): 358–66. doi:10.1046/j.1523-1739.2003.01491.x.

Phillips, Lawrence D., and Carlos a. Bana E Costa. 2007. "Transparent Prioritisation, Budgeting and Resource Allocation with Multi-Criteria Decision Analysis and Decision Conferencing." *Annals of Operations Research* 154 (1): 51–68. doi:10.1007/s10479-007-0183-3.

Plevin, Richard J., Mark A. Delucchi, and Felix Creutzig. 2014. "Using Attributional Life Cycle Assessment to Estimate Climate-Change Mitigation Benefits Misleads Policy Makers." *Journal of Industrial Ecology* 18 (1): 73–83. doi:10.1111/jiec.12074.

Pohekar, S.D., and M. Ramachandran. 2004. "Application of Multi-Criteria Decision Making to Sustainable Energy planning—A Review." *Renewable and Sustainable Energy Reviews* 8 (4): 365–81. doi:10.1016/j.rser.2003.12.007.

Ponomarov, Serhiy Y, and Mary C Holcomb. 2009. "Understanding the Concept of Supply Chain Resilience." *The International Journal of Logistics Management* 20 (1). Emerald Group Publishing Limited: 124–43.

Pressley, Phillip N., Tarek N. Aziz, Joseph F. DeCarolis, Morton A. Barlaz, Feng He, Fanxing Li, and Anders Damgaard. 2014. "Municipal Solid Waste Conversion to Transportation Fuels: A Life-Cycle Estimation of Global Warming Potential and Energy Consumption." *Journal of Cleaner Production* 70 (May): 145–53. doi:10.1016/j.jclepro.2014.02.041.

Quinn, Jason C., and Ryan Davis. 2015. "The Potentials and Challenges of Algae Based Biofuels: A Review of the Techno-Economic, Life Cycle, and Resource Assessment Modeling." *Bioresource Technology* 184 (October): 444–52.

doi:10.1016/j.biortech.2014.10.075.

Qureshi, M.E, S.R Harrison, and M.K Wegener. 1999. “Validation of Multicriteria Analysis Models.” *Agricultural Systems* 62 (2): 105–16. doi:10.1016/S0308-521X(99)00059-1.

Rainey, Hal. G, and Paula. Steinbauer. 1999. “Galloping Elephants : Developing Elements of a Theory of Effective Government Organizations.” *Journal of Public Administration Research and Theory* 9 (1): 1–32. doi:Article.

Raj, Ratan, J. W. Wang, Ashutosh Nayak, M. K. Tiwari, B. Han, C. L. Liu, and W. J. Zhang. 2015. “Measuring the Resilience of Supply Chain Systems Using a Survival Model.” *IEEE Systems Journal* 9 (2): 377–81. doi:10.1109/JSYST.2014.2339552.

Ram, Camelia, Gilberto Montibeller, and Alec Morton. 2010. “Extending the Use of Scenario Planning and MCDA for the Evaluation of Strategic Options.” *Journal of the Operational Research Society* 62 (5). Nature Publishing Group: 1–13. doi:10.1057/jors.2010.90.

Reap, John, Felipe Roman, Scott Duncan, and Bert Bras. 2008a. “A Survey of Unresolved Problems in Life Cycle Assessment: Part 2 Impact Assessment and Interpretation.” *The International Journal of Life Cycle Assessment* 13 (5): 374–88. doi:10.1007/s11367-008-0009-9.

———. 2008b. “A Survey of Unresolved Problems in Life Cycle Assessment: Part 1 Goal and Scope and Inventory Analysis.” *The International Journal of Life Cycle Assessment* 13 (4): 290–300. doi:10.1007/s11367-008-0008-x.

Richard, Tom, Kate Zipp, Mark Manasco, Rich Altman, Tom Polmateer, James Lambert, Elizabeth Connelly, and Zach Collier. 2015. “PSU Meeting.” Charlottesville, VA.

Ritman, K. 2014. "Science and Decision Making from Both Sides of the Fence." *Journal Fur Verbraucherschutz Und Lebensmittelsicherheit-Journal of Consumer Protection and Food Safety* 9: S15–18. doi:10.1007/s00003-014-0894-8.

Roberts, Griffin W., Marie-Odile P. Fortier, Belinda S. M. Sturm, and Susan M. Stagg-Williams. 2013. "Promising Pathway for Algal Biofuels through Wastewater Cultivation and Hydrothermal Conversion." *Energy & Fuels* 27 (2): 857–67. doi:10.1021/ef3020603.

Rosillo-Calle, F, D Thrän, Michael Seiffert, and Siana Teelucksingh. 2012. *The Potential Role of Biofuels in Commercial Air Transport - BioJetFuel*. *IEA Bioenergy Task*. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:The+Potential+Role+of+Biofuels+in+Commercial+Air+Transport+-+BioJetFuel#0.

Rye, L, and D Batten. 2012. "Alternative Aviation Fuel Feedstock: The Microalgae Solution?" In *ICAS2012*, 1–7. http://www.icas-proceedings.net/ICAS2012/PAPERS/222.PDF.

Sage, Andrew P, and Charles L Lynch. 1998. "Systems Integration and Architecting: An Overview of Principles, Practices, and Perspectives." *Systems Engeneering* 1 (3): 176–227. doi:10.1002/(SICI)1520-6858(1998)1:3<176::AID-SYS3>3.0.CO;2-L.

Sage, Andrew P., and James E. Armstrong. 2000. *Introduction to Systems Engineering*. New York: Wiley.

San Cristóbal, J.R. 2011. "Multi-Criteria Decision-Making in the Selection of a Renewable Energy Project in Spain: The Vikor Method." *Renewable Energy* 36 (2). Elsevier Ltd: 498–502. doi:10.1016/j.renene.2010.07.031.

Santoyo-Castelazo, Edgar, and Adisa Azapagic. 2014. "Sustainability Assessment of Energy

Systems: Integrating Environmental, Economic and Social Aspects." *Journal of Cleaner Production* 80 (June). Elsevier Ltd: 119–38. doi:10.1016/j.jclepro.2014.05.061.

Saritas, Ozcan, and Jonathan Aylen. 2010. "Using Scenarios for Roadmapping: The Case of Clean Production." *Technological Forecasting and Social Change* 77 (7): 1061–75. doi:10.1016/j.techfore.2010.03.003.

Schilling, M S, N Oeser, and C Schaub. 2007. "How Effective Are Decision Analyses? Assessing Decision Process and Group Alignment Effects." *Decision Analysis* 4 (4): 227–42. doi:10.1287/deca.1070.0101.

Schoemaker, PJH. 1991. "When and How to Use Scenario Planning: A Heuristic Approach with Illustration." *Journal of Forecasting* 10 (June 1990): 549–64. http://onlinelibrary.wiley.com/doi/10.1002/for.3980100602/abstract.

Schroeder, M.J., and J.H. Lambert. 2011. "Scenario-Based Multiple Criteria Analysis for Infrastructure Policy Impacts and Planning." *Journal of Risk Research* 14 (2): 191–214.

Schwarz, Peter. 1991. "The Art of the Long View—Planning for the Future in an Uncertain World." *Currency Doubleday, New York*.

Scott, James A., William Ho, and Prasanta K. Dey. 2012. "A Review of Multi-Criteria Decision-Making Methods for Bioenergy Systems." *Energy* 42 (1): 146–56. doi:10.1016/j.energy.2012.03.074.

Seager, Thomas P., and Igor Linkov. 2008. "Coupling Multicriteria Decision Analysis and Life Cycle Assessment for Nanomaterials." *Journal of Industrial Ecology* 12 (3): 282–85. doi:10.1111/j.1530-9290.2008.00048.x.

Seber, Gonca, Robert Malina, Matthew N. Pearlson, Hakan Olcay, James I. Hileman, and Steven R.H. Barrett. 2014. "Environmental and Economic Assessment of Producing Hydroprocessed Jet and Diesel Fuel from Waste Oils and Tallow." *Biomass and Bioenergy* 67 (August): 108–18. doi:10.1016/j.biombioe.2014.04.024.

Shafieezadeh, Abdollah, and Lindsay Ivey Burden. 2014. "Scenario-Based Resilience Assessment Framework for Critical Infrastructure Systems: Case Study for Seismic Resilience of Seaports." *Reliability Engineering & System Safety* 132 (December): 207–19. doi:10.1016/j.ress.2014.07.021.

Sheffi, Yossi. 2005. "The Resilient Enterprise." *MIT Sloan Management Review* 47 (1).

Sheffi, Yossi, and James B Rice Jr. 2005. "A Supply Chain View of the Resilient Entreprise." *MIT Sloan Management Review* 47 (1).

Sheskin, David J. 2003. *Handbook of Parametric and Nonparametric Statistical Procedures*. crc Press.

Shonnard, DR, L. Williams, and T. N. Kalnes. 2010. "Camelina-derived Jet Fuel and Diesel: Sustainable Advanced Biofuels." *Environ. Prog. Sustainable Energy* 29 (3): 382–92. doi:10.1002/ep.

Sills, Deborah L, Vidia Paramita, Michael J Franke, Michael C Johnson, Tal M Akabas, Charles H Greene, and Jefferson W Tester. 2013. "Quantitative Uncertainty Analysis of Life Cycle Assessment for Algal Biofuel Production." *Environmental Science & Technology* 47 (2): 687–94. doi:10.1021/es3029236.

Skone, Timothy J., David T. Allen, Charles Allport, Kristopher Atkins, Daniel Baniszewski, Dong G. Choi, Joyce S. Cooper, Aimee Curtright, Robert M. Dilmore, and Amgad Elgowiny. 2011. *Rapid Response R&D for the Propulsion Directorate. Delivery Order 0019: Advanced Alternative Energy Technologies, Subtask: Life Cycle Greenhouse Gas Analysis of Advanced Jet Propulsion Fuels: Fischer-Tropsch Based SPK-1 Case Study*. Dayton, OH.

Skone, TJ, and K Gerdes. 2008. *Development of Baseline Data and Analysis of Life Cycle Greenhouse Gas Emissions of Petroleum-Based Fuels*. *… Technology Laboratory, Office of Systems, Analysis …*. Pittsburg, PA. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Development+of+Baseline+Data+and+Analysis+of+Life+Cycle+Greenhouse+Gas+Emissions+of+Petroleum-Based+Fuels#0.

Sols, Alberto. 2015. "Validation of the Robustness of the Selection of the Preferred Design Concept through a Comprehensive Sensitivity Analysis." In *Systems Conference (SysCon), 2015 9th Annual IEEE International*.

Somers, Robert H. 1962. "A New Asymmetric Measure of Association for Ordinal Variables." *American Sociological Review*. doi:10.2307/2090408.

Staples, Mark D., Hakan Olcay, Robert Malina, Parthsarathi Trivedi, Matthew N. Pearlson, Kenneth Strzepek, Sergey V. Paltsev, Christoph Wollersheim, and Steven R H Barrett. 2013. "Water Consumption Footprint and Land Requirements of Large-Scale Alternative Diesel and Jet Fuel Production." *Environmental Science and Technology* 47 (21): 12557–65. doi:10.1021/es4030782.

Starr, R, J Newfrock, and M Delurey. 2003. "Enterprise Resilience: Managing Risk in the

Networked Economy.” *Strategy and Business*, no. 30: 70–79. http://www.boozallen.com/media/file/Enterprise_Resilience_Report.pdf\npapers2://publication/uuid/37D7A856-EB50-45F9-B87E-640F25E00452.

Stephenson, Anna L, Elena Kazamia, John S Dennis, Christopher J Howe, Stuart A Scott, and Alison G Smith. 2010. “Life-Cycle Assessment of Potential Algal Biodiesel Production in the United Kingdom: A Comparison of Raceways and Air-Lift Tubular Bioreactors.” *Energy & Fuels* 24 (7): 4062–77. doi:10.1021/ef1003123.

Stewart, Theodor. 2013. “Integrating Problem Analysis and Algorithmic Development in MCDA.” In *Evolutionary Multi-Criterion Optimization*, 3. Springer Berlin Heidelberg.

Stewart, Theodor J. 2005. “Dealing with Uncertainties in MCDA.” In *Multiple Criteria Decision Analysis: State of the Art Surveys*, 445–66. Springer.

Stewart, Theodor J. 1996. “Robustness of Additive Value Function Methods in MCDM.” *Journal of Multi-Criteria Decision Analysis* 5: 301–9. doi:10.1002/(SICI)1099-1360(199612)5:4<301::AID-MCDA120>3.0.CO;2-Q.

Stratton, Russell W, Philip J Wolfe, and James I Hileman. 2011. “Impact of Aviation Non-CO_2 Combustion Effects on the Environmental Feasibility of Alternative Jet Fuels.” *Environmental Science & Technology* 45 (24): 10736–43. doi:10.1021/es2017522.

Stratton, RW, HM Wong, and JI Hileman. 2010. *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels*. *Transportation Noise and Emissions*. Vol. 571. http://www.obsa.org/Lists/Documentacion/Attachments/352/Life_cycle_greenhouse_gas_emissions_alternative_jet_fuels_V.1.2_EN.pdf.

Stubbins, Aron. 2009. *Virginia Coastal Energy Research Consortium Final Report : Algal Biodiesel Studies , July 2007 to September 2009*.

Sutcliffe, Kathleen M, and Timothy J Vogus. 2003. "Organizing for Resilience." *Positive Organizational Scholarship: Foundations of a New Discipline* 94: 110.

Svensson, E. 2001. "Guidelines to Statistical Evaluation of Data from Rating Scales and Questionnaires." *Journal of Rehabilitation Medicine* 33 (1): 47–48. doi:10.1080/165019701300006542.

Swanson, Ryan M, Justinus A Satrio, Robert C Brown, and David D Hsu. 2010. *Techno-Economic Analysis of Biofuels Production Based on Gasification*. Golden, CO.

Swart, R.J, P Raskin, and J Robinson. 2004. "The Problem of the Future: Sustainability Science and Scenario Analysis." *Global Environmental Change* 14 (2): 137–46. doi:10.1016/j.gloenvcha.2003.10.002.

Teng, Kuei-Yung, Shital A. Thekdi, and James H. Lambert. 2012. "Identification and Evaluation of Priorities in the Business Process of a Risk or Safety Organization." *Reliability Engineering & System Safety* 99 (March): 74–86. doi:10.1016/j.ress.2011.10.006.

The White House. 2011. *Blueprint for a Secure Energy Future*. *Washington, DC. March*. Washington, D.C. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:BLUEPRINT+FOR+A+SECURE+ENERGY+FUTURE#0.

Thekdi, Shital A., and James H. Lambert. 2014. "Quantification of Scenarios and

Stakeholders Influencing Priorities for Risk Mitigation in Infrastructure Systems." *ASCE Journal of Management in Engineering* 30 (1): 32–40. doi:10.1061/(ASCE)ME.1943-5479.0000170.

Themelis, N. J., and Charles Mussche. 2014. *2014 Energy and Economic Value of Municipal Solid Waste (MSW), Including Non-Recycled Plastics (NRP), Currently Landfilled in the Fifty States*. http://www.americanchemistry.com/Policy/Energy/Energy-Recovery/2014-Update-of-Potential-for-Energy-Recovery-from-Municipal-Solid-Waste-and-Non-Recycled-Plastics.pdf.

Timmermans, Daniëlle, and Charles Vlek. 1996. "Effects on Decision Quality of Supporting Multi-Attribute Evaluation in Groups." *Organizational Behavior and Human Decision Processes* 68 (2): 158–70. doi:10.1006/obhd.1996.0096.

Tompkins, Emma L, Roger Few, and Katrina Brown. 2008. "Scenario-Based Stakeholder Engagement: Incorporating Stakeholders Preferences into Coastal Planning for Climate Change." *Journal of Environmental Management* 88 (4): 1580–92. doi:10.1016/j.jenvman.2007.07.025.

Tonini, Davide, and Thomas Astrup. 2012. "LCA of Biomass-Based Energy Systems: A Case Study for Denmark." *Applied Energy* 99. Elsevier Ltd: 234–46. doi:10.1016/j.apenergy.2012.03.006.

Trivedi, Parthsarathi, Hakan Olcay, Mark D. Staples, Mitch R. Withers, Robert Malina, and Steven R.H. Barrett. 2015. "Energy Return on Investment for Alternative Jet Fuels." *Applied Energy* 141 (March): 167–74. doi:10.1016/j.apenergy.2014.12.016.

Troldborg, Mads, Simon Heslop, and Rupert L. Hough. 2014. "Assessing the Sustainability of

Renewable Energy Technologies Using Multi-Criteria Analysis: Suitability of Approach for National-Scale Assessments and Associated Uncertainties." *Renewable and Sustainable Energy Reviews* 39 (November): 1173–84. doi:10.1016/j.rser.2014.07.160.

Tsoutsos, Theocharis, Maria Drandaki, Niki Frantzeskaki, Eleftherios Iosifidis, and Ioannis Kiosses. 2009. "Sustainable Energy Planning by Using Multi-Criteria Analysis Application in the Island of Crete." *Energy Policy* 37 (5): 1587–1600. doi:10.1016/j.enpol.2008.12.011.

Tversky, A, and D Kahneman. 1981. "The Framing of Decisions and the Psychology of Choice." *Science* 211 (4481): 453–58. doi:10.1126/science.7455683.

U.S. Department of Agriculture. 2010. "A USDA Regional Roadmap to Meeting the Biofuels Goals of the Renewable Fuels Standard by 2022," 1–21.

———. 2012. *Agriculture and Aviation: Partners in Prosperity*.

U.S. Department of Energy. 2011. *U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry*. Oak Ridge, TN.

———. 2012. "Replacing the Whole Barrel To Reduce U.S. Dependence on Oil." U.S. Department of Energy.

———. 2013. "Billion-Ton Update (BT2) Data Explorer." Bioenergy Knowledge Discovery Framework (Bioenergy KDF). https://bioenergykdf.net.

U.S. Energy Information Administration. 2014. "Biofuels Consumption." *International Energy Statistics*. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=79&pid=79&aid=2.

U.S. Environmental Protection Agency Office of Transportation and Air Quality. 2015. "Endicott Biofuels II, LLC Request for Fuel Pathway Determination under the RFS2." Accessed January 29. http://www.epa.gov/otaq/fuels/renewablefuels/new-pathways/documents/endicott-determination.pdf.

U.S. EPA. 2010. *Renewable Fuel Standard Program (RFS2) Regulatory Impact Analysis*. Washington, D.C. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Renewable+Fuel+Standard+Program+(RFS2)+Regulatory+Impact+Analysis#0.

United States Department of Agriculture. 2015. *Notice of Solicitation of Applications (NOSA) for the Strategic Economic and Community Development Programs for Fiscal Year (FY) 2015*. Federal Register. http://www.gpo.gov/fdsys/pkg/FR-2015-06-01/pdf/2015-13100.pdf.

United States Government Accountability Office. 2014. *Freshwater: Supply Concerns Continue, and Uncertainties Complicate Planning*. http://www.gao.gov/assets/670/663344.pdf.

Unnasch, Stefan, B Riffel, S Sanchez, and L Waterland. 2011. *Review of Transportation Fuel Life Cycle Analysis*.

Venteris, Erik R., Richard L. Skaggs, Mark S. Wigmosta, and Andre M. Coleman. 2014. "A National-Scale Comparison of Resource and Nutrient Demands for Algae-Based Biofuel Production by Lipid Extraction and Hydrothermal Liquefaction." *Biomass and Bioenergy* 64 (May): 276–90. doi:10.1016/j.biombioe.2014.02.001.

Verheye, Willy. 2007. "Growth And Production of Oil Palm." *Encyclopedia of Life Support*

Systems(EOLSS) 2. http://www.eolss.net/sample-chapters/c10/e1-05a-27-00.pdf.

Vervoort, Joost M., Philip K. Thornton, Patti Kristjanson, Wiebke Förch, Polly J. Ericksen, Kasper Kok, John S.I. Ingram, et al. 2014. "Challenges to Scenario-Guided Adaptive Action on Food Security under Climate Change." *Global Environmental Change* 28 (March): 383–94. doi:10.1016/j.gloenvcha.2014.03.001.

Vogus, Timothy J., and Kathleen M. Sutcliffe. 2007. "Organizational Resilience: Towards a Theory and Research Agenda." In *Conference Proceedings - IEEE International Conference on Systems, Man and Cybernetics*, 3418–22. doi:10.1109/ICSMC.2007.4414160.

Von Winterfeldt, Detlof, and Ward Edwards. 1986. *Decision Analysis and Behavioral Research*. Vol. 604. Cambridge University Press Cambridge.

Walker, Brian, Stephen Carpenter, John Anderies, Nick Abel, Graeme S Cumming, Marco Janssen, and Louis Lebel. 2002. "Resilience Management in Social- - Ecological Systems : A Working Hypothesis for a Participatory Approach." *Conservation Ecology* 6 (1): 1–14.

Wang, H, and M Kolhman. 2013. "FEATURE: Biojet Backers See US RINs Eligibility as Vital to Long-Term Viability." *Platts*, May 6. http://www.platts.com/RSSFeedDetailedNews/RSSFeed/Petrochemicals/21015154.

Wang, Jiang-Jiang, You-Yin Jing, Chun-Fa Zhang, and Jun-Hong Zhao. 2009. "Review on Multi-Criteria Decision Analysis Aid in Sustainable Energy Decision-Making." *Renewable and Sustainable Energy Reviews* 13 (9): 2263–78. doi:10.1016/j.rser.2009.06.021.

Wang, Michael. 2013a. “GREET Model.” Argonne, Illinois: Argonne National Laboratory.

———. 2013b. “Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation.” Argonne National Laboratory.

———. 2014. *The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model: GREET 2014*. Argonne, Illinois.

Wang, Michael, Hanjie Lee, and John Molburg. 2004. “Allocation of Energy Use in Petroleum Refineries to Petroleum Products: Implications for Life-Cycle Energy Use and Emission Inventory of Petroleum Transportation Fuels.” *Int J LCA* 9 (1): 34–44.

Watson, Mark. 2011. “Aviation Sustainable Biofuels: An Asian Airline Perspective.” In *World Biofuels Markets*. Rotterdam. http://www.unece.lsu.edu/biofuels/documents/2013Mar/bf13_09.pdf.

Weiser, Christian, Vanessa Zeller, Frank Reinicke, Bernhard Wagner, Stefan Majer, Armin Vetter, and Daniela Thraen. 2014. “Integrated Assessment of Sustainable Cereal Straw Potential and Different Straw-Based Energy Applications in Germany.” *Applied Energy* 114 (February): 749–62. doi:10.1016/j.apenergy.2013.07.016.

Wiltsee, G. 1998. *Urban Waste Grease Resource Assessment*.

Woods, David D. 2015. “Four Concepts for Resilience and the Implications for the Future of Resilience Engineering.” *Reliability Engineering & System Safety* 141 (September): 5–9. doi:10.1016/j.ress.2015.03.018.

Wu, May, Zhonglong Zhang, and Yi-wen Chiu. 2014. “Life-Cycle Water Quantity and Water Quality Implications of Biofuels.” *Current Sustainable/Renewable Energy Reports* 1 (1):

3–10. doi:10.1007/s40518-013-0001-2.

Yokota, Fumie, and Kimberly M Thompson. 2004. "Value of Information Analysis in Environmental Health Risk Management Decisions: Past, Present, and Future." *Risk Analysis : An Official Publication of the Society for Risk Analysis* 24 (3): 635–50. doi:10.1111/j.0272-4332.2004.00464.x.

You, Haowen. 2013. "Priority Setting and Integrated Assessment of Transportation System Vulnerabilities to Deep Uncertainties." University of Virginia.

You, Haowen, Elizabeth B. Connelly, James H. Lambert, and Andres F. Clarens. 2014. "Climate and Other Scenarios Disrupt Priorities in Several Management Perspectives." *Environment Systems and Decisions* 34 (4): 540–54. doi:10.1007/s10669-014-9525-2.

You, Haowen, JH Lambert, AF Clarens, and BJ McFarlane. 2013. "Quantifying the Influence of Climate Change to Priorities for Infrastructure Projects." *IEEE Transactions on Systems Man and Cybernetics: Part A.*, 1–13. http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6495481.

Youn, Byeng D., Chao Hu, and Pingfeng Wang. 2011. "Resilience-Driven System Design of Complex Engineered Systems." *Journal of Mechanical Design* 133 (October): 101011. doi:10.1115/1.4004981.

Young, N., and J. Heimlich. 2010. "From 'Alternative' Fuels to 'Additional' Fuels: Overcoming the Challenges to Commercial Deployment." In *Sustainable Alternative Fuels for Aviation*, 182–85.

Zhou, Dong, Liang Zhang, Shicheng Zhang, Hongbo Fu, and Jianmin Chen. 2010.

"Hydrothermal Liquefaction of Macroalgae Enteromorpha Prolifera to Bio-Oil." *Energy & Fuels* 24 (7): 4054–61. doi:10.1021/ef100151h.

Zhu, Yunhua, Karl O. Albrecht, Douglas C. Elliott, Richard T. Hallen, and Susanne B. Jones. 2013. "Development of Hydrothermal Liquefaction and Upgrading Technologies for Lipid-Extracted Algae Conversion to Liquid Fuels." *Algal Research*, August. doi:10.1016/j.algal.2013.07.003.

Zhuang, Qianlai, Zhangcai Qin, and Min Chen. 2013. "Biofuel, Land and Water: Maize, Switchgrass or Miscanthus ?" *Environmental Research Letters* 8 (1): 015020. doi:10.1088/1748-9326/8/1/015020.

APPENDIX A: LIFE CYCLE ASSESSMENT SENSITIVITY ANALYSIS

This appendix contains simulated distributions of EROI and GWP life cycle assessment results for AHTL gasoline, diesel and aviation biofuel under both industrial and extracted CO_2-source scenarios. In addition, this appendix contains tornado charts revealing the most influential parameters to the AHTL life cycle assessment model results.

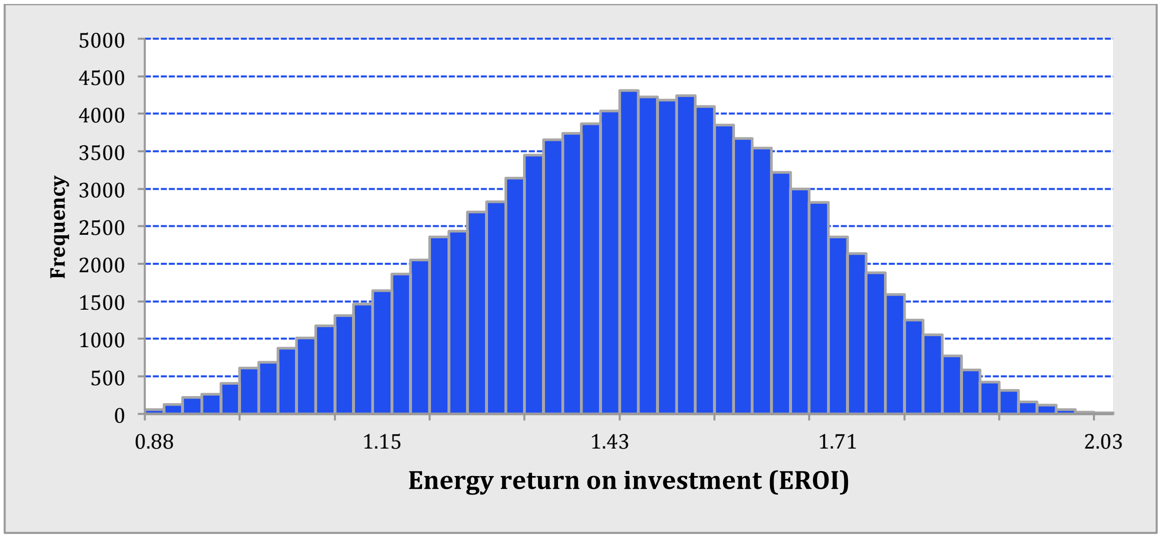

Figure 27. EROI sensitivity results for AHTL diesel produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

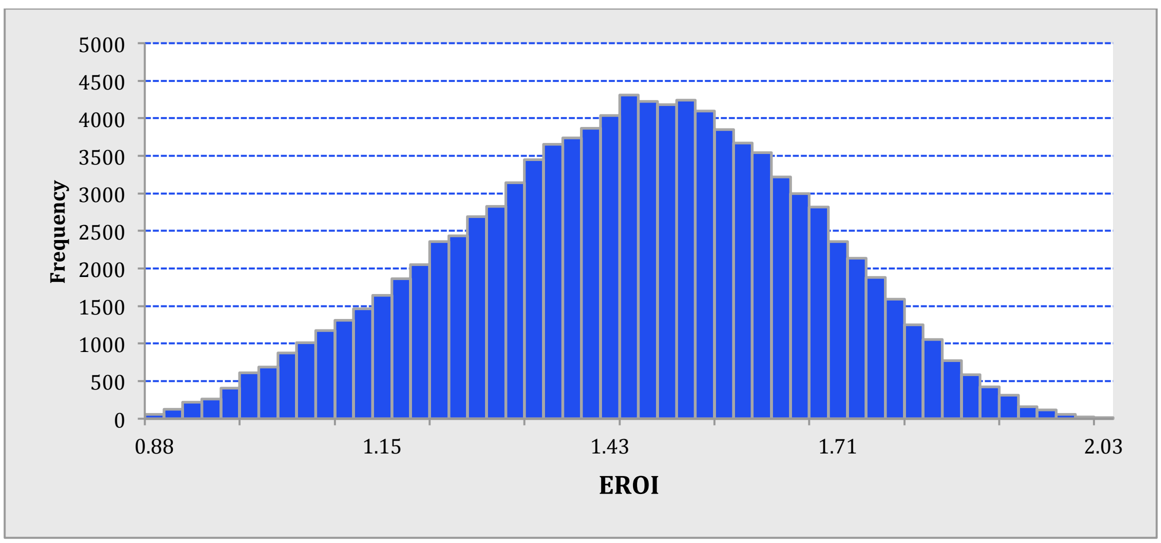

Figure 28. EROI sensitivity results for AHTL jet fuel produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

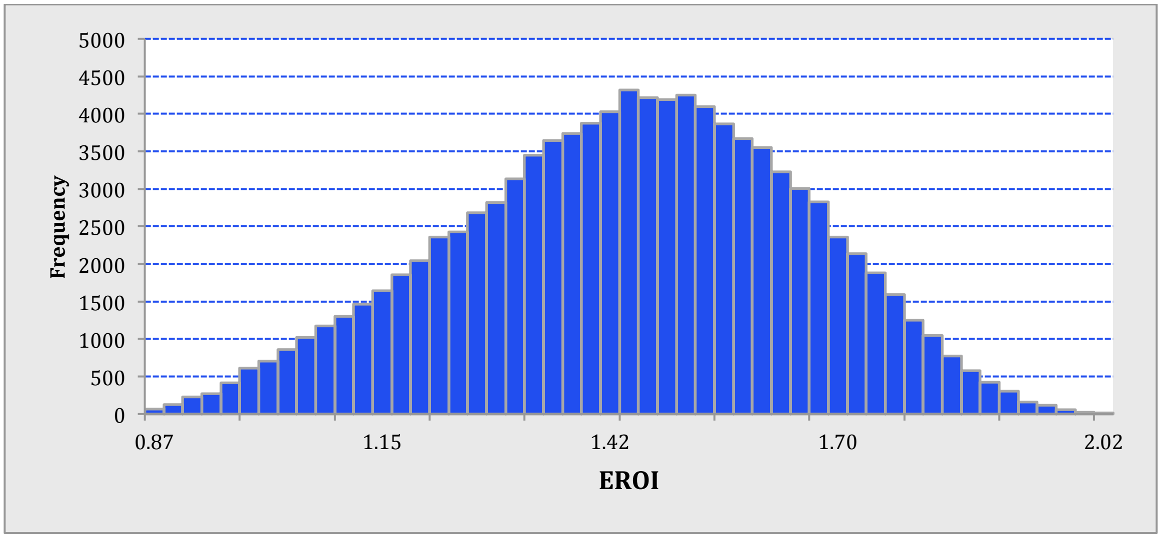

Figure 29. EROI sensitivity results for AHTL gasoline produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

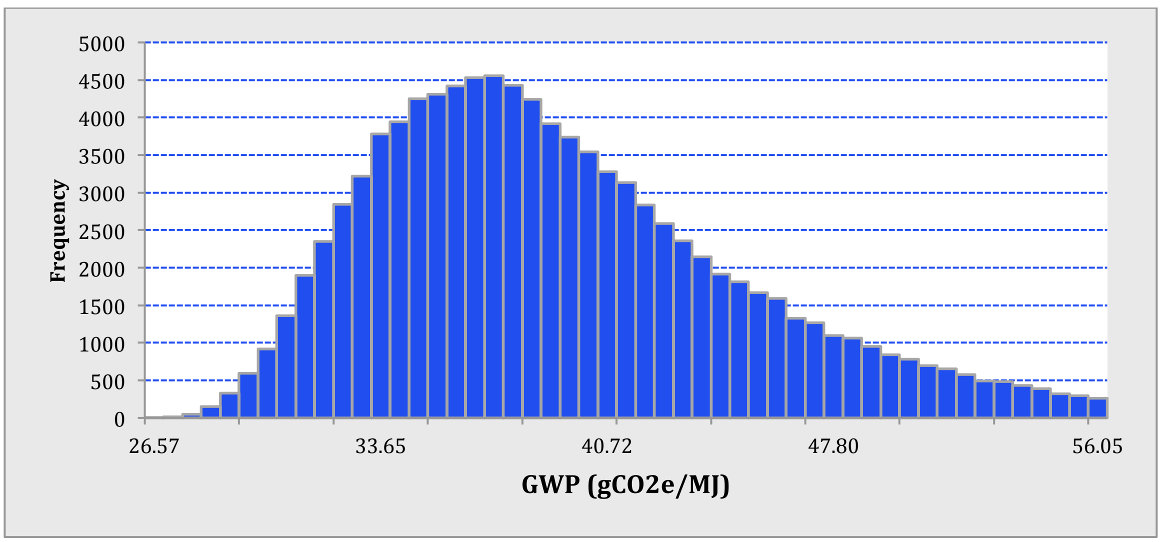

Figure 30. GWP sensitivity results for AHTL diesel produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

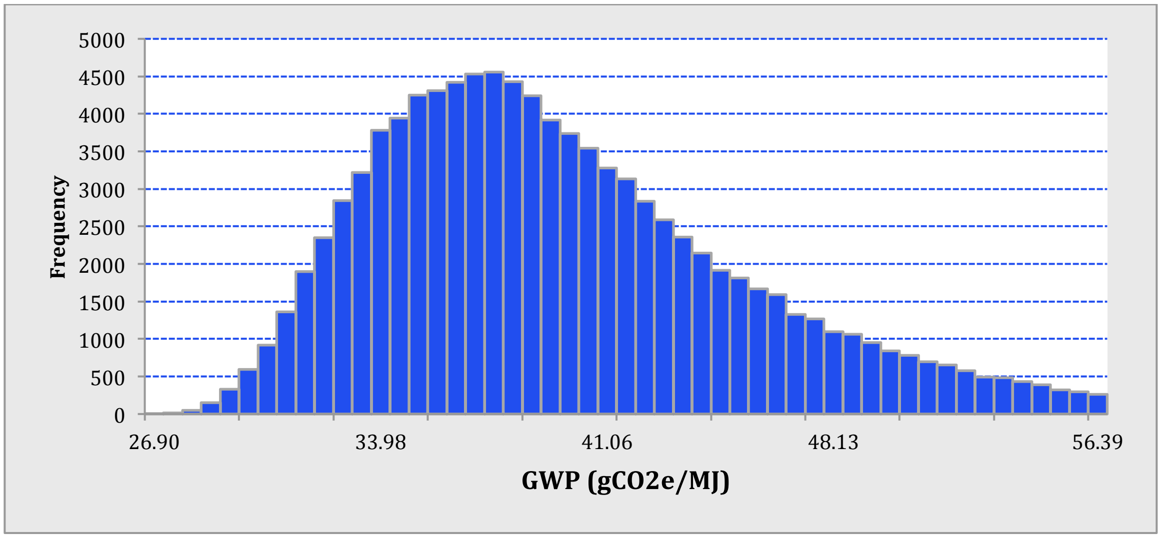

Figure 31. GWP sensitivity results for AHTL gasoline produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

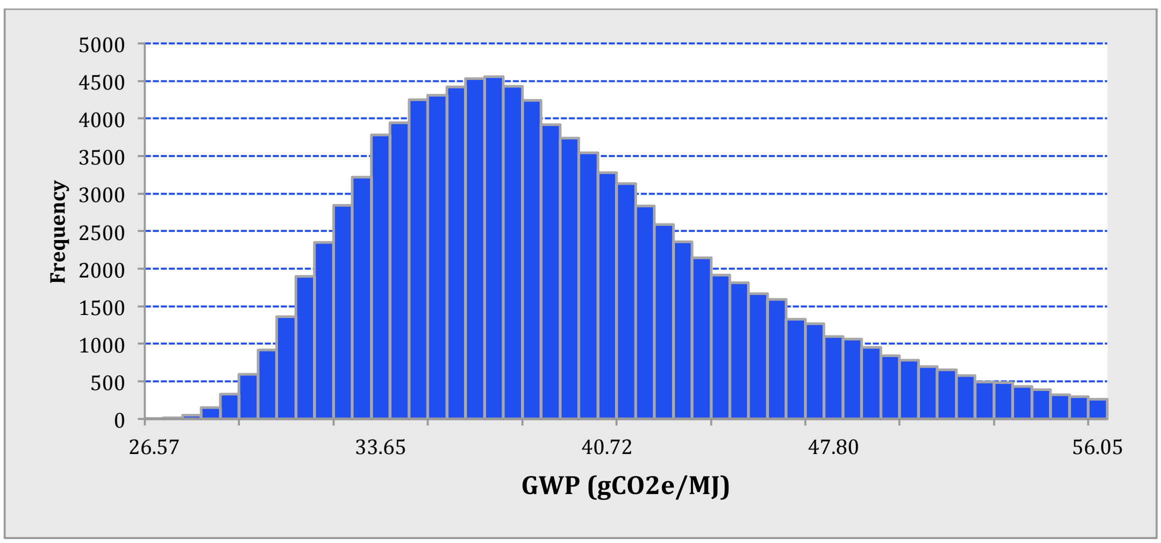

Figure 32. GWP sensitivity results for AHTL jet fuel (without combustion multiplier) produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

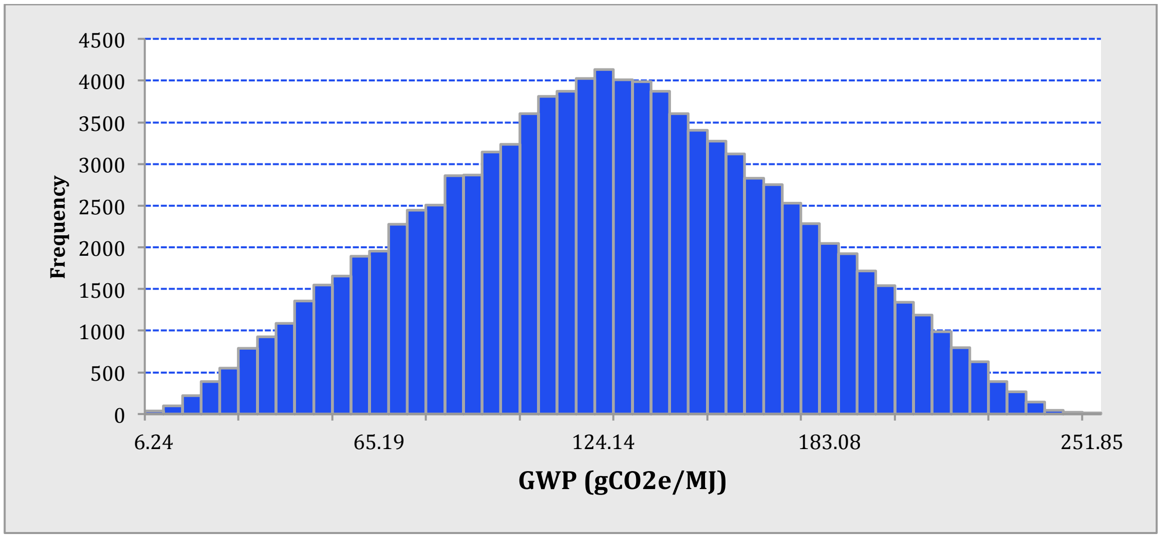

Figure 33. GWP sensitivity results for AHTL jet fuel (with combustion multiplier) produced with CO_2 from ethanol production (industrially-sourced CO_2 scenario)

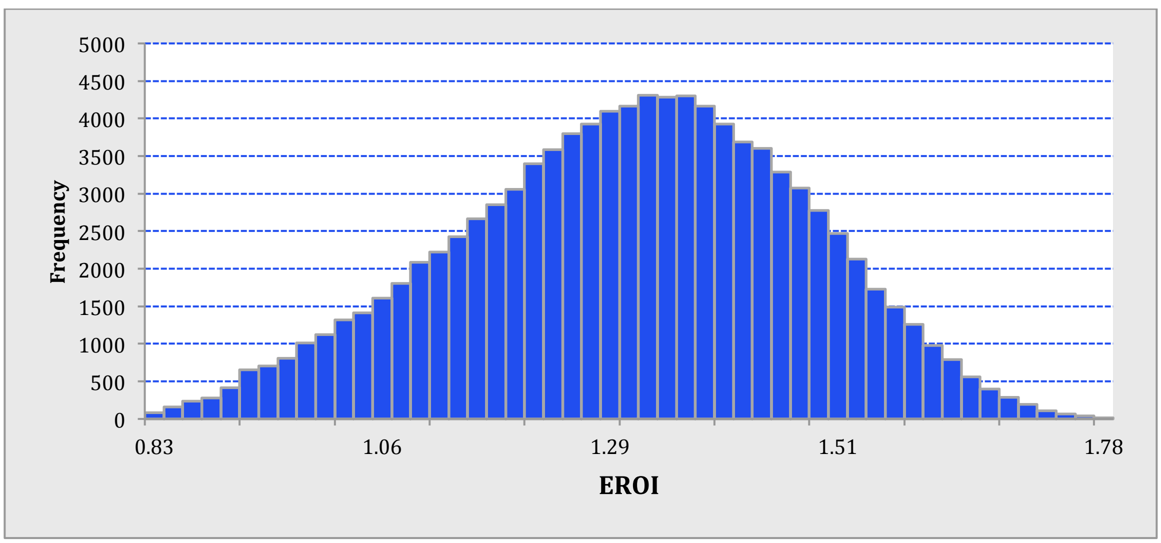

Figure 34. EROI sensitivity results for AHTL diesel produced with CO_2 from natural wells (extracted CO_2 scenario)

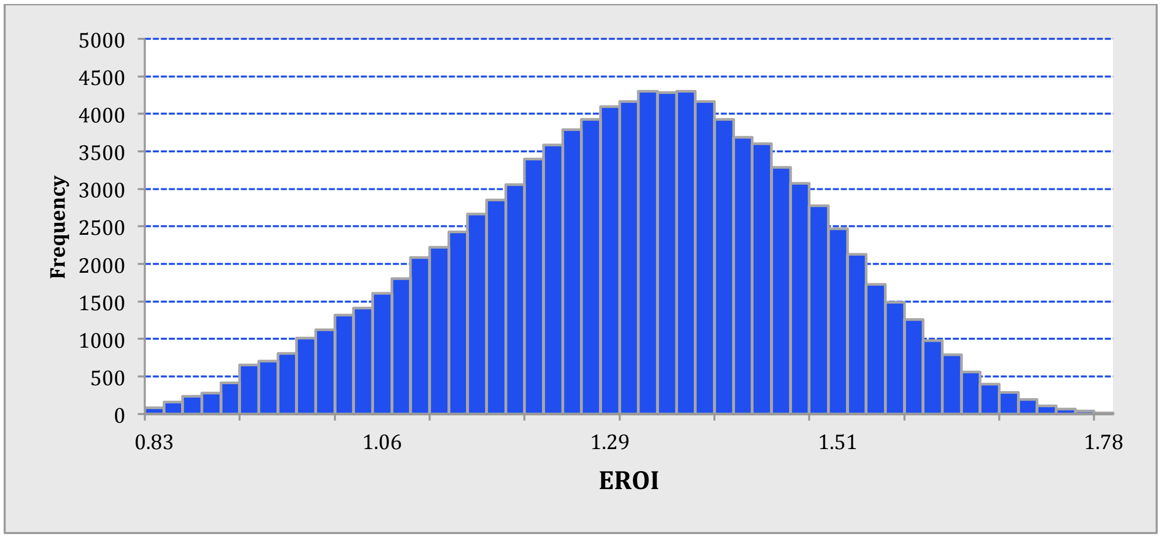

Figure 35. EROI sensitivity results for AHTL jet fuel produced with CO_2 from natural wells (extracted CO_2 scenario)

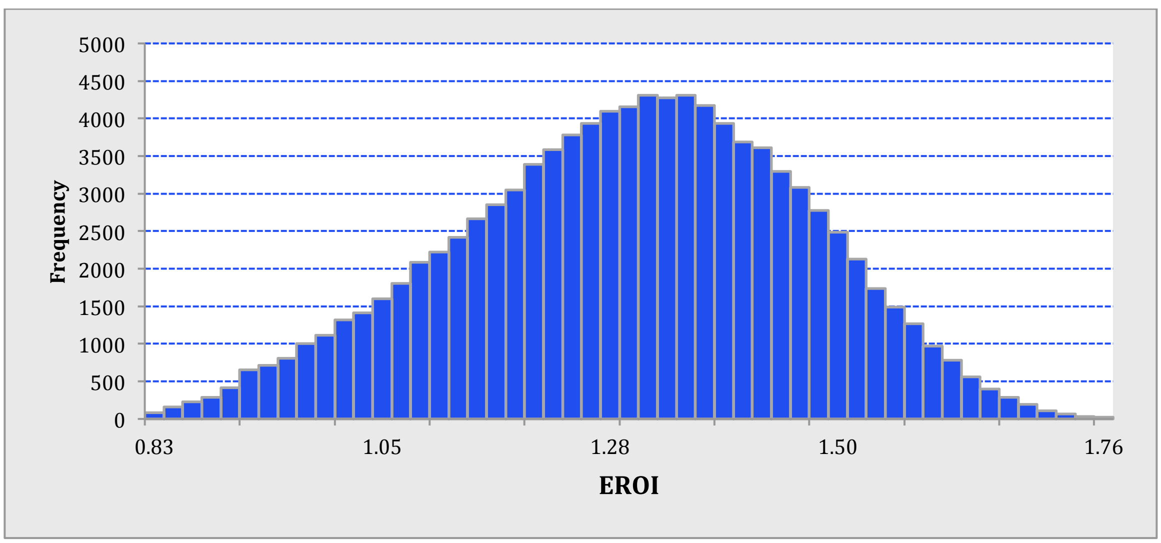

Figure 36. EROI sensitivity results for AHTL gasoline produced with CO_2 from natural wells (extracted CO_2 scenario)

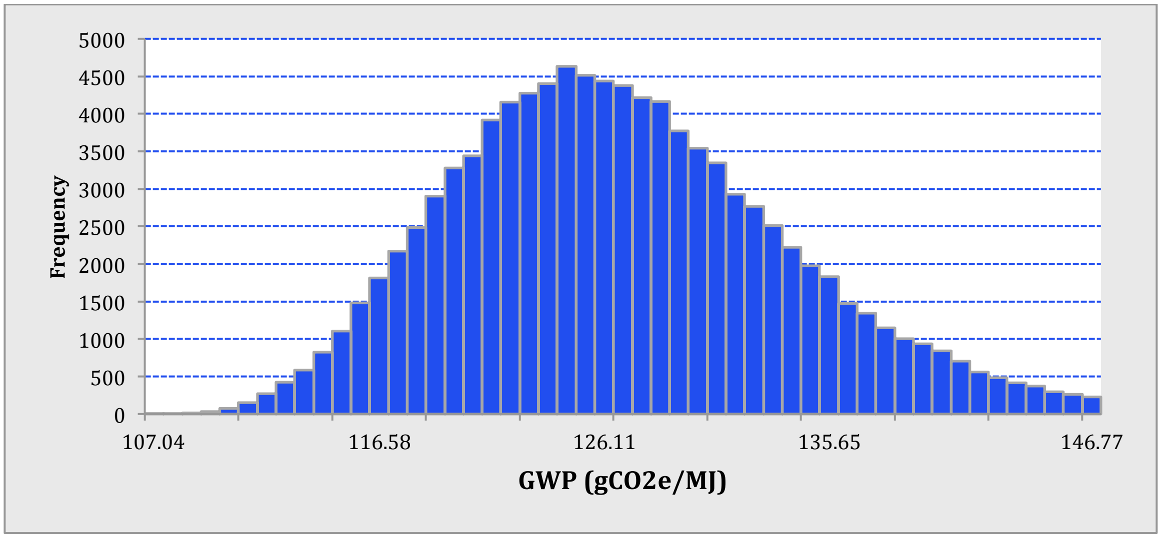

Figure 37. GWP sensitivity results for AHTL diesel produced with CO_2 from natural wells (extracted CO_2 scenario)

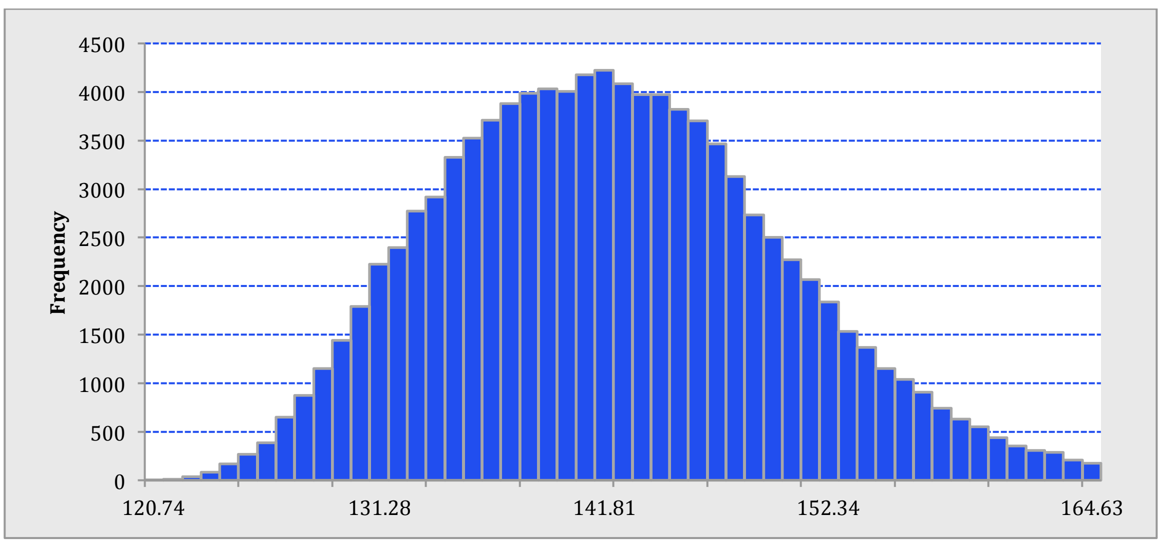

Figure 38. GWP sensitivity results for AHTL gasoline produced with CO_2 from natural wells (extracted CO_2 scenario)

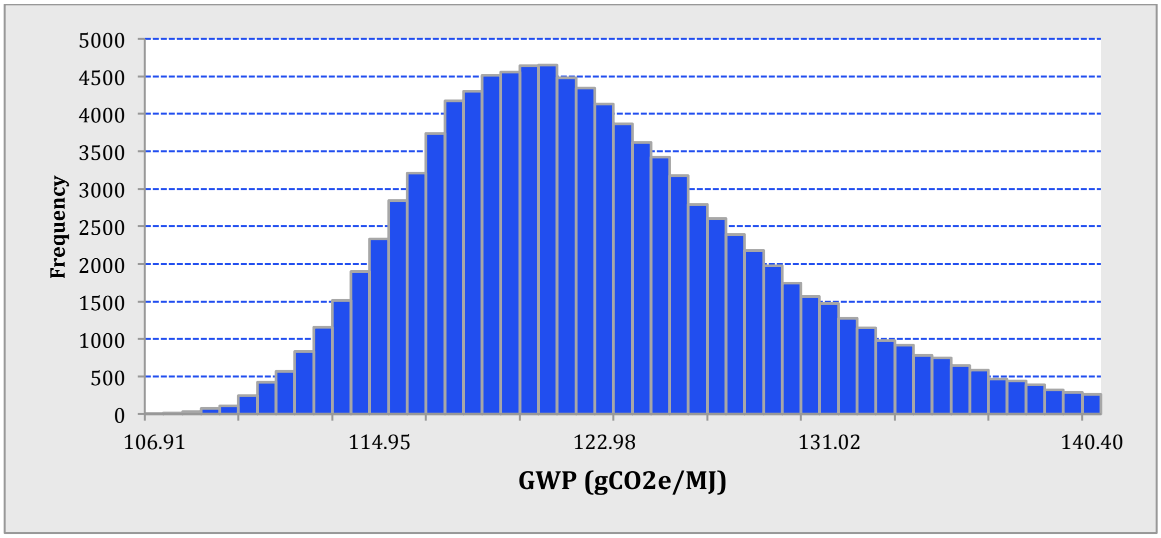

Figure 39. GWP sensitivity results for AHTL jet fuel (without combustion multiplier) produced with CO_2 from natural wells (extracted CO_2 scenario)

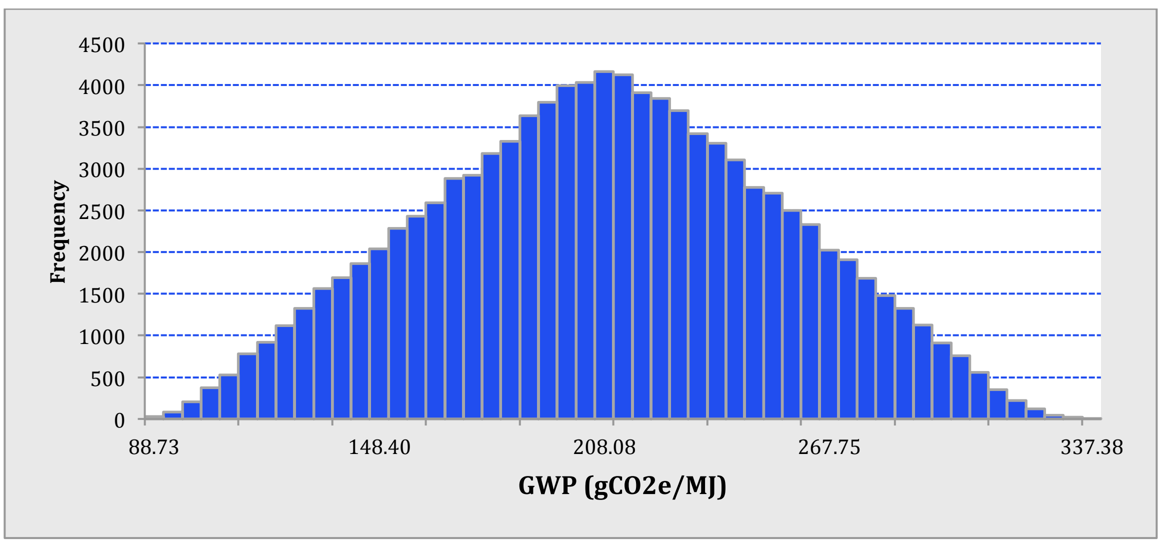

Figure 40. GWP sensitivity results for AHTL het fuel (with combustion multiplier) produced with CO_2 from natural wells (extracted CO_2 scenario)

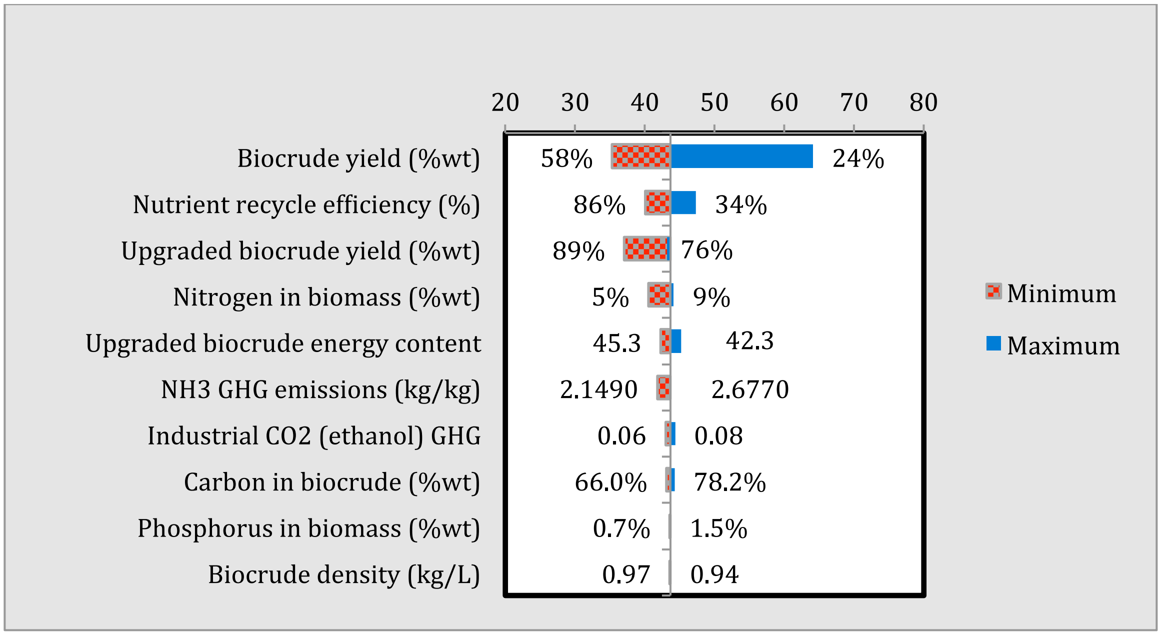

Figure 41. Tornado chart for sensitivity of AHTL diesel (produced with industrial CO_2 from ethanol production) to changes in single parameters, with parameters in descending order of influence to GWP.

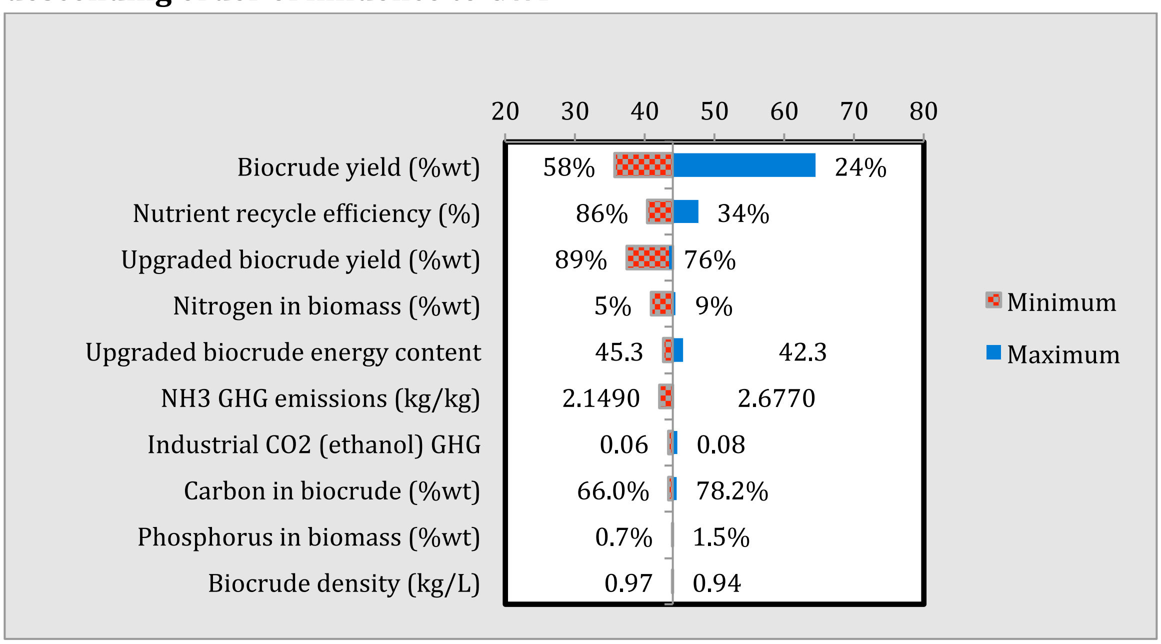

Figure 42. Tornado chart for sensitivity of AHTL gasoline (produced with industrial CO_2 from ethanol production) to changes in single parameters, with parameters in descending order of influence to GWP.

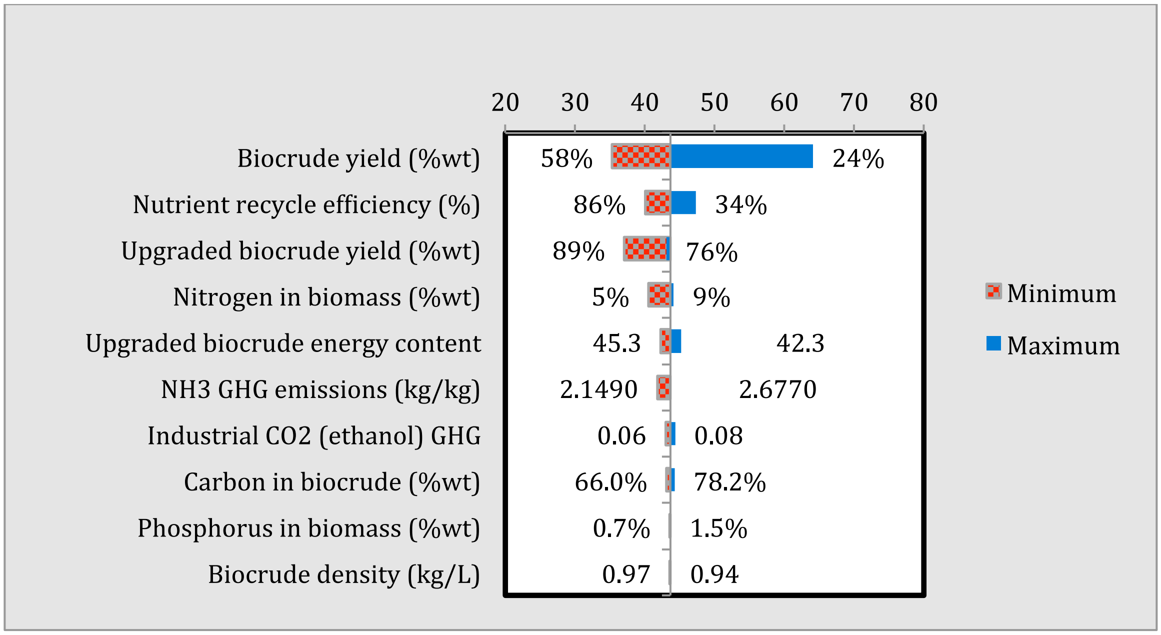

Figure 43. Tornado chart for sensitivity of AHTL jet fuel (without combustion multiplier, produced with industrial CO_2 from ethanol production) to changes in single parameters with parameters in descending order of influence to GWP.

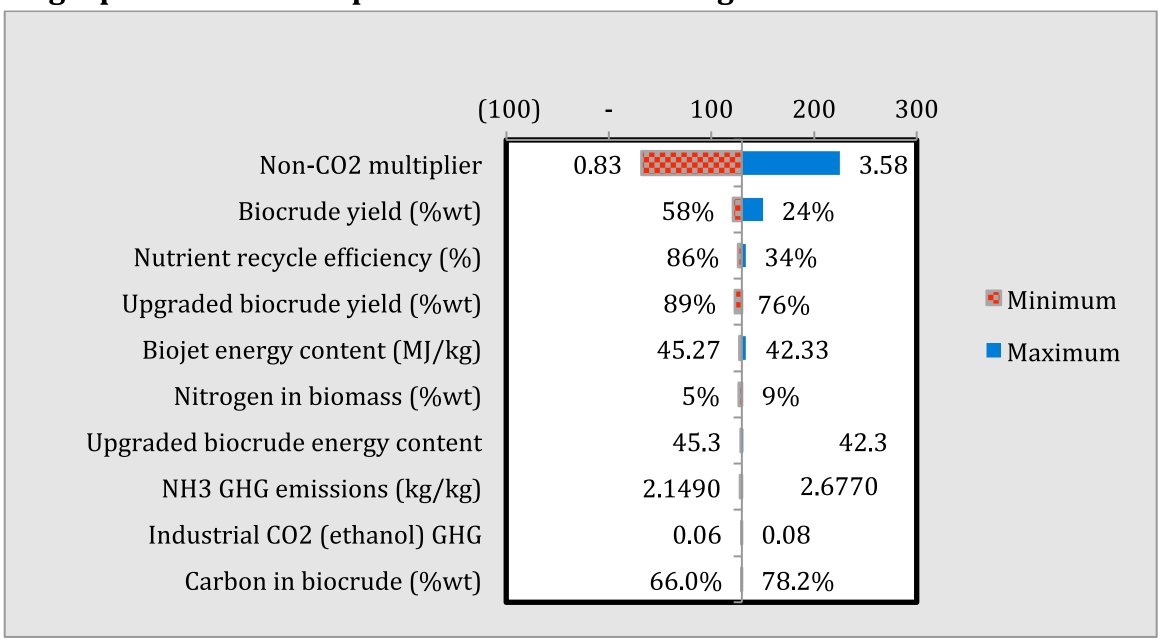

Figure 44. Tornado chart for sensitivity of AHTL jet fuel (with combustion multiplier, produced with industrial CO_2 from ethanol production) to changes in single parameters with parameters in descending order of influence to GWP.

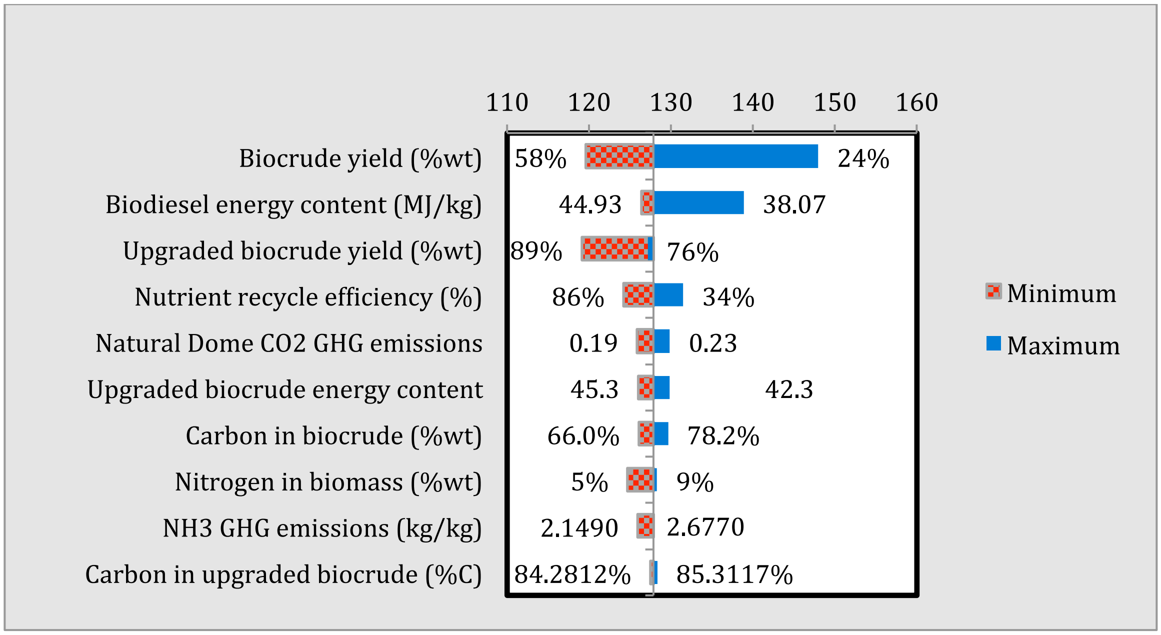

Figure 45. Tornado chart for sensitivity of AHTL diesel (produced with extracted CO_2 from natural wells) to changes in single parameters, with parameters in descending order of influence to GWP.

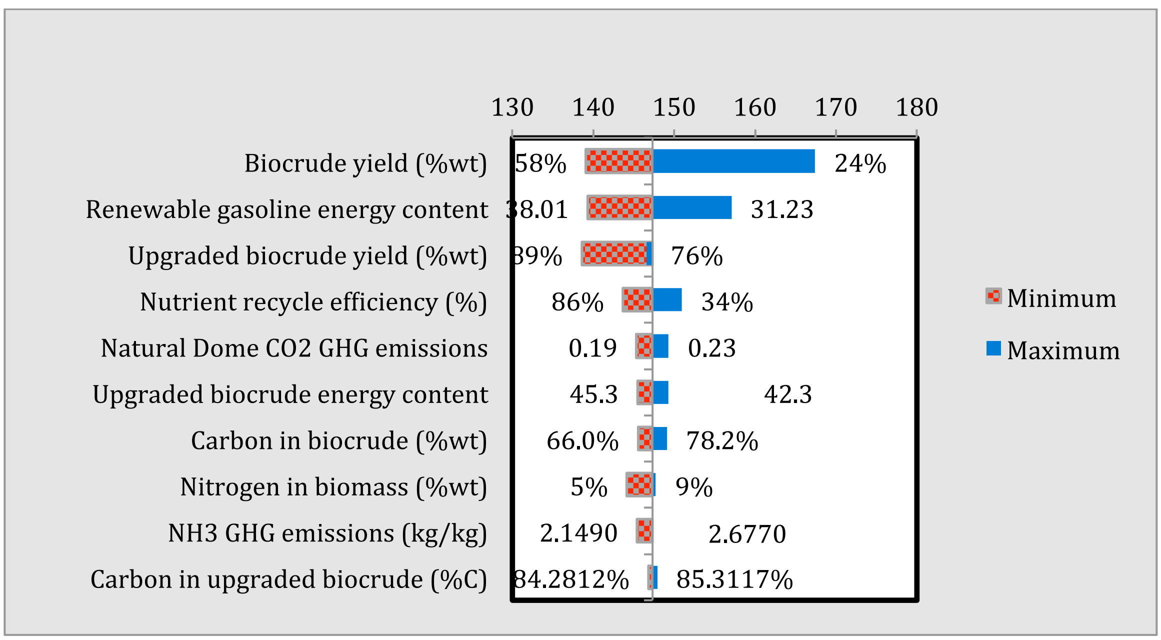

Figure 46. Tornado chart for sensitivity of AHTL gasoline (produced with extracted CO_2 from natural wells) to changes in single parameters, with parameters in descending order of influence to GWP.

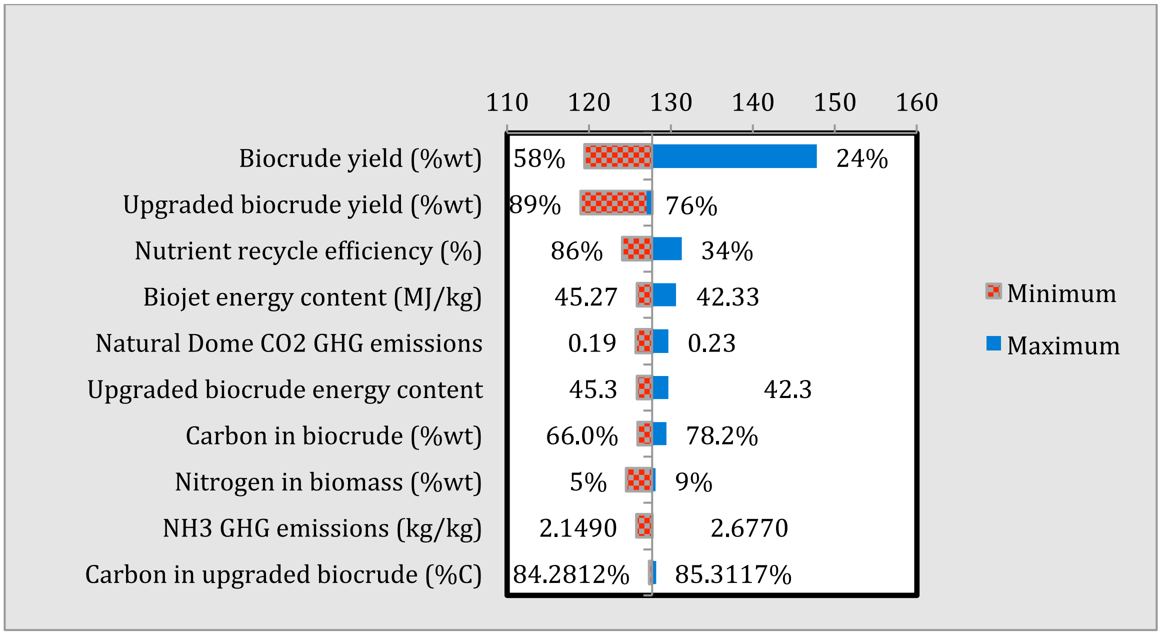

Figure 47. Tornado chart for sensitivity of AHTL jet fuel (without combustion multiplier, produced with extracted CO_2 from natural wells) to changes in single parameters with parameters in descending order of influence to GWP.

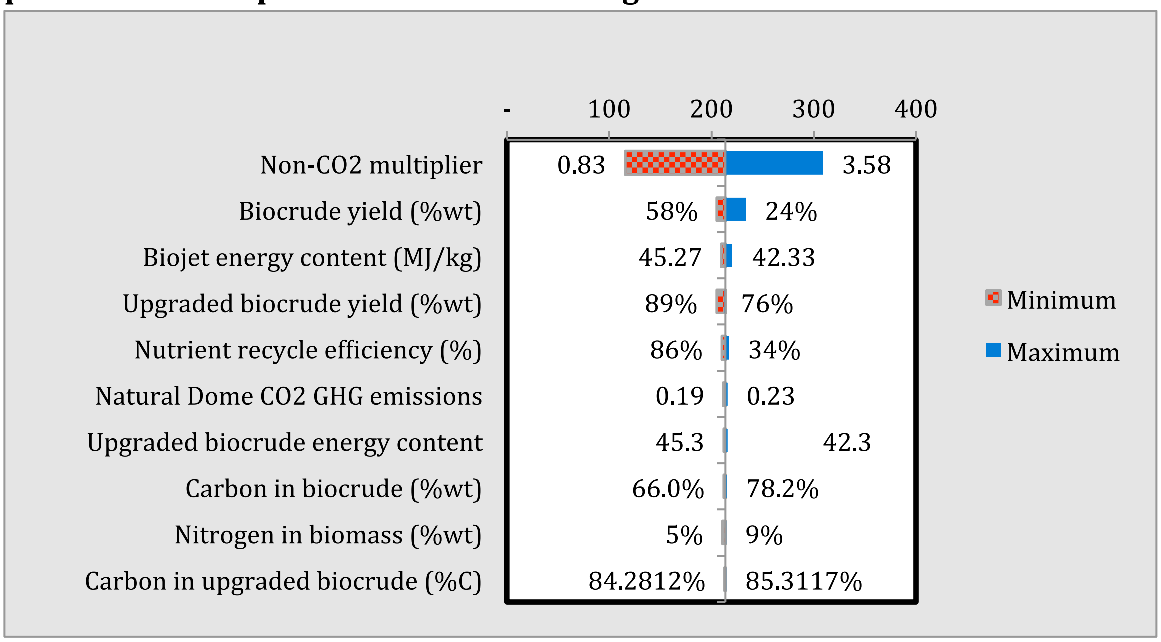

Figure 48. Tornado chart for sensitivity of AHTL jet fuel (with combustion multiplier, produced with extracted CO_2 from natural wells) to changes in single parameters with parameters in descending order of influence to GWP.

APPENDIX B: SENSITIVITY ANALYSIS OF FEEDSTOCK RESILIENCE ANALYSIS

This appendix contains the Frame I^{k+1} results obtained when using minimum and maximum life cycle assessments estimates, as opposed to average values, cited in the literature. Based on the range of values cited in the literature, sensitivity analysis is performed by using minimum and maximum values for life cycle GHG emissions, energy demand, water use, and cost, each individually. This appendix describes how initiative-criteria assessments are changed and the impact on results. For each iteration of sensitivity analysis all other values and assessments are kept the same as described in Chapter 7.

B.1 Sensitivity to GHG emissions estimates

Table 48 describes the minimum, average, and maximum LC-GHG emissions estimates for the sixteen biofuel feedstocks analyzed in Chapter 7. Table 49 describes how using minimum and maximum estimates, as opposed to average, changes the assessment of how each initiative addresses the GHG emissions criterion. Figure 49 compares the baseline ranking of initiatives (represented by the triangle) under when using minimum, average, and maximum LC-GHG emissions values. The bars indicate how the initiative ranking changes under the scenarios, revealing initiative robustness. Table 50 describes the disruptiveness of scenarios based on the calculated Spearman coefficient.

Table 48. Life-cycle GHG emissions of biofuel pathways presented as the minimum, maximum, and average of the results from referenced studies.

Feedstock	Process	LC-GHG Emissions (gCO_2e/MJ)			References
		min	baseline (average)	max	
Agricultural residue	Biochemical	13	18	41	Karlsson, et al. (2014); Baral & Malins (2014)
Algae	Hydroprocessing (lipid extraction)	14	73	193	Agusdinata et al. (2011); Lokesh et al. (2015); Stratton et al. (2010)
	HTL	21	68	132	Fortier et al. (2014); Connelly et al. (2015)
Camelina	Hydroprocessing	20	33	60	Agusdinata et al. (2011); Han et al. (2013); Lokesh et al. (2015);Novelli (2011); Shonnard, et al. (2010); Carter et al. (2011)
Corn stover	Gasification and FT	8	10	14	Agusdinata et al. (2011); Han et al. (2013); Baral & Malins (2014)
	Pyrolysis	24	27	30	Han et al. (2013)
Forest residue	Pyrolysis	13	21	34	Karlsson, et al. (2014); Baral & Malins (2014)
Jatropha	Hydroprocessing	28	42	53	Han et al. (2013); Lokesh et al. (2015);Novelli (2011); Stratton et al. (2010)
Miscanthus	Gasification and FT	10	10	10	Novelli (2011)
Municipal solid waste	Gasification and FT	-164	-99	-34	Baral & Malins (2014); Pressley et al. (2014)
Palm oil	Hydroprocessing	29	31	33	Han et al. (2013); Novelli (2011); Stratton et al. (2010)
Rapeseed	Hydroprocessing	41	54	63	Han et al. (2013); Dufour & Iribarren (2012); Novelli (2011); Stratton et al. (2010)
Sorghum	Biochemical	37	62	97	Daystar et al. (2012); Olukoya et al. (2015)
Soybean	Hydroprocessing	26	35	40	Han et al. (2013); Dufour &

					Iribarren (2012); Stratton et al. (2010)
Switchgrass	Gasification and FT	0	25	62	Agusdinata et al. (2011); Novelli (2011); Stratton et al. (2010); Carter et al. (2011)
Tallow	Hydroprocessing	16	45	84	Seber et al. (2014) Dufour & Iribarren (2012)
Wood	Gasification and FT	-2	11	26	Agusdinata et al. (2011); Novelli (2011)
	Pyrolysis	23	23	23	Han et al. (2013)
Yellow grease	Hydroprocessing	17	19	21	Seber et al. (2014) Dufour & Iribarren (2012)

Table 49. Change in assessment of Frame I² feedstock initiative to GHG emissions criterion based on minimum and maximum LCA literature estimates. Gray shading indicates where the assessment changes from that made using average LCA estimates.

Feedstock	Average-based Assessment	Minimum-based Assessment	Maximum-based Assessment
Agricultural residue	Strongly addresses	Strongly addresses	Addresses
Algae	Does not address	Somewhat addresses	Does not address
Camelina	Somewhat addresses	Somewhat addresses	Somewhat addresses
Corn stover	Addresses	Somewhat addresses	Addresses
Forest residue	Addresses	Strongly addresses	Addresses
Jatropha	Somewhat addresses	Does not address	Somewhat addresses
Miscanthus	Strongly addresses	Strongly addresses	Strongly addresses
Municipal solid waste	Strongly addresses	Strongly addresses	Strongly addresses
Palm oil	Somewhat addresses	Does not address	Addresses
Rapeseed	Does not address	Does not address	Somewhat addresses
Sorghum	Does not address	Does not address	Does not address
Soybean	Somewhat addresses	Somewhat addresses	Addresses
Switchgrass	Addresses	Strongly addresses	Somewhat addresses
Tallow	Does not address	Addresses	Does not address
Wood	Addresses	Somewhat addresses	Strongly addresses
Yellow grease	Strongly addresses	Addresses	Strongly addresses

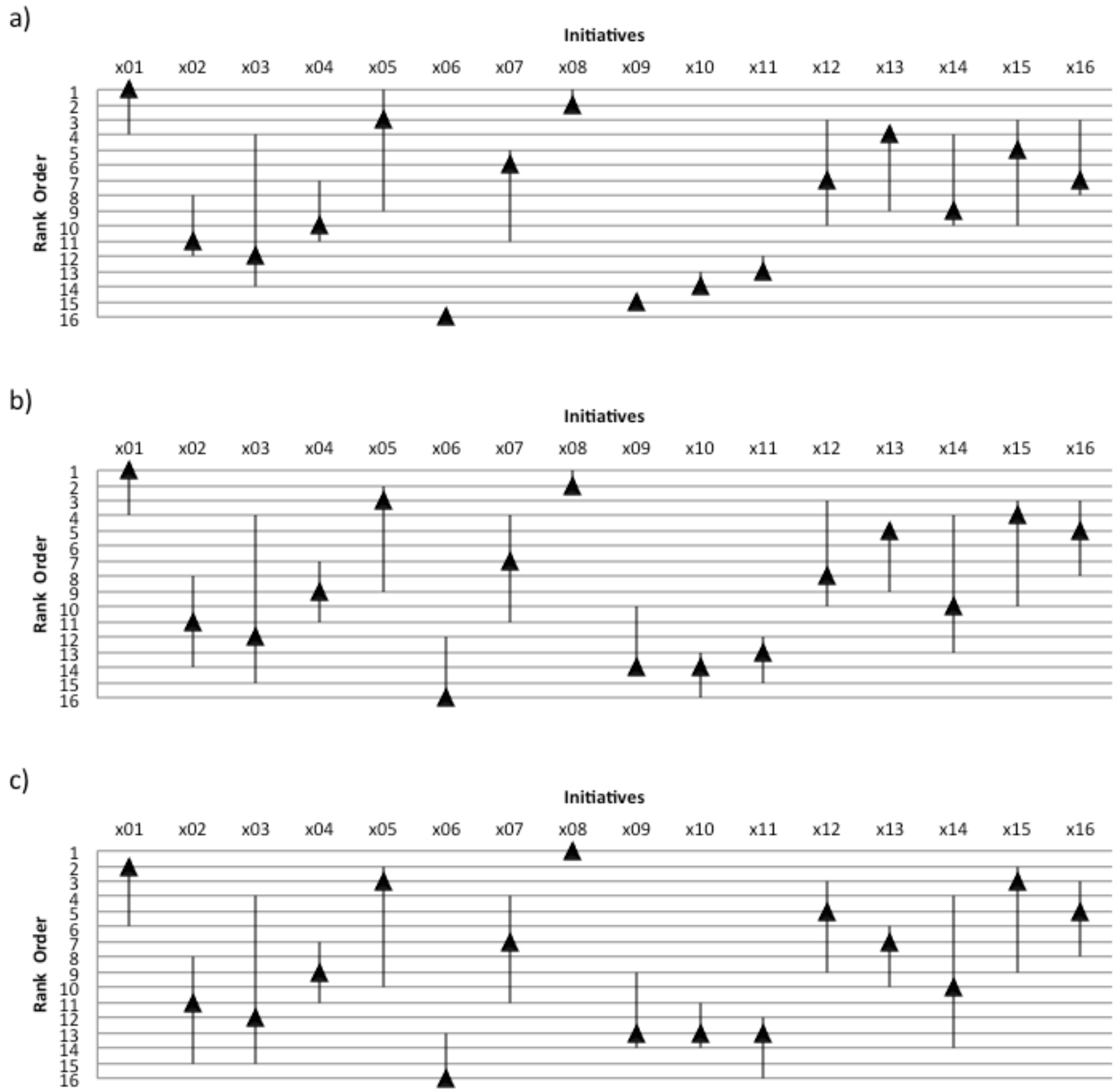

Figure 49. Frame I² initiative rankings using a) minimum, b) average, and c) maximum GHG emissions estimates from the literature. The triangle represents the rank in the baseline scenario and the high and low bars indicate the change in rank under the scenarios of preference changes.

Table 50. Description of differences in scenario disruptiveness when using minimum, average, and maximum LCA GHG emissions estimates.

	Spearman Coefficient			Disruptiveness Rank		
	Min	Avg	Max	Min	Avg	Max
s_{01}	0.9647	0.8721	0.8265	5	2	3
s_{02}	0.9044	0.9279	0.9412	3	5	5
s_{03}	0.8632	0.8779	0.8676	2	4	4
s_{04}	0.7368	0.7221	0.7338	1	1	1
s_{05}	0.9603	0.8765	0.8265	4	3	3

B.2 Sensitivity to energy demand estimates

Table 51 describes the minimum, average, and maximum life cycle fossil energy demand estimates for the sixteen biofuel feedstocks analyzed in Chapter 7. Table 52 describes how using minimum and maximum estimates, as opposed to average, changes the assessment of how each initiative addresses the energy demand criterion. Figure 50 compares the baseline ranking of initiatives (represented by the triangle) under when using minimum, average, and maximum fossil energy demand values. The bars indicate how the initiative ranking changes under the scenarios, revealing initiative robustness. Table 53 describes the disruptiveness of scenarios based on the calculated Spearman coefficient.

Table 51. Life-cycle fossil energy use of biofuel pathways presented as the minimum, maximum, and average of the results from referenced studies.

Feedstock	Process	LC Fossil Energy Demand (MJ in/MJ out)			References
		min	baseline (average)	max	
Agricultural residue	Biochemical	0.024	0.110	0.196	Karlsson, et al. (2014)
Algae	Hydroprocessing (lipid extraction)	0.534	0.802	0.942	Wang (2014); Lokesh et al. (2015)
	HTL	0.450	0.508	0.571	Delrue et al. (2013)
Camelina	Hydroprocessing	0.400	0.587	0.864	Wang (2014); Lokesh et al. (2015); Shonnardet al. (2010)
Corn stover	Biochemical	0.120	0.146	0.172	Wang (2014); Dunn et al. (2013)
Forest residue	Pyrolysis	-0.71	-0.127	0.202	Wang (2014); Karlsson, et al. (2014)
Jatropha	Hydroprocessing	0.570	0.679	0.859	Wang (2014); Lokesh et al. (2015);Trivedi et al. (2015)
Miscanthus	Gasification and FT	0.137	0.137	0.137	Wang (2014)
Municipal solid waste	Gasification and FT	0.417	0.417	0.417	Pressley et al. (2014)
Palm oil	Hydroprocessing	0.300	0.391	0.483	Wang (2014); Trivedi et al. (2015)
Rapeseed	Hydroprocessing	0.500	0.545	0.576	Wang (2014); Dufour & Iribarren (2012); Trivedi et al. (2015)
Sorghum	Biochemical	0.630	0.893	1.300	Olukoya et al. (2015)
Soybean	Hydroprocessing	0.279	0.385	0.510	Wang (2014); Dufour & Iribarren (2012); Trivedi et al. (2015)
Switchgrass	Gasification and FT	0.070	0.119	0.161	Wang (2014); Daystar et al. (2014); Trivedi et al. (2015)
Tallow	Hydroprocessing	0.432	0.432	0.432	Dufour & Iribarren (2012)
Wood	Pyrolysis	0.300	0.300	0.300	Han et al. (2013)
Yellow grease	Hydroprocessing	0.314	0.314	0.314	Serber et al. (2014); (Dufour and Iribarren 2012)

Table 52. Change in assessment of Frame I² feedstock initiative to fossil energy demand criterion based on minimum and maximum LCA literature estimates. Gray shading indicates where the assessment changes from that made using average LCA estimates.

Feedstock	Average-based Assessment	Minimum-based Assessment	Maximum-based Assessment
Agricultural residue	Strongly addresses	Addresses	Strongly addresses
Algae	Does not address	Does not address	Does not address
Camelina	Does not address	Somewhat addresses	Does not address
Corn stover	Addresses	Addresses	Strongly addresses
Forest residue	Strongly addresses	Strongly addresses	Strongly addresses
Jatropha	Does not address	Does not address	Does not address
Miscanthus	Strongly addresses	Addresses	Strongly addresses
Municipal solid waste	Somewhat addresses	Somewhat addresses	Somewhat addresses
Palm oil	Somewhat addresses	Somewhat addresses	Somewhat addresses
Rapeseed	Somewhat addresses	Does not address	Somewhat addresses
Sorghum	Does not address	Does not address	Does not address
Soybean	Addresses	Somewhat addresses	Somewhat addresses
Switchgrass	Strongly addresses	Addresses	Strongly addresses
Tallow	Somewhat addresses	Somewhat addresses	Somewhat addresses
Wood	Addresses	Somewhat addresses	Addresses
Yellow grease	Addresses	Somewhat addresses	Addresses

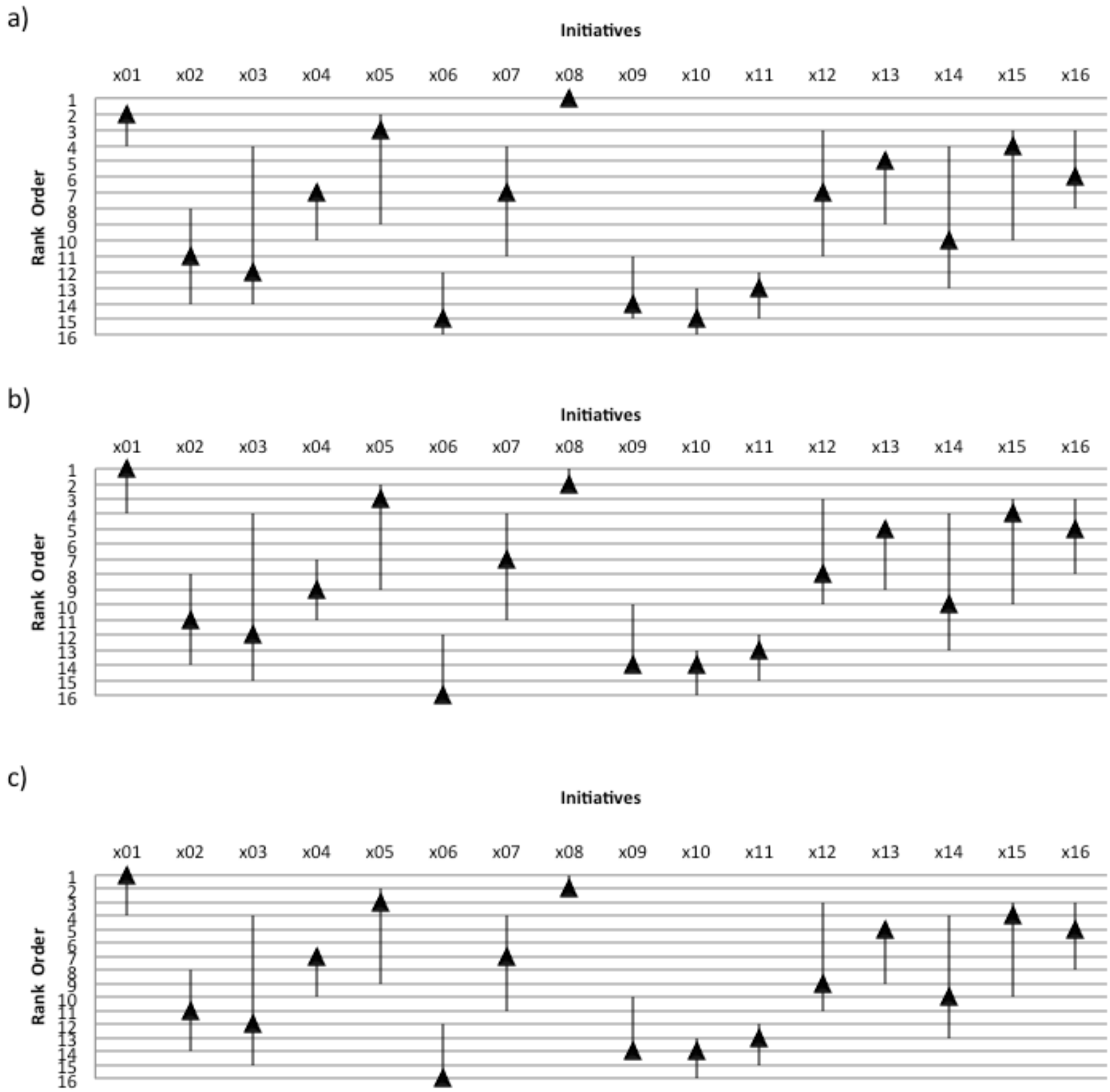

Figure 50. Frame I^2 initiative rankings using a) minimum, b) average, and c) maximum fossil energy demand estimates from the literature. The triangle represents the rank in the baseline scenario and the high and low bars indicate the change in rank under the scenarios of preference changes.

Table 53. Description of differences in scenario disruptiveness when using minimum, average, and maximum LCA fossil energy demand estimates.

	Spearman Coefficient			Disruptiveness Rank		
	Min	**Avg**	**Max**	**Min**	**Avg**	**Max**
s01	0.8824	0.8721	0.8735	4	2	3
s02	0.9471	0.9279	0.9265	5	5	5
s03	0.8456	0.8779	0.8706	2	4	2
s04	0.7426	0.7221	0.7118	1	1	1
s05	0.8824	0.8765	0.8779	4	3	4

B.3 Sensitivity to water use estimates

Table 54 describes the minimum, average, and maximum life cycle fresh water demand estimates for the sixteen biofuel feedstocks analyzed in Chapter 7. Table 55 describes how using minimum and maximum estimates, as opposed to average, changes the assessment of how each initiative addresses the energy demand criterion. Figure 51 compares the baseline ranking of initiatives (represented by the triangle) under when using minimum, average, and maximum water use values. The bars indicate how the initiative ranking changes under the scenarios, revealing initiative robustness. Table 56 describes the disruptiveness of scenarios based on the calculated Spearman coefficient.

Table 54. Life-cycle fresh water use of biofuel pathways presented as the minimum, maximum, and average of the results from referenced studies.

Feedstock	Water consumption (L blue water/ L fuel)			Reference
	min	baseline (average)	max	
Agricultural residue	6	6	6	Chiu & Wu (2012)
Algae	36	456	1818	Gerbens-Leens, et al. (2014); Wu et al. (2014)
Camelina	-	-	-	
Corn stover	22	860	1697	Chiu & Wu (2012); Wu et al. (2014)
Forest residue				
Jatropha	21	8,267	16,515	Staples et al. (2013); Wu et al. (2014)
Miscanthus	667	745	822	Wu et al. (2014; Zhuang et al. (2013)
Municipal solid waste	-	-	-	
Palm oil	-	-	-	
Rapeseed	0	2,505	22,545	Gerbens-Leens et al. (2014); Staples et al. (2013); Wu et al. (2014)
Sorghum	1,250	1,250	1,250	Wu et al. (2014)
Soybean	0	1,724	7,455	Chiu & Wu (2012); Gerbens-Leens et al. (2014); Staples et al. (2013); Wu et al. (2014)
Switchgrass	129	1,065	2,000	Staples et al. (2013); Zhuang et al. (2013)
Tallow	-	-	-	
Wood	2	31	61	Chiu & Wu, (2013); Wu et al. (2014)
Yellow grease	-	-	-	

Table 55. Change in assessment of Frame I[2] feedstock initiative to fresh water use criterion based on minimum and maximum LCA literature estimates. Gray shading indicates where the assessment changes from that made using average LCA estimates.

Feedstock	Average-based Assessment	Minimum-based Assessment	Maximum-based Assessment
Agricultural residue	Strongly Addresses	Addresses	Strongly Addresses
Algae	Addresses	Addresses	Somewhat addresses
Camelina	Does Not Address	Does Not Address	Does Not Address
Corn stover	Somewhat Addresses	Addresses	Somewhat Addresses
Forest residue	Addresses	Addresses	Addresses
Jatropha	Does Not Address	Addresses	Does Not Address
Miscanthus	Addresses	Somewhat addresses	Addresses
Municipal solid waste	Strongly Addresses	Strongly Addresses	Strongly Addresses
Palm oil	Does Not Address	Does Not Address	Does Not Address
Rapeseed	Does Not Address	Strongly addresses	Does Not Address
Sorghum	Somewhat Addresses	Does not address	Somewhat Addresses
Soybean	Somewhat Addresses	Strongly addresses	Does not address
Switchgrass	Somewhat Addresses	Somewhat Addresses	Somewhat Addresses
Tallow	Strongly Addresses	Strongly Addresses	Strongly Addresses
Wood	Addresses	Strongly addresses	Addresses
Yellow grease	Strongly Addresses	Strongly Addresses	Strongly Addresses

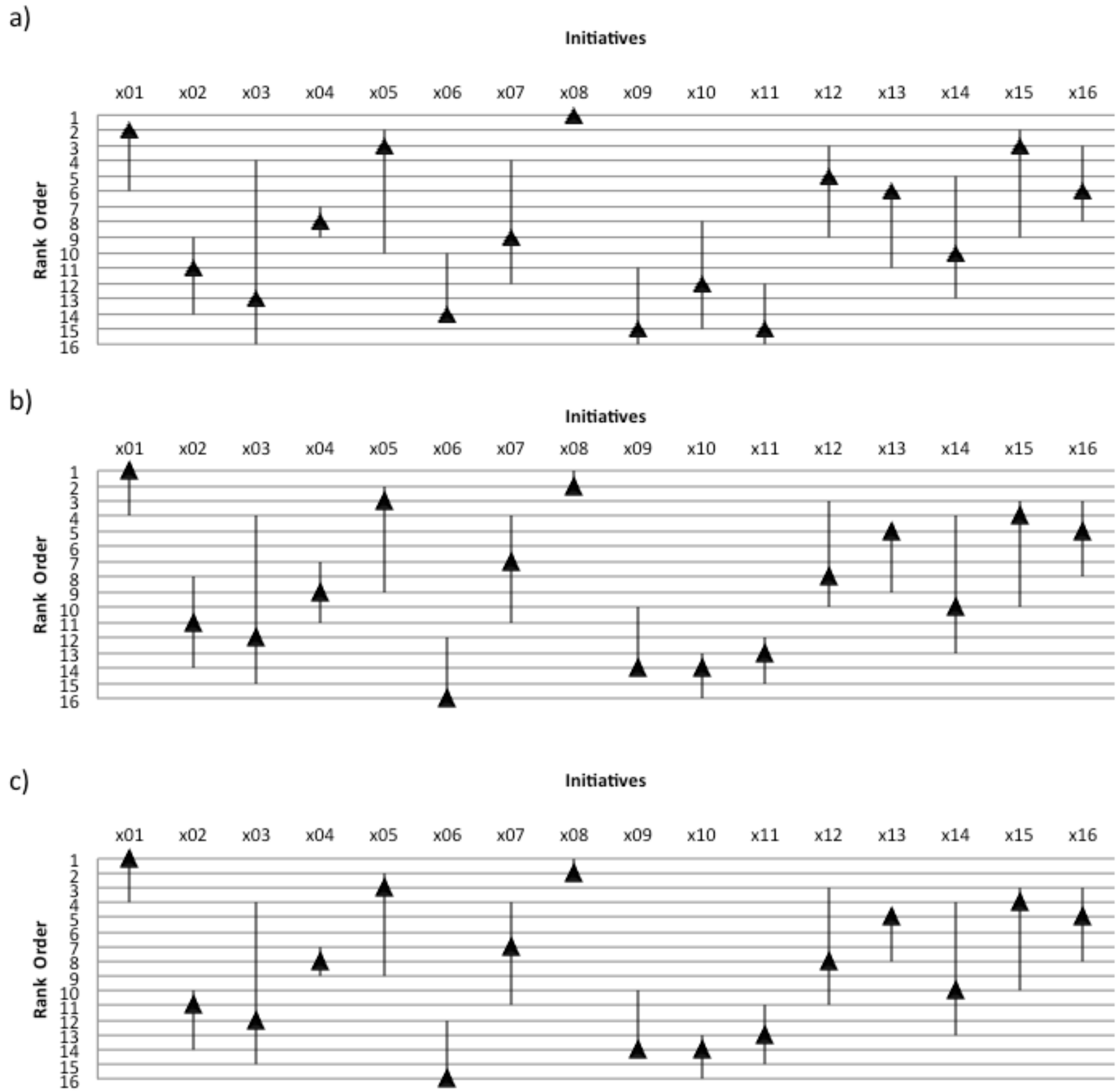

Figure 51. Frame I² initiative rankings using a) minimum, b) average, and c) maximum fresh water use estimates from the literature. The triangle represents the rank in the baseline scenario and the high and low bars indicate the change in rank under the scenarios of preference changes.

Table 56. Description of differences in scenario disruptiveness when using minimum, average, and maximum LCA fresh water demand estimates.

	Spearman Coefficient			Disruptiveness Rank		
	Min	**Avg**	**Max**	**Min**	**Avg**	**Max**
s_{01}	0.8235	0.8721	0.8735	4	2	2
s_{02}	0.9471	0.9279	0.9368	5	5	5
s_{03}	0.8191	0.8779	0.8926	2	4	4
s_{04}	0.7309	0.7221	0.7265	1	1	1
s_{05}	0.8221	0.8765	0.8779	3	3	3

B.4 Sensitivity to cost estimates

Table 57 describes the minimum, average, and maximum life cycle cost estimates for the sixteen biofuel feedstocks analyzed in Chapter 7. Table 58 describes how using minimum and maximum estimates, as opposed to average, changes the assessment of how each initiative addresses the energy demand criterion. Figure 52 compares the baseline ranking of initiatives (represented by the triangle) under when using minimum, average, and maximum cost values. The bars indicate how the initiative ranking changes under the scenarios, revealing initiative robustness. Table 59 describes the disruptiveness of scenarios based on the calculated Spearman coefficient.

Table 57. Life-cycle fresh water use of biofuel pathways presented as the minimum, maximum, and average of the results from referenced studies.

Feedstock	Process	Estimated Cost ($/L)			Reference
		min	baseline (average)	max	
Agricultural residue	Biochemical and gasification	0.28	0.30	0.33	Laser et al. (2009)
Algae	Hydroprocessing (lipid extraction)	0.40	3.19	10.02	Agusdinata et al. (2011); Carter (2012); Quinn & Davis (2015)
	HTL	1.25	2.52	3.28	Davis et al. (2014); Jones et al. (2014); Quinn & Davis, (2015)
Camelina	Hydroprocessing	0.79	0.90	1.02	Agusdinata et al. (2011)
Corn stover	Gasification and FT	0.79	1.06	1.27	Agusdinata et al. (2011); Swanson et al. (2010)
Forest residue	Gasification and FT	1.42	1.42	1.42	Brown et al. (2014)
	Pyrolysis	0.97	1.04	1.11	Li et al. (2015)Li
Jatropha		-	-	-	
Miscanthus		-	-	-	
Municipal solid waste	Biochemical	0.04	0.11	0.18	Holtzapple et al. (1999)
Palm oil		-	-	-	
Rapeseed		-	-	-	-
Sorghum		-	-	-	-
Soybean	Hydroprocessing	0.12	0.76	1.23	Pearlson et al. (2013); Seber et al. (2014)
Switchgrass	Gasification and FT	0.52	1.05	1.45	Agusdinata et al. (2011); Laser et al. (2009)
Tallow	Hydroprocessing	1.04	1.08-	1.14	Seber et al. (2014)
Wood	Gasification and FT	1.12	1.32	1.52	Agusdinata et al. (2011)
Yellow grease	Hydroprocessing	0.85	0.93	1.04	Seber et al. (2014); Glisic & Orlović (2014); Laser et al. (2009)

Table 58. Change in assessment of Frame I^2 feedstock initiative to cost criterion based on minimum and maximum LCA literature estimates. Gray shading indicates where the assessment changes from that made using average LCA estimates.

Feedstock	Average-based Assessment	Minimum-based Assessment	Maximum-based Assessment
Agricultural residue	Strongly addresses	Strongly addresses	Strongly addresses
Algae	Somewhat addresses	Somewhat addresses	Does not address
Camelina	Strongly addresses	Addresses	Strongly addresses
Corn stover	Addresses	Addresses	Addresses
Forest residue	Somewhat addresses	Somewhat addresses	Somewhat addresses
Jatropha	Does not address	Does not address	Does not address
Miscanthus	Somewhat addresses	Does not address	Does not address
Municipal solid waste	Strongly addresses	Strongly addresses	Strongly addresses
Palm oil	Does not address	Does not address	Does not address
Rapeseed	Does not address	Does not address	Does not address
Sorghum	Does not address	Does not address	Does not address
Soybean	Strongly addresses	Strongly addresses	Addresses
Switchgrass	Addresses	Addresses	Somewhat addresses
Tallow	Addresses	Somewhat addresses	Addresses
Wood	Somewhat addresses	Somewhat addresses	Somewhat addresses
Yellow grease	Addresses	Addresses	Addresses

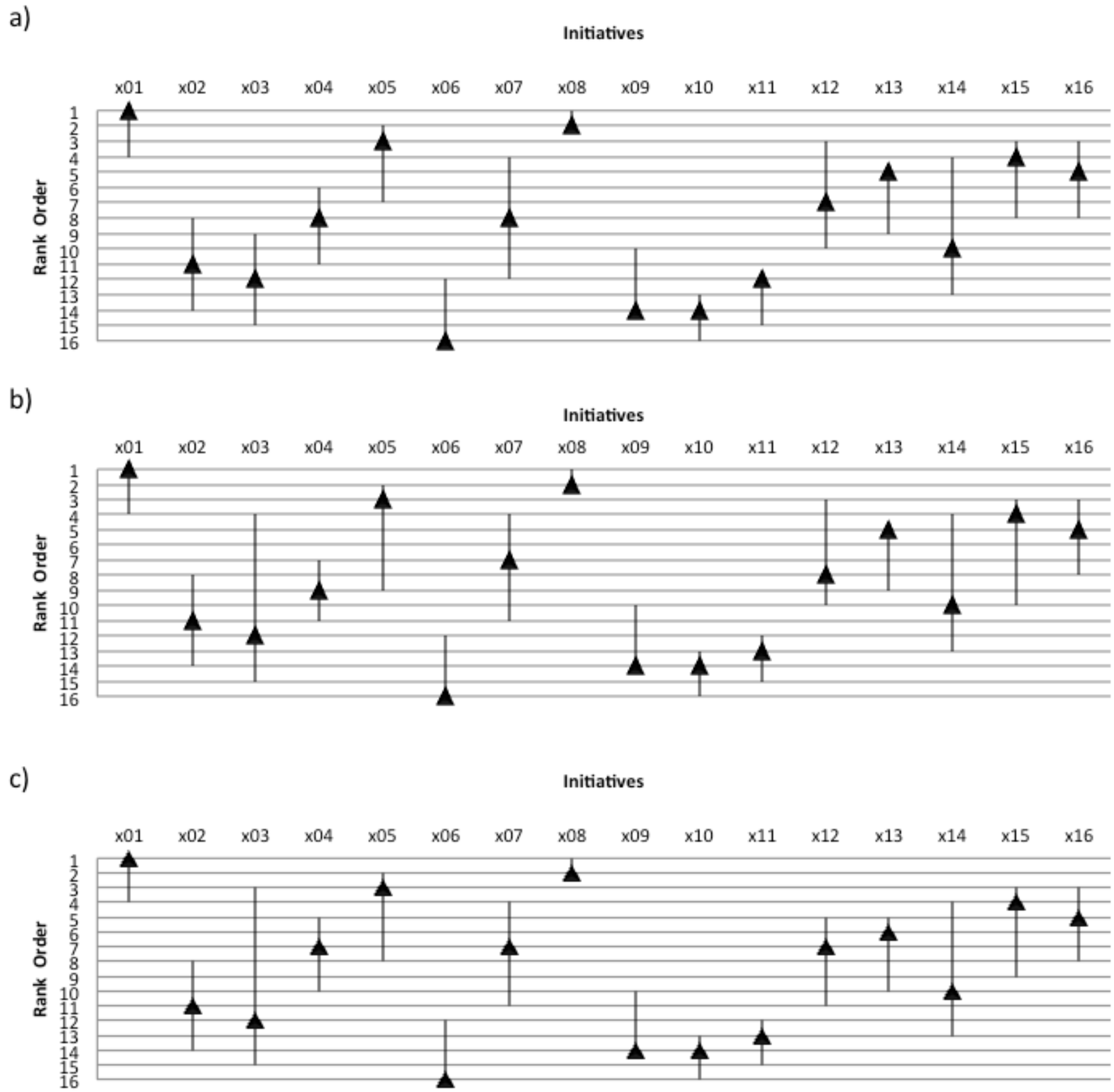

Figure 52. Frame I^2 initiative rankings using a) minimum, b) average, and c) maximum cost estimates from the literature. The triangle represents the rank in the baseline scenario and the high and low bars indicate the change in rank under the scenarios of preference changes.

Table 59. Description of differences in scenario disruptiveness when using minimum, average, and maximum life cycle cost estimates.

	Spearman Coefficient			Disruptiveness Rank		
	Min	Avg	Max	Min	Avg	Max
s01	0.8515	0.8721	0.8721	1	2	3
s02	0.9382	0.9279	0.9368	5	5	5
s03	0.8632	0.8779	0.8632	3	4	2
s04	0.8809	0.7221	0.7294	4	1	1
s05	0.8559	0.8765	0.8765	2	3	4

APPENDIX C: SUPPORT OF MODEL VALIDATION

This appendix contains response to questions developed to infer the usefulness of the proposed method of resilience analytics for the case study of aviation biofuels. These questions were submitted to stakeholders from the Commonwealth Center for Advanced Logistics Services (Tom Polmateer) and the Commercial Aviation Alternative Fuels Initiative (Rich Altman). Due to time conflicts, only responses from Tom Polmateer of CCALS were received. This appendix contains the questions and responses referred to in Chapter 10, Section 10.2.

Survey administered to CCALS representative Tom Polmateer to support validation of the methods. Feedback was received November 12, 2015.

Questions to Support Validation of Methodology:

Q1. Do you think these methods offer an improvement on current approaches to selecting aviation biofuel pathways?

A1. Current biofuel research approaches are feedstock technology centric and do not meet stakeholders and investors need in a constantly changing environment. Virginia supported an ethanol plant that closed in 2010 before it started production citing "unfavorable market conditions." Subsequent after action reviews state the planners failed to consider a resilient and robust supply chain. From a strategic planning perspective, the proposed methodology is a definite improvement and value added for evaluating alternatives and reducing risk.

Q2. Do you think these methods proved useful in analyzing the tradeoffs between various aviation biofuel pathways?

A2. We are already seeing the direct interest in and the value of these methods with respect to a research grant from the Center for Innovative Technology (CIT) to evaluate the tradeoffs for aviation drop-in biofuels feedstock pathways in Virginia. Sufficient production and transportation capabilities are critical but there is also significant political emphasis on Chesapeake Bay environmental quality and a Delmarva Peninsula region life cycle assessment (LCA). These methods support, sustain and guide our R&D tradeoff strategy for this award.

Q3. Do you think these methods proved useful in identifying disruptive emergent conditions to inform strategic planning for aviation biofuel industry development?

A3. Recently a Delegate from the General Assembly asked what made this biofuel research effort different. The previous efforts failed to consider and plan for disruptive emergent market conditions and the significance of the feedstock supply-chain. Their planning assumption was build a biofuel plant and they will come. The Commercial Aviation Alternative Fuels Initiative (CAAFI) is supporting this R&D effort because the methods are proving useful to inform strategic planning.

Q4. Do you think the use of multi-criteria analysis is useful in this context?

A4. The scenario based preference analysis methods of iterative problem framing are proving to be very useful in this biofuel context. When stakeholders are engaged in multi-criteria analysis defining criteria, scenarios, preferences, and risks there is immediate value for resilience analytics. For stakeholders, this effort may also be the first time they consider the broader comprehensive strategic context that sets the foundation for the scenario analysis.

Q5. Do you think the use of scenario analysis is useful in this context?

A5. The scenario analysis brings the broad multi-criteria analysis into focus defining the effort in terms stakeholders recognize and appreciate. In discussions with the USDA, their state planning experts were most engaged during the scenario based preferences modeling effort because this step directly related to their day-to-day efforts.

Survey administered to CCALS representative Tom Polmateer to support validation of the methods. Feedback was received November 12, 2015.

Q6. Do you think the use of life cycle assessment and other supplementary analytical tools are useful in this context?

A6.The LCA is key to resilience analytics for a complex system that values the changing landscape of uncertain budget priorities, technology disruptions, environmental concerns and sustainability. Insights from LCAs provide additional data to reduce the level of subjectivity and inform the overall analysis. Supplemental analytical tools resonate with decision makers, provide opportunity for additional context and further address their concerns.

Q7. Do you think taking an iterative approach, whereby the scenario-based preferences model is updated with current information and knowledge increases the usefulness of the methods?

A7. Updating the sub-systems model is fundamental to the credibility and usefulness of this methodology. Strategic planning requires an updated iterative approach to meet stakeholders changing needs and preferences as new information becomes available over time. Stakeholders value the system-of systems approach that is transparent, flexible, and documents the thought process. This model requires understanding and communicating the system interdependencies and interactions.

Q8.Do you think this method is generalizable to other applications, specifically for strategic planning for R&D in other fields?

A8. There is a direct correlation to DoD's Cost-Benefit Analysis (C-BA) preference method for evaluating alternatives. To make the case for a R&D proposal or project the U.S. Army requires the proponent to weigh the total expected costs against the total expected benefits over the near, far, and life cycle timeframes from an enterprise perspective. Costs and benefits include quantifiable and non-quantifiable emergent domains such as opportunity, perception, risk/uncertainty, political capacity, availability, quality and morale. This strategic planning C-BA "case" is updated regularly with current information to increase its usefulness for senior leaders. The resilience analytics lessons are directly transferable to the cost-benefit analysis method.

APPENDIX D: SUPPORTING SOFTWARE

This appendix contains screenshots of the Excel-based tool built for analysts and stakeholders to model scenario-based preferences. Visual Basic (VBA) was used to insert buttons that function to create tabs for each initiative where LCA data can be entered. The VBA script is also included in this appendix, with comments to explain the purpose of each command and to facilitate future adaptations.

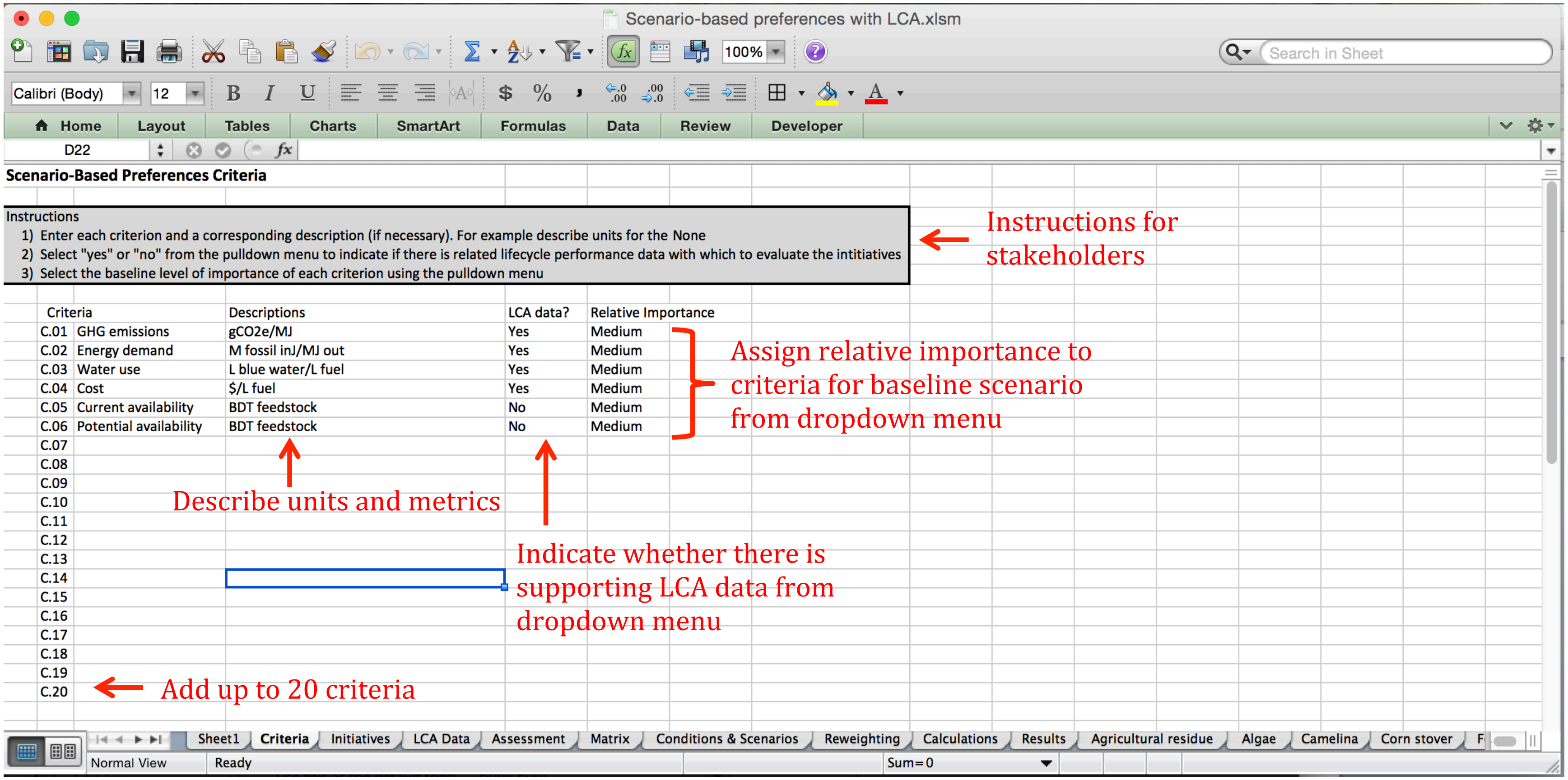

Figure 53. Screenshot of "Criteria" tab in Excel-based decision support tool with LCA integration.

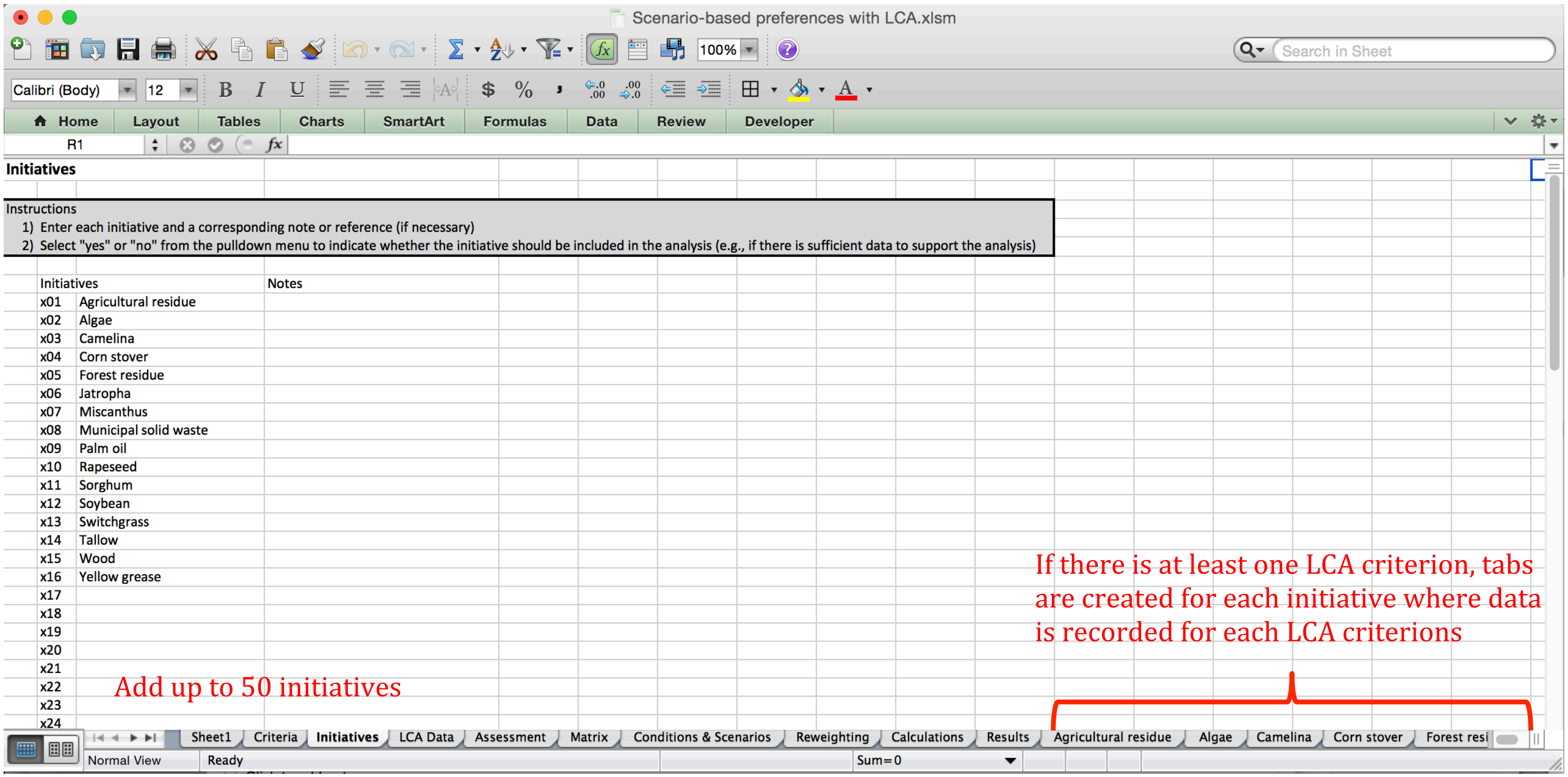

Figure 54. Screenshot of "Initiatives" tab of Excel-based decision support tool with LCA integration.

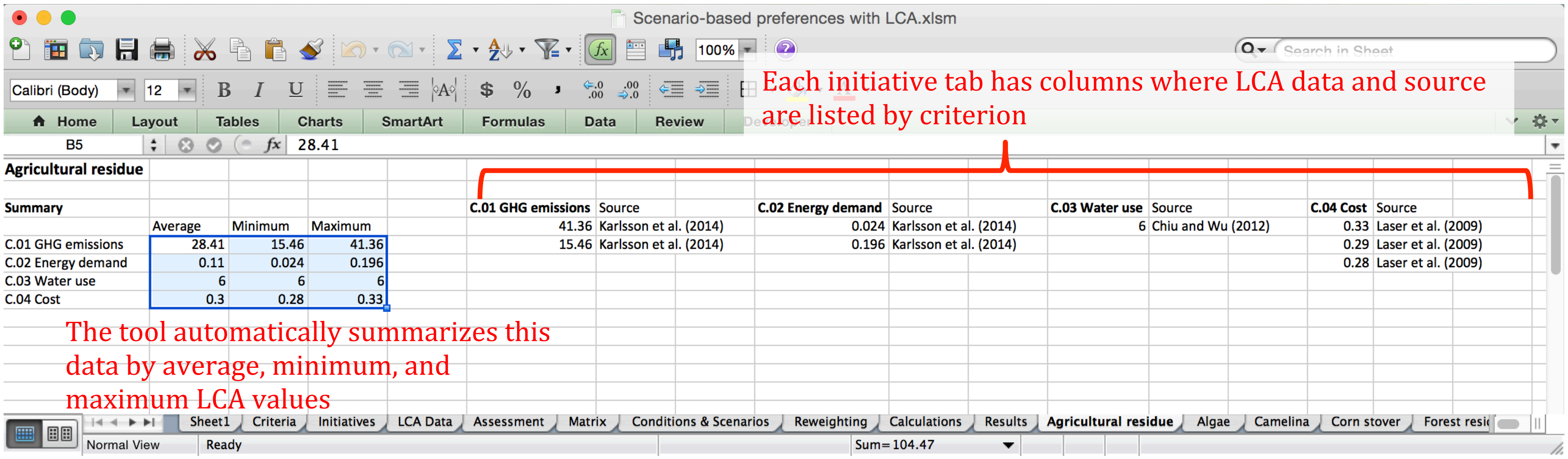

Figure 55. Screenshot of example initiative tab in Excel-based decision support tool. The tab is created to allow user to enter LCA data, which is automatically summarized by average, minimum, and maximum LCA value

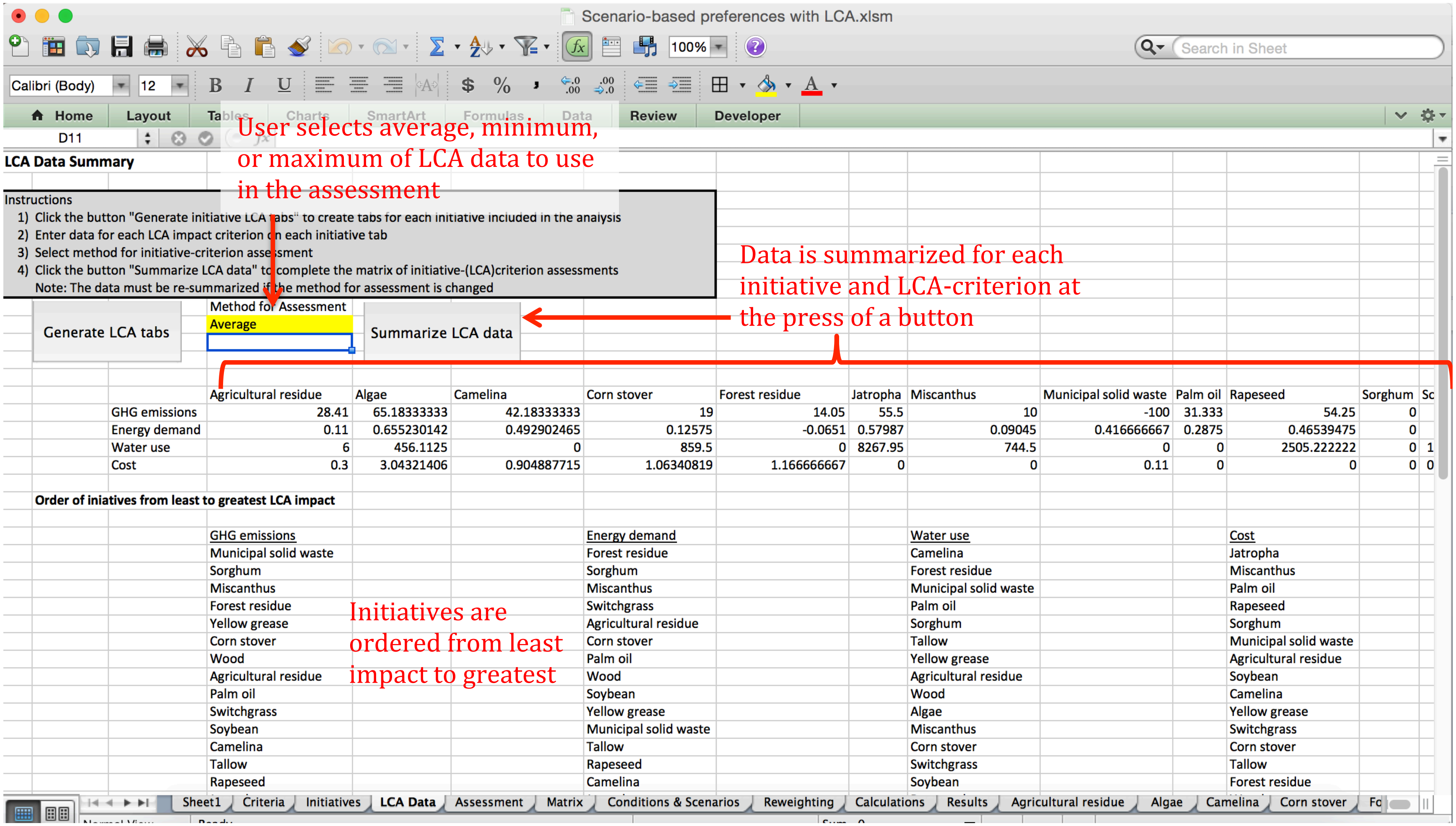

Figure 56. Screenshot of "LCA Data" tab of Excel-based decision support tool. At the press of a button, LCA data is summarized for all initiatives based on the "Method for Assessment" (i.e., average, minimum, maximum) selected by the user.

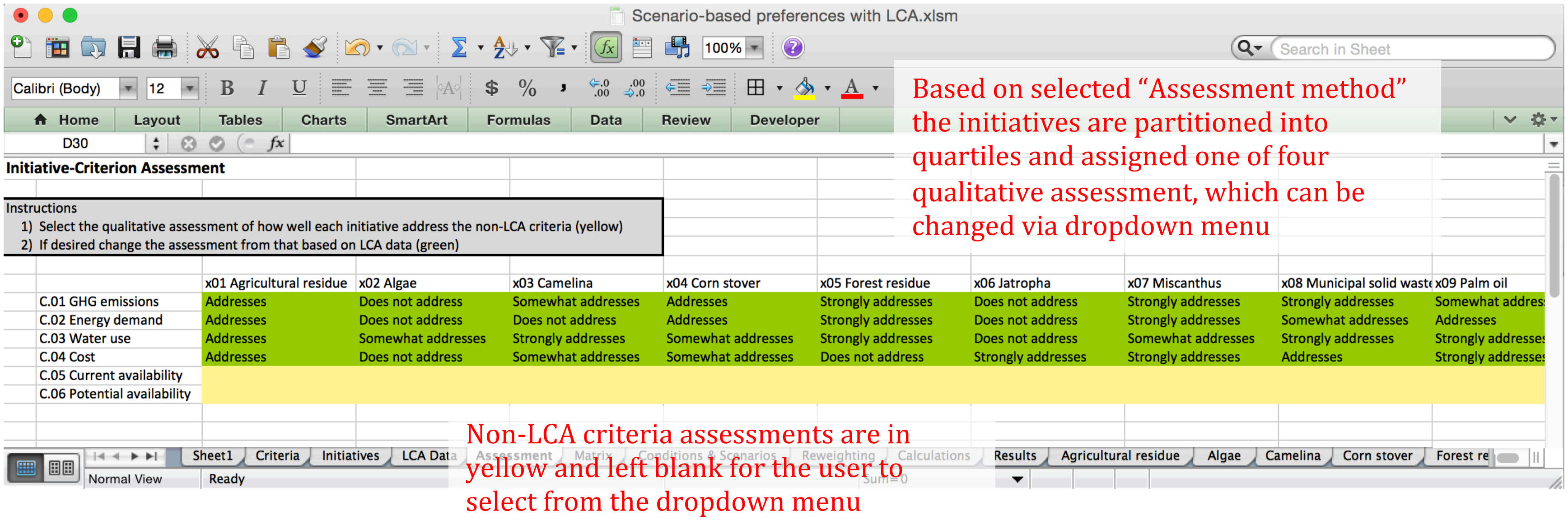

Figure 57. Screenshot of "Assessment" tab of Excel-based decision support tool, where qualitative assessments are automatically made for LCA-criteria for all initiatives.