Landscape Analysis Framework for Low Carbon Energy

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As the era of "cheap" oil comes to a close in the early 21st century and the negative environmental impacts of fossil fuels are better understood, key stakeholders of the aerospace industry are investing billions to develop low carbon alternative jet fuels. The aviation industry spans political, industrial, economical, and cultural boundaries like few other industries. As such, the number of stakeholders involved in the development, selection, and transition to alternative aviation energy sources is expansive and diverse. Therefore, a comprehensive framework is needed to consider the various drivers of the low carbon energy landscape. This research developed a landscape analysis framework that initially considers 31 short and long-term low carbon energy technologies. The framework enables a user to rapidly explore and compare how well these alternatives are predicted to meet the hypothetical needs of 19 key industry stakeholders and perform in 26 market adoption metrics. Visualization techniques are applied to enable the identification of trends and energy alternative characteristics. The framework may be expanded by users to consider further stakeholders and energy alternatives. Additionally, dynamic functionality supports studies by users from diverse backgrounds and industries. The framework was used to conduct an example analysis from the perspective of NASA strategic decision makers. The case study illustrates the types of results, insights, and tradeoffs the framework may support.

I. Introduction

NEGLECTING the flurry of vehicle efficiency and alternative fuel research programs briefly started in response to the 1973 oil crisis, the contemporary to develop for low carbon energy alternatives was publically marked by the *Energy Policy Act of 2005*.[1] This piece of legislation characterized a tipping point in the nation's mood towards the growing energy problems of the 21st century and the associated environmental, economic, and strategic impacts that were becoming more well understood. The act began a new era of research programs focused on vehicle efficiency and alternative fuels. Most significantly, the United States committed to produce and utilize 7.5 billion gallons of biofuel annually by 2012 (a goal that was expanded to 36 billion gallons by 2022 through the *Energy Independence and Security Act of 2007*).[2] These policies provided financial incentives through public grant programs and tax breaks for alternative energy research, certification, and production.

Within two years of the Energy Policy Act of 2005, numerous government agencies, including NASA, developed their own programs to support the development and implementation of alternative and low carbon fuels. As the government's largest consumer of jet fuel, the United States Air Force (USAF) became the first group to act through the issuance of the *Office of the Secretary of Defense Assured Fuels Initiative* in 2006. This initiative set ambitious plans for the air force to certify and transition their aircraft to synthetic jet fuel blends.[3] NASA quickly followed suit with the release of a study titled *Alternative Fuels and Their Potential Impact on Aviation* at the International Council of the Aeronautical Sciences (ICAS) meeting in late 2006. In this study, NASA reached similar conclusions to the USAF that synthetic fuels made from coal, natural gas, or biomass were the most promising short-term alternative fuel options.[4] Finally, through the establishment of the *Commercial Aviation Alternative Fuels Initiative*

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(CAAFI) in late 2006, as well as the creation of the *International Air Transport Association Sustainable Alternative Fuels Strategy*,[5] the commercial sector embarked upon organized synthetic jet fuel development as well.

Each of the programs described above represent a commitment of substantial resources for alternative fuel research and development. Since 2006, the NASA Aeronautics Mission Research Directorate (ARMD) has operated six major programs related to alternative fuel development, particularly synthetic jet fuel: AAFEX, AAFEX II, Glenn Alternative Fuel Research Laboratory, Glenn Low NOx Fuel Flexible Combustion, ACCESS I, and ACCESS II.[6] In lockstep with NASA developments, private entities and government interests worldwide have explored opportunities and developed infrastructure for dozens of alternative fuels. Through the efforts of these early investors, the industry has narrowed down the acceptable short-term energy alternatives and is relatively united in the pursuit of synthetic jet fuels. Two types of synthetic jet fuels have been certified for use in commercial aircraft as 50% blends with petroleum fuel; up to four more synthetic jet fuels are expected to be certified by 2020.[7]

Despite industry alignment for a short-term alternative, there is not currently alignment on a long-term, low carbon energy alternative. As hydrocarbon fuels, synthetic jet fuels will continue to release greenhouse gas (GHG) emissions during flight. If the ultimate sector goal is carbon neutral missions, then synthetic fuels must eventually be replaced or supplemented (it is of note that a carbon neutral *lifecycle* is possible with synthetic fuels). Although a variety of electric vehicle research and flight tests occurred over the past few decades, these represent diverse research directions and investments which lack a central organization coordinating a joint effort.

In 2008 the aviation industry publically adopted a sweeping plan for commercial flight lifecycle carbon emissions through the *Aviation Industry Commitment to Action on Climate Change* at the 3rd Aviation & Environmental Summit.[8] This commitment emphasized the urgency of the search for low carbon energy source alternatives. With dozens of entities pursuing multiple alternative energy technologies for aviation, a comprehensive landscape analysis is critical to support effective strategic leadership and investment by entities such as NASA. The analysis must not only identify the potential low carbon energy alternatives, but it must also provide a means to evaluate each option against a diverse set of technical, political, and commercial criteria and adoptions challenges.

Recognizing these needs, the proposed framework was dynamically structured to allow for a variety of analyses and interpretations dependent upon the requirements of the user. This paper details the development of the framework and its subsequent utilization in a case study of NASA low carbon energy research opportunities. The purpose of this case study is to convey the types of results, insights, and tradeoffs the framework may support.

II. Landscape Analysis Framework Development

The primary deliverable of this research is a landscape analysis framework for low carbon energy. This framework is formatted as a dynamic spreadsheet where users interact with two inter-related analyses:

A) A *stakeholder analysis* evaluates 31 low carbon energy alternatives based upon value-driven criteria from 19 key aviation stakeholders. The framework allows new alternatives and stakeholders to be added by the user in addition to those provided.
B) An *adoption challenge analysis* considers eight categories of low carbon energy alternatives with respect to 26 industry metrics to identify potential challenges or barriers to market entry. Additional categories and metrics may also be added.

Sections A and B provide further information about the assumptions and processes employed to develop each of these analyses in the framework.

A. Stakeholder Analysis

The stakeholder toolset was designed through a value-driven approach. Four primary stakeholders and 15 secondary stakeholders were identified that had substantial interests in the aviation industry adoption of low carbon alternatives. The stakeholders considered are listed in

Table I. Aviation stakeholders. *The initial set of stakeholders included in the low carbon framework grouped by major category and sub category.*

Primary	*Airline Industry*	Commercial Airlines
		Corporate Aviation
		Airports
	Regulation	FAA
Secondary Stakeholders	*United States Government*	NASA
		DoD
		DoE
		USPS
		TSA
		EPA
		ITA
	Airline Support Industry	Airframers
		Engine Manufacturers
		Aeronautics Communities
		Oil and Fuel Companies
	Other	Passengers and Clients
		Political Reaction
		International Adoption
		Agriculture Industry

Table I along with their subcategory and major category groupings.

It should be noted that this initial group of stakeholders is not considered to be complete; rather, these stakeholders were selected to provide a representative view of the low carbon alternative landscape to enable initial trending insights for the case study.

The "value" criteria of each stakeholder were defined based upon information available in the public domain including current programs, press releases, and planned developments. Future studies should elicit criteria from each stakeholder through interviews, surveys, or other methods.

Twenty-one "emerging low carbon drop-in fuel" options, or short-term alternatives, were identified and divided into two general categories:

A) "Biofuels" are currently in production in the ground transportation industry and have substantially different chemical and performance properties than petroleum jet fuels. Biofuels include alcohols and fatty acid methyl esters.
B) "Synthetic Jet Fuels" have nearly identical chemical and performance characteristics to petroleum jet fuel.

Ten "revolutionary low carbon concepts" were also evaluated as long-term, low carbon energy options. A second set of stakeholder value criteria were used that more accurately represented the projected long-term (2050 time frame) stakeholder criteria. These long-term energy options were evaluated independently from the short-term options. The framework also accounted for the potential impact of transition from the short-term solution to the proposed long-term solution. These ten futuristic energy alternatives were broken into two primary categories:

Table II. Low carbon energy alternatives for aviation. *The 31 low carbon energy concepts considered in the framework case study organized by tiers of classification and near-term or far-term implementation.*

Emerging Low Carbon Drop-in Fuels	Biofuels	Soy Methyl Ester	
		Rapeseed Methyl Ester	
		Ethanol (CF)	
		Ethanol (NCF)	
	Synthetic Jet Fuels	FT	SPK (Coal/natural gas)
			SPK (CF)
			SPK (NCF)
			SKA (Coal/natural gas)
			SKA (CF)
			SKA (NCF)
		HEFA	SPK
			SKA
		SKM/ DSHC	SKM-SPK (CF)
			SKM-SPK (NCF)
			DSHC-SKA
		ATJ	SPK (CF)
			SPK (NCF)
			SKA (CF)
			SKA (NCF)
		Other	CH-SKA (NCF)
			HDCJ-SKA
Revolutionary Low Carbon Concepts	Brayton Cycle	Liquid Natural Gas	
		Liquid Hydrogen	
		Hybrid Electric	
		Hybrid Electric - Fuel Cell	
		Nuclear	
	Full Electric	Onboard Energy Storage	
		Fuel Cell	
		Onboard Solar Cell	
		Nuclear	
		Power Beaming	

A) "Brayton Cycle" alternatives that utilize the traditional gas turbine engine operating cycle in a novel way.
B) "Full electric" alternatives that solely use electricity to power electric propulsors (electricity may be stored or produce onboard the aircraft in a variety of ways).

The 31 low carbon energy concepts are provided in Table II grouped by their major and minor categories. The categories and acronyms for the synthetic fuels are further discussed in Section III. The labels CF and NCF represent renewable fuels produced from "consumable feedstock" and "non-consumable feedstock", respectively. At this time it is appropriate to comment that while the aviation industry and relevant political entities have indicated that alternative fuels produced from consumable feedstocks will not be considered as viable jet fuel alternatives, this framework and case study included these alternatives for completeness.

Each of the 31 low carbon energy sources were evaluated individually with regard to how well they fulfilled the presumed requirements of each of the 19 stakeholders. (In a full application of this framework, a survey would be distributed to stakeholder representatives to elicit the utility of each alternative according to the values of that stakeholder.) A Likert-type scale was used to assign a 0, 3, or 6 to an energy option if it met none of the stakeholder requirements, some of the stakeholder requirements, or all of the stakeholder requirements, respectively. The primary rationale driving the assignment of the rankings for each stakeholder was documented in a centralized reference sheet for each energy alternative to foster user inspection. A brief description and discussion of the primary challenges facing each energy alternative was also included in these reference sheets.

A Likert-type rating was developed to represent each of the 19 stakeholders for every energy alternative. A total "score" was calculated (on a 100 point scale) that described the overall "goodness of fit" of the energy source with respect to the criteria of all stakeholders, subject to relevance weighting to reflect user preferences. The spreadsheet is dynamic in that these stakeholder "weighting factors" may be changed at any time to influence the alternative score; this capability is intended to enable customizable analyses where the relevance of each stakeholder is "tuned" by the user.

B. Adoption Challenge Analysis

The adoption challenge analysis considered 26 metrics that characterize potential challenges an alternative energy source for aviation would face for global market entry; these 26 metrics are provided as Table III. The metrics represent six major potential challenge areas, or "drivers."

A) *Infrastructure* – Does the energy alternative require significant changes to the legacy infrastructure?
B) *Implementation* – Are the development and introduction timeline and costs appropriate?
C) *Business* – Is the business case of the energy alternative competitive with current fuels?
D) *Energy* – Are the production costs and scale of the energy alternative competitive with current fuels?
E) *Environment* – Are environmental concerns of the stakeholders improved through the use of the energy alternative?
F) *Other* – Are safety, energy independence, and political support improved by the energy alternative?

The adoption challenge analysis was organized similarly to the stakeholder study. A one to nine Likert-type scale was used to represent qualitative adoption challenge information for each alternative energy category as quantitative information with respect to the 26 metrics. Table IV displays the criteria and displays how the criteria varied depending upon which driver the metric was a subset of.

Table III. Adoption challenge drivers and metrics. *The 26 adoption challenge metrics are organized into the six major challenge areas, or "drivers."*

Infrastructure	*1*	Vehicle Architecture
	2	Engine Architecture
	3	Energy Infrastructure
	4	Airport Design
Implementation	*5*	2020 Implementation
	6	2050 Implementation
	7	Development Cost
	8	Development Risk
	9	Defined Certification Route
	10	Global Adoption
Business	*11*	Vehicle Operating Expense
	12	Initial Cost of Vehicle
	13	Fulfills current conOps
	14	Business Adoption
Energy	*15*	Production Scalability
	16	Production Volatility
	17	Production Diversity
	18	Long Term Availability
	19	Inter-Sector Competition
Environment	*20*	Mission Carbon Emissions
	21	Lifecycle Carbon Emissions
	22	Other Lifecycle Emissions
	23	Reduction of Fossil Fuel Reliance
Other	*24*	Safety
	25	Energy Independence
	26	Political Resistance

Table IV. Adoption challenge Likert-type ranking system. *Two separate evaluation systems were employed, based on a Likert-type scale, to characterize the adoption challenge of each alternative energy source category. The evaluation type was dependent upon the relevant driver of the adoption challenge.*

Evaluation Type	#	Criteria	Relevant Drivers
Jet-A Comparative	*1*	> 50% better	Business Energy Environment Other
	3	10-50% better	
	5	Within 10% (same)	
	7	10-50% worse	
	9	> 50% worse	
Relative Investment Required	*1*	Negligible investment	Infrastructure Implementation
	3	Company investment	
	5	Sector investment	
	7	Nation investment	
	9	Global investment	

III. Case Study Discussion

Based upon the stakeholder weighting factors and the Likert-type rankings developed for the case study, the stakeholder analysis tool identified six synthetic jet fuel options (each from a different production process) that scored over 90. This indicates that these fuel types meet the stakeholders' requirements well and may suggest these top fuels show promise as short-term petroleum alternatives. Investigation of the Likert-type ranking rationale suggests that the primary challenge facing the ultimate success of these six synthetic jet fuels is the production of sufficient quantity of low cost, responsibly grown feedstocks. The energy demands of the aviation industry are such that no single synthetic jet fuel could likely be produced at a scale to meet US, let alone worldwide, demand.[4] The stakeholder analysis tool also revealed trends that suggest various configurations of Brayton cycle hybrid-electric or full-electric vehicles (with or without fuel cells) are the leading long-term alternative energy options for aviation.

The adoption challenge analysis suggested the 1st and 2nd generation synthetic fuels face the fewest barriers to entry. The hybrid and full-electric energy options faced the second fewest barriers to entry. It was identified that synthetic fuels were most prepared for market adoption as these fuels were already in service on some airlines. A lower barrier to entry for more-electric aircraft in comparison to liquid hydrogen and liquid natural gas vehicles was evident through this case study. This trend may suggest the industry could benefit from a focus of long-term alternative energy resources on more-electric aircraft development as the technology may be more readily adopted.

These high level trends in the low carbon energy landscape analysis case study are discussed in depth through the remainder of this section. More detail is provided on the feasibility, challenges, and potential industry impacts each of the proposed alternative fuel categories. It should be considered that this case study is primarily intended to display the capabilities of the low carbon energy landscape framework. The analysis presented is based upon publically available information and the interpretation of stakeholder values and adoption barriers by the lead author. More extensive subject matter expert input could enhance the value and accuracy of the results produced by the case study and better validate the framework. Ideally, an expert representing each stakeholder would be engaged to populate the stakeholder analysis and a group of experts familiar with the technologies and industry would review the adoption challenge analysis. The individuals elicited to populate the adoption challenge analysis should be independent from the stakeholders to prevent biasing of the results based upon stakeholder preferences.

A. Biofuels

Four biofuels were considered in the case study. Each fuel was in production and use by the ground transportation market. As a group, these four fuels received total stakeholder scores well below the lowest scoring synthetic jet fuel. This was primarily a result of the inability of these fuels to act as "drop-in" alternatives due to their substantially different chemical and performance properties. This factor, combined with a lack of production scalability and competition with the ground vehicle market, also resulted in biofuels receiving a low adoption score.

However, although it is unlikely biofuels will directly play a role as additives or fuel sources for future large aircraft (ethanol may have potential for general aviation aircraft), these four biofuels may all be further refined into synthetic jet fuels. In this case, primary concerns will be competition with the existing ground transportation biofuel industry and political concerns as these fuels are primarily produced from commercial foodstuffs such as corn. With increasing petroleum prices, biofuels are becoming economically competitive.[9]

B. Synthetic Jet Fuels

Synthetic jet fuels were identified in this case study as the most promising short-term alternative fuel for the aviation industry. However, the validity of these fuels as low carbon alternatives depends upon the feedstock and refinement processes used. Furthermore, production scalability to meet aviation needs is a significant concern.

1. Synthetic Jet Fuel Trends

This analysis considered five categories of synthetic jet fuels that corresponded to how the fuels are produced:

A) Fischer-Tropsch (FT) fuels
B) Hydrotreatment of Esters and Fatty Acids (HEFA) fuels
C) Metabolically derived Kerosene (SKM) fuels
D) Alcohol to Jet (ATJ) fuels
E) Other fuels including Catalytic Hydrothermolysis (CH) and Hydrotreated Depolymerized Cellulosic Jet (HDCJ)

Within each of these categories, multiple manufacturers have developed proprietary refinement processes that utilize unique feedstocks or produce fuels with slightly different properties. Based upon this analysis, the most desired properties of the aviation sector are the inclusion of aromatics, the use of renewable feedstocks, and the use of non-foodstuff (non-consumable) feedstocks.

Recognizing these three properties, a trend was identified in the first four synthetic jet fuel groupings: scores generally increased in the stakeholder analysis from the first fuel listed to the last fuel listed. The fuels are listed within each group from the "first generation" fuel of that type to the most recent derivative. This trend may suggest that recent development of synthetic jet fuels have produced more beneficial fuel derivatives. This trend may be visualized through Figure 1 where blue arrows indicate increasing scores as the technology improved.

A similar trend was identified in the adoption challenge analysis where the 2nd generation synthetic fuels faced fewer barriers to entry than the 1st generation counterparts. This was primarily due to the inclusion of aromatics in the 2nd generation fuels that made them fully drop-in without the need for blending with petroleum jet fuel.

Synthetic Jet Fuels	FT	SPK (Coal/natural gas)	65.8
		SPK (CF)	72.4
		SPK (NCF)	82.9
		SKA (Coal/natural gas)	64.5
		SKA (CF)	80.3
		SKA (NCF)	90.8
	HEFA	SPK	85.5
		SKA	93.4
	SKM/ DSHC	SKM-SPK (CF)	64.5
		SKM-SPK (NCF)	77.6
		DSHC-SKA	93.4
	ATJ	SPK (CF)	72.4
		SPK (NCF)	85.5
		SKA (CF)	80.3
		SKA (NCF)	93.4
	Other	CH-SKA (NCF)	93.4
		HDCJ-SKA	96.1

Figure 1. Case study synthetic fuel score trends. *The scores of each synthetic jet fuel category tend to increase down the column. This trend displays the progression from 1st generation to more advanced fuel processes which add aromatics (SKA vs. SPK) and utilize non-consumable feedstock (NCF vs. CF).*

Two of the primary criticisms of synthetic jet fuels concern questionable environmental benefits and a perceived lack of scalability.[10] Through Figure 1 it may be seen that FT fuels that use fossil fuels as feedstock received lower scores as they failed to meet the GHG emission requirements of many stakeholders. Interestingly however, these fuels are some of the only alternatives to fully meet the goals of the Department of Defense (DoD), in part because the availability and price of these fuels is not unduly affected by crop yield.

The only non-fossil fuel based synthetic to fully meet the DoD requirements is Hydrotreated Depolymerized Cellulosic Jet (HDCJ). This process may use woody, lignocellulosic biomass as a feedstock. Woody biomass is a fairly stable resource and reduces risk to production even during poor growing years or natural disasters.

Despite meeting the requirements of nearly every stakeholder, even the top ranked fuels were not anticipated to satisfy the aeronautics community at large. This was primarily because it is unlikely that synthetic fuels produced from renewable biomass could meet the full industry demand. Early studies have suggested there is simply not enough available land to produce the required feedstock, let alone to do this without negative environmental or economic effects.[4] It may be possible that aeronautics energy demands could be met through the development of multiple synthetic fuel types produced from diverse feedstock sources adapted for local cultivation around the globe. However, the agricultural industry currently faces barriers to entry due to unstable political attitude and poor economic incentives. These are challenges which plague the alternative fuel industry as a whole.[11]

It was observed that FT fuels do not generally met the requirements for international adoption, despite having a market presence for decades. This trend is observed for FT fuels because in order to be economically viable, FT refineries must be built to massive scale. The most recent FT plant was built in Qatar by Shell at a cost of 18 billion dollars.[12] While one of the goals of low carbon energy production is to diversify production locations and countries, the expense of FT plants may limit production to select locations by wealthy countries or entities.

Figure 1 also displays the impact of the "food vs. fuel" stigma surrounding some renewable biofuel and synthetic jet fuels on stakeholder value for that fuel type. Fuels that utilize corn, soybean, or other consumables as feedstock are not accepted by the aviation industry as viable alternatives. Additionally, countries where arable land is at a premium are unlikely to readily adopt these fuels. It should be noted that although production through non-consumable feedstocks does not use foodstuffs directly, these fuels will also face resistance if their "energy crops" utilize previously forested land or compete with foodstuff land. Therefore, the development of energy crops that are able to grow in previously undesirable land, or other feedstock alternatives such as algae and lignocelluloses, is necessary.[13]

Figures 2 and 3 provide a visualization of the stakeholder and adoption challenge analyses and conduct comparisons between alternative energy types. The radar plots suggest that 2nd generation synthetic fuels may be more promising low carbon energy alternatives than other short-term options along most metrics and for most stakeholders.

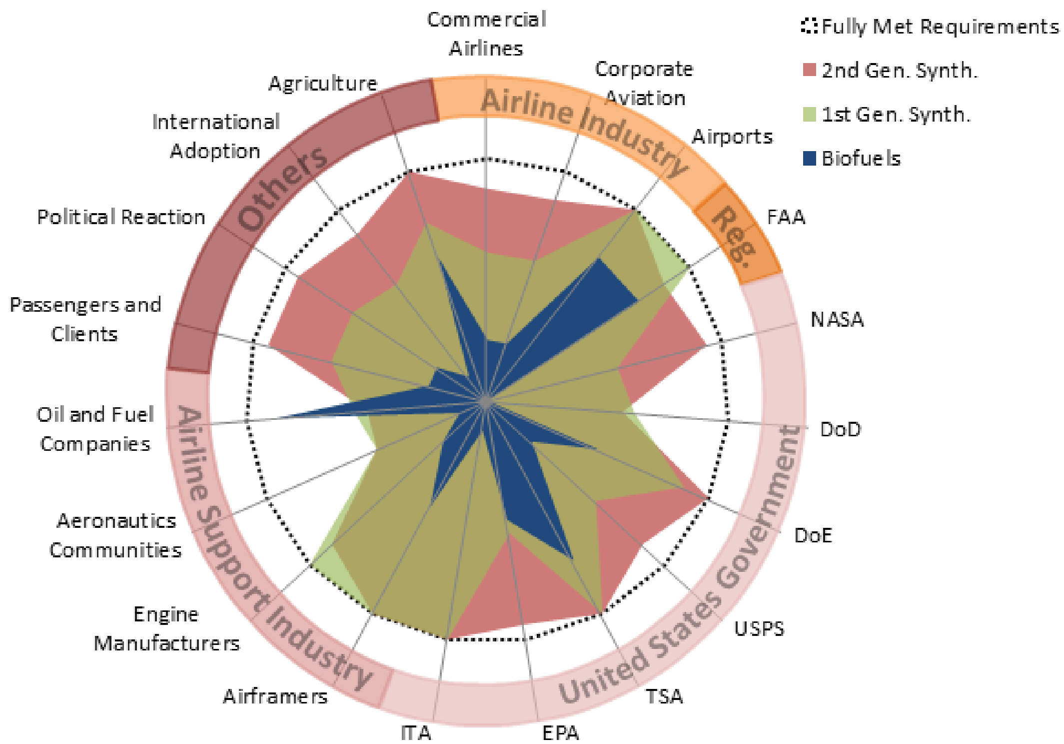

Figure 2. Short-term low carbon alternatives stakeholder analysis comparison. *The synthetic fuels meet substantially more stakeholder requirements than biofuels and appear as the most promising choice to be the short term aviation alternative.*

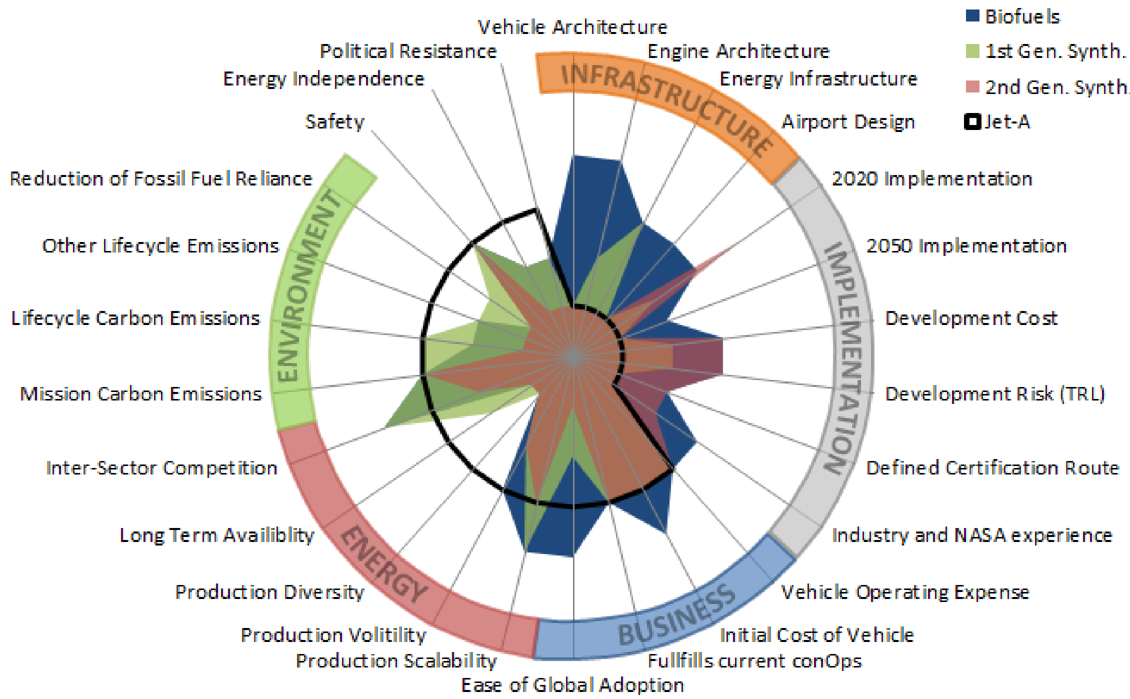

Figure 3. Short-term low carbon alternatives adoption challenge comparison. The *2nd generation synthetic fuels face the lowest overall barrier to market entry. They perform especially well in the environmental and infrastructure drivers. Biofuels face infrastructure and business challenges while the 1st generation synthetics fuels perform the poorest in the environmental adoption challenges.*

2. Fischer-Tropsch (FT) Synthetic Jet Fuels

The Fischer-Tropsch process was the first commercially utilized method to develop synthetic jet fuels. Sasol, a South African energy corporation, constructed the first FT plant in 1952 and has been producing a majority of the country's diesel fuels since. In 1999 the company received certification for the first "drop-in" synthetic jet fuel. The primary driver behind Sasol development of the FT process was the lack of oil reserves and an abundance of coal and natural gas reserves within South Africa.[14]

Following Sasol's leadership, multiple major corporations around the world have developed or are developing FT plants that utilize coal and natural gas as feedstocks due to their availability in economies of scale. However, since these FT processes utilize large amounts of energy for refinement of fossil fuel feedstocks, life-cycle carbon emissions may be up to 2.5 times those of petroleum unless carbon capture systems are used.[15,16] Therefore, while providing an alternative to oil, fossil fuel FT processing without carbon capture is not a viable low carbon option. FT conversion of biomass has been proven in lab testing, but no world-scale facilities have been built at this time.[17]

A primary issue with FT production is the high initial capital and market risk assumed in order to construct and operate the facility. Unlike other processes, in order to be economically viable FT refineries are of massive scale. This may lead to difficulty securing enough consistently available biomass feedstock as well as providing stable value return considering the volatility of world oil prices.

The 1st generation FT fuels do not contain aromatics. This results in sealing issues which prohibits their use as pure drop-in fuels. These fuels must be blended with traditional jet fuel to reach acceptable aromatic content. The top scoring FT fuel is produced from non-consumable biomass feedstock in a new FT process that adds aromatics. This 2nd generation FT fuel will be fully drop-in and certification was underway at the time of writing.

As the first entrant into the synthetic jet fuel field, FT is furthest in development and has the most momentum behind it. Major energy companies, such as Shell and Sasol, have constructed multi-billion dollar FT facilities. The DoD and Department of Energy (DoE) have provided substantial support for R&D and construction cost sharing for FT production. The fuel was certified in 2009 for use in commercial aircraft as a blended fuel with petroleum jet fuel up to a 50:50 ratio.

Fischer-Tropsch alternative jet fuels show promise to play a key role in the market. They were the first mass produced alternative aviation fuels and have begun to diversify aviation sourcing. Based upon the landscape analysis case study, a user may deduce that it is in the best interest of the aviation community to promote the transition from fossil fuel based FT fuel to biomass FT fuels and other more environmentally friendly production processes due to GHG emissions reduction as a driving criterion. However, it may also be recognized that some stakeholders place high value on energy security and may resist transition from readily available fossil fuel based FT synthetics.

3. Hydroprocessed Esters and Fatty Acids (HEFA) Synthetic Jet Fuels

In 2011 HEFA fuels became the second type of synthetic jet fuel to receive certification for use in aircraft in up to a 50:50 blend with petroleum jet. The HEFA process utilizes a feedstock of plant oils, animal fats, or used cooking oil. Depending upon the source of the plant oils, this process may use renewable resources that do not impact commercial food production.

Unlike FT production, HEFA facilities are smaller in scale at potentially 1/10th the land area footprint (and cost). The smaller size of HEFA facilities mitigates multiple FT challenges such as obtaining sufficient feedstock locally, resource and product transportation, and required initial capital. It is possible these plants may be able to co-locate with existing ethanol or petroleum refineries, or perhaps even at airport locations.[18]

The primary challenges facing HEFA fuels are scalability issues and cost competitiveness. The production of sufficient, responsibly sourced feedstock may limit the eventual scope of HEFA production. However, 2nd generation advanced energy crops and algae show potential to fulfill the aviation community demand. Without government subsidies or continued increases in oil prices, HEFA is unable to compete economically. Initial HEFA fuels do not contain aromatics. However, new processes add aromatics to produce a superior product.[19]

Similar to FT fuels, HEFA fuels benefitted from earlier development than most other alternatives. The DoD purchased substantial quantities of HEFA for Air Force aircraft, and multiple manufacturers currently operate or are developing production facilities.

4. Metabolically derived Kerosene (SKM)/Direct Sugar to Hydrocarbon (DSHC) Synthetic Jet Fuels

Metabolically derived Kerosene (SKM) refers to the production of synthetic jet fuels through the use of biological processes such as bacterial or yeast fermentation. Direct Sugar to Hydrocarbon (DSHC) is the most well developed SKM technique at this time. No SKM processes are currently certified as "drop-in" fuels, although DSHC produced by Amyris received certification for up to 10% blending in 2014. Both SKM and DSHC fuels contain aromatics that provide benefits over the 1st generation HEFA and FT fuels which do not have aromatics.[20]

Biological processes will produce chemically homogeneous fuels. Unlike petroleum fuels that may contain numerous chemical species, SKM fuels present some new challenges and questions to the gas turbine industry regarding the flammability range and various other combustion properties. Due to the potential to customize microbes for particular feedstocks, SKM fuels may offer flexibility in production facility sizing and the feedstocks accepted. The responsible sourcing of feedstock is also an issue for SKM production, similar to other synthetic jet fuels. If matured, SKM processes could reduce GHG emissions and potentially support global adoption.

Significant SKM research has been a fairly recent development in the alternative fuels market. While one DSHC method has moved through the certification process, because each company has a proprietary biological agent it is likely that the independent certification of each process may be necessary. The market currently has a mix of established and startup companies pursuing SKM development.

Direct Sugar to Hydrocarbon fuels received one of the highest scores from the stakeholder analysis due to its near-term availability, the inclusion of aromatics, and a heterogeneous chemical composition of the fuel which avoids potential problems characteristic of other SKM alternatives.

5. *Alcohol to Jet (ATJ) Synthetic Jet Fuels*

Alcohol to Jet is a promising synthetic jet fuel production process that will open the industry to alcohol feedstocks such as ethanol. The production of the feedstock alcohol may occur through a variety of chemical or biological processes. Advances in alcohol production will allow for cellulosic feedstocks as well. The production of ATJ fuel benefits from a more readily available feedstock base than most other synthetic fuels, as well as a relatively low cost of initial investment. Production facility size is variable from small, local scale facilities co-located with farms or airports to world-scale facilities.[21]

Initial ATJ processes produce synthetic fuels without aromatics; this limits industry application. These fuels are expected to be the next synthetic jet fuel to receive certification. A second generation of ATJ processes that produce fuels that include aromatics have been co-developed and may be certified as soon as 2015.[7] Since ATJ does not use biological processes to move directly from feedstock to final product, but rather a chemical process for the final refinement, it does not experience some of the homogeneous and consistency issues of some SKM's.

Alcohol to Jet recently became a promising opportunity in the aviation industry and received interest from the DoD, major airframers, and the energy production industry. Multiple international companies are developing facilities and processes suggesting ATJ will likely ramp up production quickly following certification. The ATJ variants produced from non-consumable feedstocks scored highly in the stakeholder analysis of the case study (with the aromatics inclusive fuel most highly rated for ATJ). If the process to develop ATJ from cellulosic material is matured, these fuels are likely to experience significant increases in market potential and industry impact.

6. *Other Leading Processes for Synthetic Jet Fuel Production*

Two other production processes are currently seeking certification to produce commercial synthetic jet fuel. Catalytic Hydrothermolysis (CH) is a recent entrant into the synthetic fuel market. Development was driven primarily by the work of a single company: Applied Research Associates. The fuel utilizes similar feedstock to HEFA fuels but processes the fuel through a more economical and less energy intensive process. Catalytic Hydrothermolysis fuels contain aromatics. The fuel is currently in production by ReadiFuels and Chevron Lummus Global. Certification of CH fuels is in progress.[22]

The second process is called Hydrotreated Depolymerized Cellulosic Jet (HDCJ), or pyrolysis. The process is unique in that it utilizes lignocellulosic biomass, such as forest residues and agricultural waste, to develop hydrocarbon fuel with aromatics. Advantageously, HDCJ is a low carbon fuel that utilizes feedstocks considered as waste, and it may be suitable for production in retrofitted legacy petroleum refining facilities. Due in part to these characteristics, HDCJ received the highest stakeholder score for any short-term alternative in the case study. Certification is expected in 2015, and major challenges include sufficient feedstock collection and economic competitiveness. This fuel is a relatively new entrant into the market spearheaded by KiOR and Honeywell UOP.

C. Revolutionary Low Carbon Concepts

The short-term, low carbon synthetic jet fuels may offer opportunities to reduce the lifecycle emissions of the aviation industry; some synthetic fuels may even have the potential for lifecycle "carbon fixing" removing more carbon from the atmosphere during feedstock growth than is released when the fuel is burned. However, as all drop-in fuels rely on the burning of hydrocarbons at altitude for aircraft flight, all short-term synthetic fuels may not sufficiently reduce the *mission* CO_2 emissions to meet stakeholder needs.

Therefore, a wide variety of long-term, low carbon energy alternatives and propulsion solutions for aircraft were reviewed through this case study. The criteria of each stakeholder were modified to reflect long-term goals, and the fuels were evaluated based upon a 2050 entrance into service expectation. No clear path to long-term adoption was identified in the aeronautics community. Aircraft face unique challenges that may prohibit or limit the application of the more-electric technologies that are coming to dominate the ground based motor vehicle long-term strategies.

1. Revolutionary Low Carbon Concept Trends

The energy sources explored as revolutionary low carbon concepts were highly varied in form, function, and industry impact. Unlike the short-term alternatives, which displayed trends clearly identifying the top fuels as those with aromatics produced from a renewable resources, the "best" long-term option was not clearly identifiable.

The landscape analysis case study indicated that due to the safety and political regulations of aviation, all options utilizing nuclear fuels or "power beaming" were not in line with stakeholder needs. Similarly, as shown in Figure 4, systems that necessitate the transition of the industry to a cryogenic fuel scored poorly. Cryogenic fuels did not perform well by the metrics utilized in the framework because they are expensive to produce, limited in either lifespan or production capacity, and require complete infrastructure transition.

Brayton Cycle	Liquid Natural Gas	27.6
	Liquid Hydrogen	51.3
	Hybrid Electric*	86.8
	Hybrid Electric - Fuel Cell*	81.6
	Nuclear	15.8
Full Electric	Onboard Energy Storage	75.0
	Fuel Cell*	81.6
	Onboard Solar Cell	75.0
	Nuclear	10.5
	Power Beaming	14.5

Figure 4. Long-term low carbon energy options. *Red options are not viable; green are energy storage technology limited; orange are fuel cell limited; yellow is incapable of stand-alone operation.*

This leaves five propulsion concepts that may be viewed as various shades of hybrid-electric or full-electric propulsion. Each proposed alternative contains some low TRL technologies that may prohibit the ultimate success of implementation by 2050. Unlike liquid hydrogen, liquid natural gas, power beaming, or nuclear propulsion (which all received low scores), the more-electric concepts generally received higher scores. This was in part because they may be slowly introduced into the industry alongside conventional infrastructure. More-electric technologies may be prototyped and adopted beginning with small, general aviation aircraft to reduce market risk.

Of the four electric options down-selected, the most significant division between them is the use of fuel cells (presumably run on hydrocarbon fuels) for energy conversion, and those alternatives which use other energy storage mechanisms. Shown in Figure 4, the analysis was inconclusive about whether fuel cells appear to be a superior technology over energy storage devices. More research into high density energy storage and fuel cell technologies must be conducted before this framework could support a strategic industry decision to choose a fuel cell or energy storage device path. Investments and incremental development may ultimately lead to full-electric vehicles as hybrid-electric aircraft are improved.

Figure 5, the stakeholder visualization, implies that more-electric aircraft outperform the next most highly ranked energy alternative, liquid hydrogen (LH_2), in numerous stakeholder metrics. The adoption challenge plot displayed as Figure 6 enables further insights. Full-electric and LH_2 each have ideal environmental performance and a relatively low barrier to entry in terms of energy. However, these alternatives face significant infrastructure and implementation challenges, as well as moderate business barriers. The hybrid-electric options face lower infrastructure and implementation barriers to entry on average, however they do not perform as well environmentally.

2. Brayton Cycle Derivatives

The concept of revolutionary, low carbon, Brayton cycle propulsion is to modify the fundamental architecture or operation of gas turbine engines to reach efficiency levels unreachable with conventional technology. These technologies move beyond incremental innovation in materials and component improvements, but rather involve a radical transition to new energy sources or hybrid engine architectures.

Of the Brayton cycle options in the case study, the two hybrid-electric architectures received the most promising scores. The hybrid-electric option utilizing electric motors, energy storage devices, and traditional gas turbine technologies received the highest score. Unlike the full-electric options, Brayton cycle hybrid-electric propulsion is unlikely to be prototyped and developed through GA aircraft.

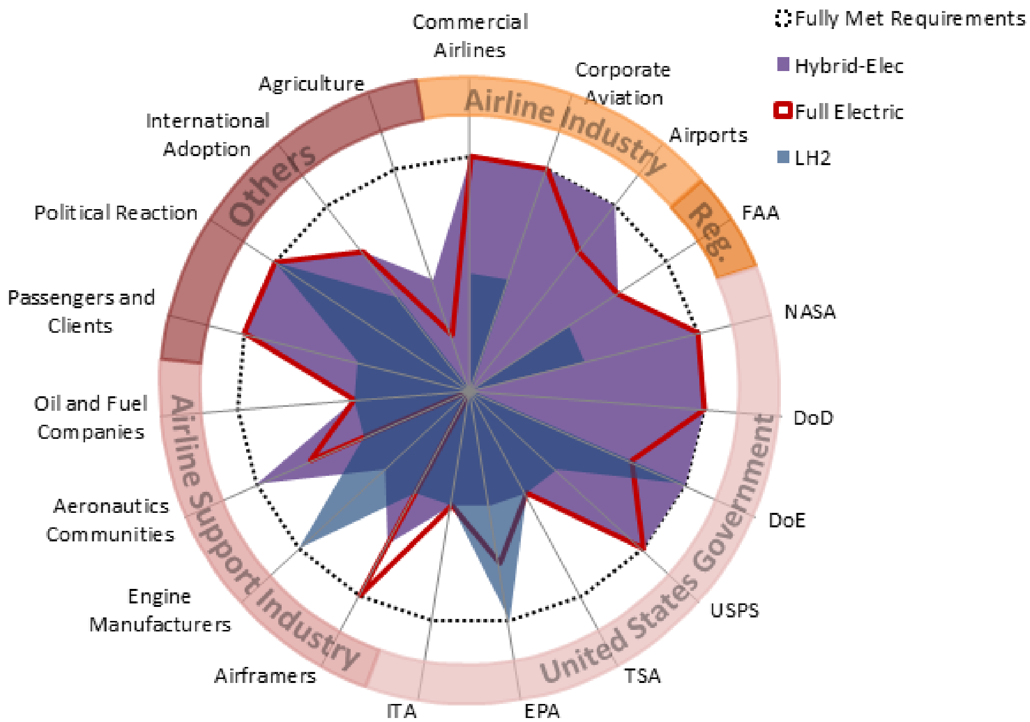

Figure 5. Highly ranked long-term low carbon alternatives adoption challenge analysis comparison. *Full-electric and LH_2 energy options face low barrier to entry from the environmental and most of the energy drivers; these energy types have significant scalability, infrastructure, implementation, and business challenges however. The hybrid-electric architecture faces moderate challenges in most drivers.*

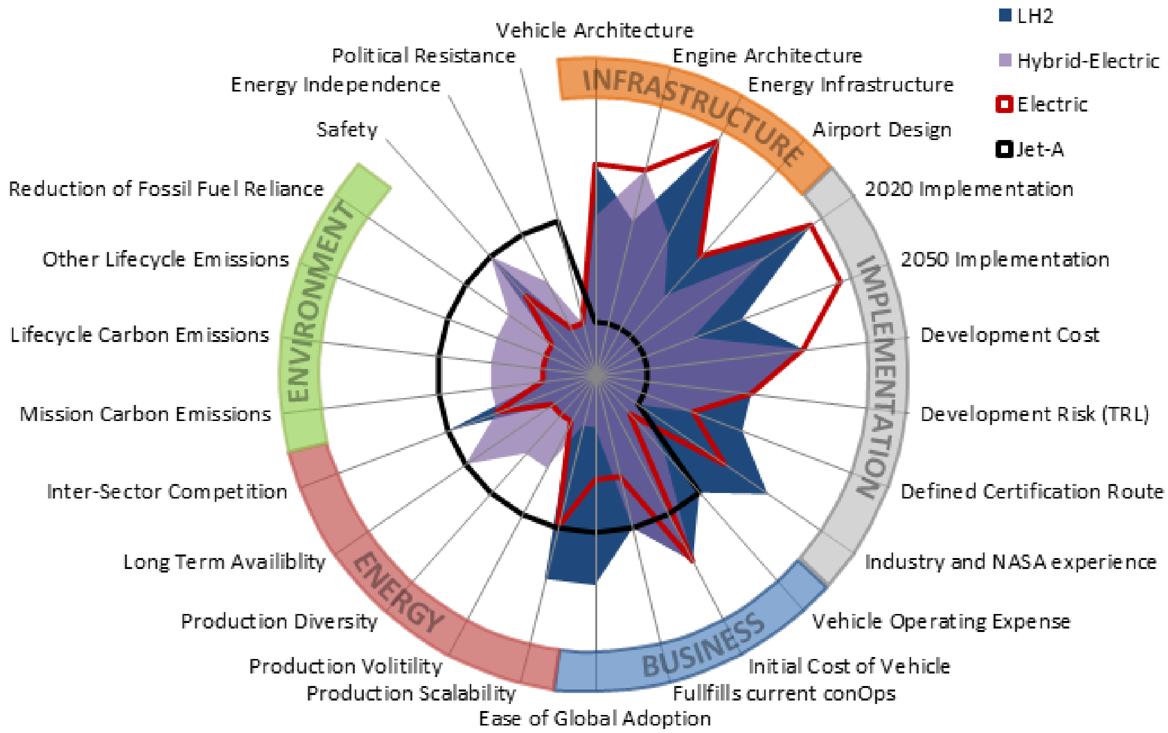

Figure 6. Highly ranked long-term low carbon alternatives stakeholder analysis comparison. *The more electric aircraft options meet significantly more stakeholder options than the liquid hydrogen concepts, especially for the airline industry and regulatory sectors.*

3. *Full Electric Concepts*

The full-electric propulsion options remove traditional gas turbine engines and combustion from aircraft. Electric motors, either a few large engines or distributed propulsion concepts, are solely utilized for propulsion.

Unlike the Brayton cycle options, the fuel cell hybrid technologies scored higher than the energy storage options in terms of stakeholder criteria. It is not anticipated that energy storage devices will be capable of supplying the total required energy for flight of a large aircraft by the year 2050. Onboard solar energy generation is not capable of providing a significant portion of energy needed by large aircraft. However, efficient solar technology could provide numerous benefits to the industry to support more-electric aircraft on the ground or in air.

D. Promising Alternative Energy for Aviation

Table V provides a summary of the scores from the landscape analysis architecture case study. The table contains the scores from both the adoption challenge and stakeholder toolsets, as well as an "overall" score which is the average of these two. Rather than displaying every fuel, major energy categories have been shown for simplicity.

Based upon the assumptions and data of the case study, the 2nd generation synthetic fuels received the highest overall score. The two electric aircraft categories scored most highly among the long-term potential alternative energy options.

Figure 7 displays the adoption challenge visualization for the 2nd generation fuels and two of the electric architectures. The synthetic fuels, benefitting from current certification and application to flight, faced the fewest barriers to entry for full scale implementation. The hybrid-electric architecture had the lowest scalability and business adoption challenges, but faced increased environmental and infrastructure issues. Full-electric vehicles faced significant infrastructure and implementation challenges.

Table V. Landscape analysis architecture scoring for low carbon energy alternatives for aviation. *The individual analyses scores for adoption challenges and stakeholder value are presented for each of the energy source categories. An overall score is the average of the two component analyses' scores.*

Energy Source	Overall Score	Adoption Score	Stakeholder Score
Biofuels	**47%**	56%	39%
1st Gen. Synth.	**73%**	70%	77%
2nd Gen. Synth	**83%**	78%	88%
Nuclear	**26%**	39%	13%
LH_2	**55%**	58%	51%
LNG	**41%**	55%	28%
Hybrid Electric	**75%**	65%	84%
Full Electric	**71%**	64%	78%

E. Low Carbon Energy Recommendations from Landscape Analysis Framework Case Study

The following recommendations were developed from the results of the case study presented in this paper. These recommendations are intended to display the types of conclusions which may be supported by the landscape analysis framework, but are not complete due to the limited access to stakeholders in this research.

The development path for the short-term low carbon alternative fuels is well defined. Alternative "drop-in" jet fuels have a great deal of momentum behind their development and offer clear benefits for rapid adoption by industry. The primary challenge facing synthetic jet fuels is the cost effective, environmentally responsible production of a sufficient quantity of feedstock for production. There is not a single synthetic option or production process that could meet worldwide demand. Therefore, industry may need to adopt an approach where synthetic jet fuel production is maximized worldwide through the manufacture of all six of the leading synthetic fuels based upon the local environment and cultivation capabilities.

NASA played a key role in the flight testing and environmental analysis of many of the synthetic jet fuel options. This research (along with the gas turbine and airframe efficiency research NASA conducts) is important for NASA to continue. The joint effort behind synthetic fuel development engaged dozens of contributors and industry players. Because much of the development and application of synthetic fuels is now carried by entities outside of NASA, the agency's role in synthetic fuel development will likely not expand.

The long-term, low carbon energy source for the aviation industry is less clear. This landscape analysis framework suggests hybrid-electric or full-electric vehicles show the most promise to meet stakeholder needs while facing manageable barriers to market entry and should be pursued. However, hydrogen aircraft have also been a focus of industry and government research. Short-term transition to synthetic fuels with the gradual implementation of more-electric propulsion over time presents a likely route for long-term, low carbon energy development.

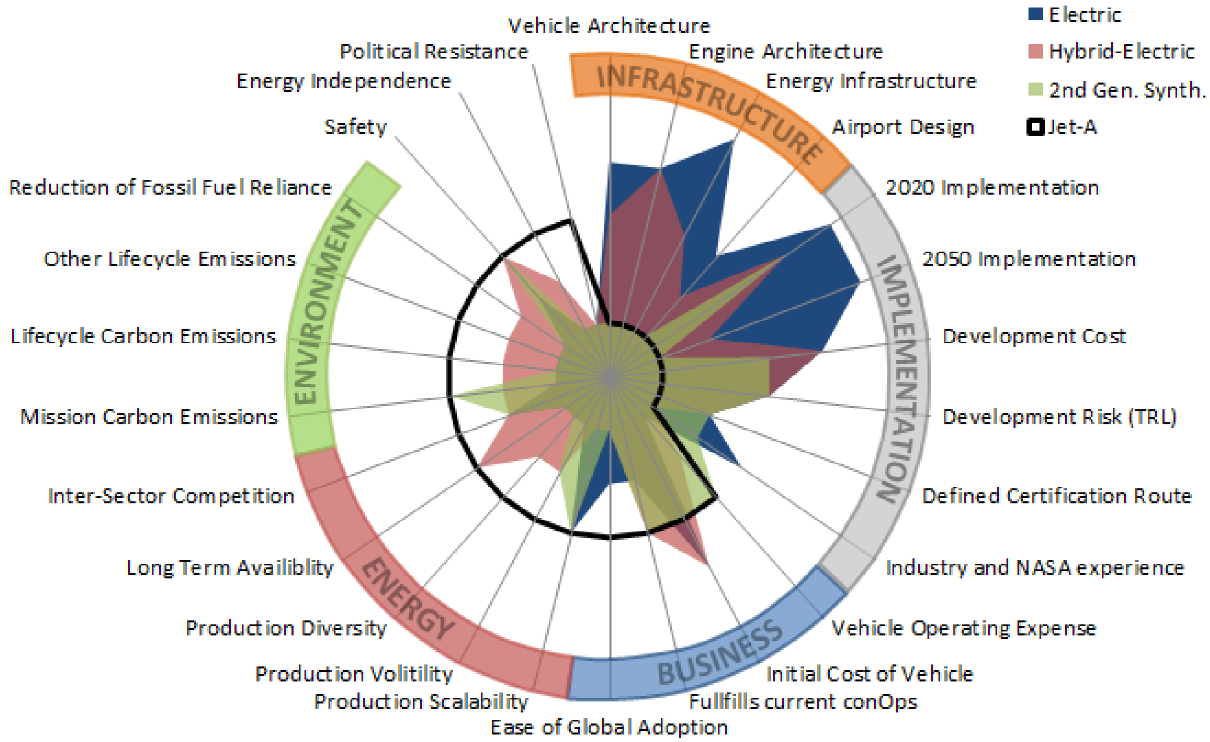

Figure 7. Comparison of the adoption challenges for the most promising low carbon alternatives. *The 2nd generation synthetic jet fuels face the fewest adoption challenges in nearly every category. The hybrid-electric alternatives, while exhibiting fewer adoption challenges in infrastructure and implementation than full-electric alternatives, do not perform as well in the environment and energy sectors. Based on adoption challenges, the 2nd generation synthetic fuels may be market ready while hybrid-electric and full-electric are under development.*

Due to the risk of development in these long-term technologies, industry leadership may not move quickly in these technologies. Therefore, it may be appropriate for NASA to provide direction to this field, and work to resolve many of the questions and variables that cloud the future of long-term alternative energy for aviation. In particular, fundamental research into fuel cell and hybrid-electric technologies shows great potential to revolutionize the industry beginning with small, general aviation and private aircraft.

F. Future Vision for Landscape Analysis Framework for Low Carbon Energy

The focus of this research was the development of the landscape analysis framework for low carbon fuels. The case study presented in this paper was intended to illustrate the types of results, insights, and decision making efforts the framework may support. Multiple areas of improvement and expansion are offered below along with a vision for the application of this framework.

The landscape analysis framework was developed with a limited scope of energy alternatives and stakeholders. In order to more accurately characterize the broad alternative energy landscape, additional energy types and engine cycles must be considered. Dozens of other relevant stakeholders have been identified by the Air Transportation Action Group (ATAG) and should also be considered for inclusion in the framework.[23]

The cases study represents an interpretation of publically available information by the lead author. In order to significantly increase the fidelity and ultimate value of the case study, subject matter experts from each stakeholder group should be engaged to complete or validate the Likert-type rating for each energy type. A group of experts familiar with the technologies and industry should also be convened to review the adoption challenge analysis.

Finally, the language and terminology used in this framework may not necessarily represent current industry standards. Therefore care should be taken to update the fuel types and language to align the framework with the sector and enable more effective communication.

The vision for this framework is to provide a tool that allows users to adjust the analysis weighting factors to “tune” and explore the sensitivities of the low carbon energy space (including turning on or off specific energy types and stakeholders). Given appropriate Likert-type assignments that accurately represent stakeholder utility for each energy type, the framework can accurately portray the landscape of the low carbon energy alternatives design space and represent diverse interests to support analysis of alternatives and decision making. The framework is anticipated to be most useful in the exploration of long-term, low carbon alternatives for aviation. The stakeholder and adoption challenge analyses may identify subtle trends that inform strategic investment and research planning activities.

IV. Conclusion

The drivers of alternative fuel usage in the aviation industry are well known: oil cost volatility, energy independence, and environmental concerns, among others. Following government legislation in 2005, the aviation industry quickly explored potential short-term alternatives to petroleum and aligned behind a transition to synthetic jet fuels. While it is unlikely production of these fuels through renewable sources could ever meet worldwide demand to fully replace petroleum jet fuel, the implementation of multiple leading synthetic production processes may be capable of fulfilling a major percentage of the industry energy needs.

NASA played a key role to help aviation move towards greater energy security. Through the Environmentally Responsible Aviation (ERA) program NASA set ambitious goals for emissions, fuel consumption, and noise standards to be met by 2025. NASA technology development under ERA in combustion systems and synthetic jet fuels accelerated industry progress. Additionally, synthetic fuel flight tests and emissions measuring supported the certification of synthetic fuels and characterized environmental benefits.

With many of these programs concluded, there may be an opportunity for NASA to focus resources to identify the leading long-term, low carbon energy alternative for aviation. NASA is in a unique position to provide leadership and direction to industry and global development. The long-term aviation energy solution must push environmental and economic benefits beyond those available in synthetic jet fuels if the industry is to meet perceived stakeholder needs.

To provide a mechanism for both NASA and other low carbon energy stakeholders to grapple with the diverse requirements, viewpoints, and challenges of the long-term alternative energy design space, a framework for landscape analysis was developed and demonstrated in this research. An initial set of stakeholders and alternative energy types were entered into this framework to illustrate the high-level analysis and insight it may provide to decision makers. Through the expansion of the framework to include additional alternatives and stakeholders, as well as the vetting of the Likert-type rankings by subject matter experts, the framework may prove to be a valuable tool to support strategic decision making for long-term, low carbon energy investments.

Acknowledgments

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