A Roadmap Toward a Sustainable Aviation Ecosystem

Brett Oakleaf, Scott Cary, Darin Meeker, Doug Arent, John Farrell, Marc Day, Robert McCormick, Zia Abdullah, Stanley Young, Jacquelin Cochran, and Chris Gearhart

National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
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Abstract

This report outlines a holistic view of pathways to a sustainable aviation ecosystem, focusing on low-net-carbon aircraft energy carriers (fuels), airport ecosystems (airports and bases), and developments in sustainable aircraft components (aircraft). Taking this holistic ecosystem perspective, we identify critical components that contribute to sustainable energy solutions necessary to achieve deep decarbonization of the aviation industry, as well as the integrated energy system interfaces that must be comprehensively understood, planned for, and realized. Further, we outline necessary R&D needs to achieve sustainability across the aviation ecosystem, including advancing breakthrough innovations to rapidly achieve scalable solutions, with attention to their cross-sectoral dependencies and implications.

List of Acronyms

CO_2	carbon dioxide
DOE	U.S. Department of Energy
FAA	Federal Aviation Administration
ICAO	International Civil Aviation Organization
NREL	National Renewable Energy Laboratory
RDD&D	research, development, demonstration, and deployment
SAF	sustainable aviation fuel

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1 Introduction

Around the world, entities of all sizes—from the public to private sector—are moving to modernize the aviation industry through route optimization and autonomy, efficiency gains in aircraft, and transitions away from fossil fuel-based energy sources. This precarious balancing act must satisfy growing forecasted passenger and cargo demand worldwide, focusing on safety and achieving deep decarbonization (IEA 2021a). Globally, aviation accounts for approximately 1 Gt of greenhouse gas emissions per year, or approximately 2% of global emissions in 2019, and is poised to increase without concerted approaches (IEA 2021b). The aviation industry is committed to meeting this decarbonization goal with the introduction of sustainable fuels, continued energy-efficiency efforts, and new aerial vehicles. Currently, the focus for aviation decarbonization centers on fuels for flight operations (IEA 2021a) and, to a lesser extent, low- to zero-emission ground operations. More recently, multiple alternative propulsion systems and fuels have been proposed and are under development, including electrified and hydrogen-fueled aircraft.

Current U.S. and international goals surrounding sustainable aviation fuel (SAF) require drastic and near-term improvements in carbon reduction and advancements in current technology or new technologies to meet 2050 goals (IEA 2021a). The need to identify, coordinate, and implement deep decarbonization of the aviation industry grows more apparent each day with greater scientific validation linking climate change with increased carbon dioxide (CO_2) levels in the upper atmosphere and other aviation-induced factors (Grobler et al. 2019). CO_2 and non-CO_2 aircraft emissions exacerbate climate change with impacts varying with the altitude at which they are emitted (Matthes et al. 2021). Non-CO_2 impacts from aircraft include nitrogen oxides, contrail cirrus, water vapor, aerosol sulfate, and soot emissions that—combined with CO_2—create a positive radiative forcing effect that causes warming (Grobler et al. 2019).

Beyond passenger and freight transportation, airports and ground operations contribute approximately 10% of total aviation greenhouse gas emissions, often with disproportionate impacts on surrounding lower- and middle-income communities (Wolfe et al. 2014). Many airports have committed to decarbonization and transformation of their operations as they prepare to serve a more diverse aircraft portfolio (Greer, Rakas, and Horvath 2020). Figure 1 shows the sources of greenhouse gas emissions spanning fuels, aircraft, and infrastructure operations.

Figure 1. Carbon sources from aviation ecosystems.

Source: Airport Carbon Accreditation (2020)

Addressing ground operations and considering the increasing diversity of aviation propulsion systems and modes, the complexity and interdependencies required to safely move passengers and goods across transportation modes will continue to increase, prompting the need for innovative technologies and integrated solutions. Aviation adds complexity with its extremely high safety standard and global scale, as well as the current evolution of the aviation market. SAF is a priority near-term solution. Meeting industry goals of carbon neutrality requires advancing the state of SAF production, decarbonization, and deployment in the near term while also advancing other technologies and system solutions. Supporting technologies include alternative energy carriers, propulsion systems, and infrastructure. Potential alternative energy sources, including hydrogen and electricity, could add additional benefits such as noise reductions, localized emissions reductions, decreases in ongoing maintenance, and higher viability for autonomous aircraft routes due to the inherent benefit of simpler aircraft systems. As a global market, aviation requires numerous solutions based on local geographic, social, economic, and physical limitations. New aerial vehicle designs, propulsion requirements, uses, and automation are further driving complexity while also offering new value.

Since its inception at Kitty Hawk, North Carolina, the aviation industry has evolved into a safe and reliable system that continues to improve en route efficiency and aircraft efficiency in a complex system that balances safety, economics, available infrastructure, and advancements in aviation technology. As major energy users, transportation systems play a key role in many communities, whether from energy transport, noise, emissions, or mobility connectivity. Deep decarbonization of the aviation sector requires contributions from environmental, economic, human, operational, and energy perspectives. Opportunities for efficiency, lowering emissions, and business innovation can benefit from a thorough, holistic view that strengthens existing targeted initiatives—potentially unlocking unforeseen opportunities and overcoming constraints.

Focusing on any one set or even related sets of systems for transformation within the aviation industry likely addresses only part of the challenge; however, as aviation operations and fuels diversify to include electrified options, hydrogen, SAF, and other low-carbon fuels, the interdependencies and relationships between aviation support systems require a holistic assessment and development of multiple solution set pathways to achieve full decarbonization. Across the aviation ecosystem, integrated system analysis can provide the ability to develop well-coordinated approaches prior to implementation. The ability to develop and de-risk solutions for global implementation will provide the assurances for impacted stakeholders (e.g., regulatory agencies, airport authorities, manufacturers, cities/towns around the world, financial institutions, and the public) to choose implementation pathways at appropriate pace and scale.

This report lays out a framework for achieving decarbonization across the aviation ecosystem while meeting growing demand and addressing environmental justice inequities. Realizing these goals requires simultaneous advancements across multiple energy systems, including addressing decarbonization and accelerating market adoption of numerous interdependent challenges through comprehensive solutions across three main pillars: fuels (energy carriers), aviation infrastructure (the network of locations servicing and routing aerial vehicles), and aircraft (all aerial vehicles, crewed and uncrewed).

2 The Aviation Ecosystem

The interdependencies across the aviation industry can be visualized in Figure 2. Within each set of systems (communications/technology, energy justice, energy solutions, human systems, and transportation networks) are subsystems that begin to portray the connectivity within this industry, and thus the need to approach solutions holistically. Each subsystem influences other subsystems and supports the critical infrastructure of aviation-based operations.

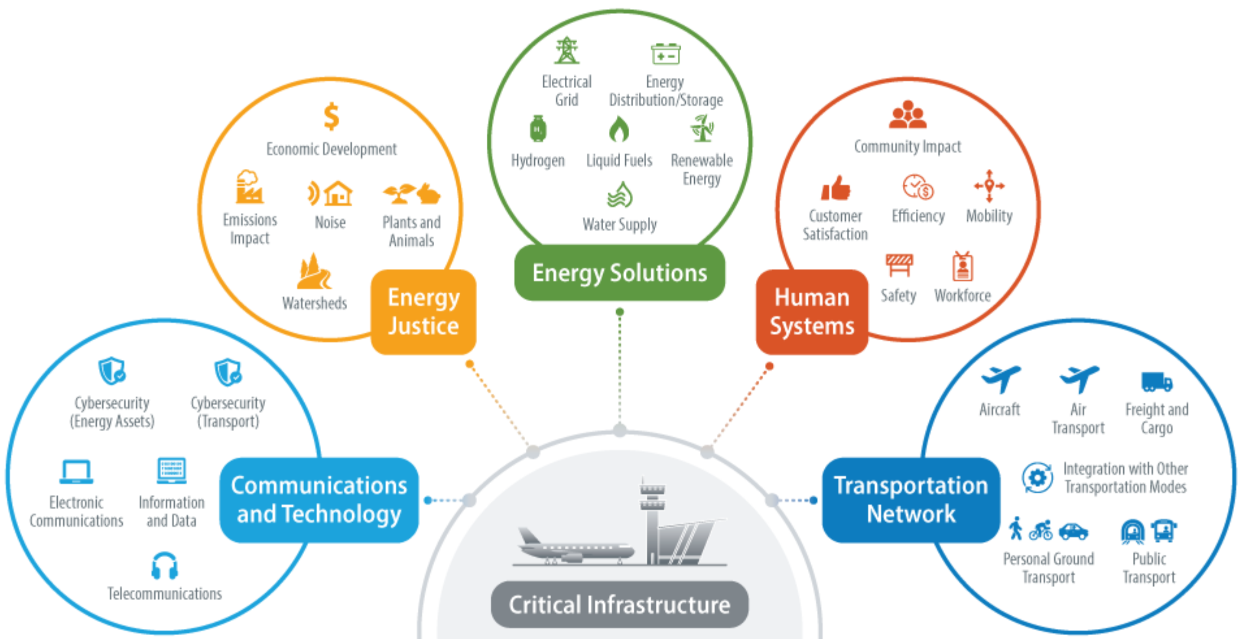

Figure 2. Interdependencies in the aviation industry

Infusing low- and no-carbon solutions throughout the aviation industry represents opportunities to improve efficiencies, innovate new solutions, and address local and global issues, including improving energy justice by influencing jobs, emissions, noise, or other factors. Physical, electrical, and cyber resilience are paramount for communications/technology to support the transportation of fuels, passengers, and goods. Human systems demand the highest safety factors throughout the three pillars of fuels, airport ecosystems, and aircraft while also recognizing related needs of the transportation market driven by customer experience, accessibility to transportation, and community impact of established or emerging transportation amenities.

3 Transforming the Aviation Ecosystem

Decarbonizing the aviation industry requires steady and transformational growth. Efforts are already underway and growing, with commitments from coalitions within the industry from the Federal Aviation Administration (FAA), International Civil Aviation Organization (ICAO), International Air Transport Association (IATA), and others to reduce CO_2, other emissions, and environmental impacts. For example, ICAO's global coalition for sustainable aviation includes companies like Airbus and Archer pursuing zero-emission aircraft and universities such as Cranfield and Eindhoven researching novel fuels (ICAO 2022). This coalition includes 47 partners dedicated to sustainable aviation, demonstrating the steps toward transformation beginning to take place in the industry. To date, major efforts are focused on SAF, and leading airports are evaluating pathways to both modernize and decarbonize, targeting net-zero operations by 2050 or sooner (IEA 2021a). In order to meet these goals and create financially viable low-carbon solutions at unprecedented speed and scale, public and private stakeholders have expressed the need to collaborate to develop and accelerate solution pathways. Along with combined public and private coordination, new approaches are needed to bring these solution pathways to fruition. These approaches will require a coordinated research, development, demonstration, and deployment (RDD&D) focus.

The three major pillars of the aviation ecosystem are energy carriers (fuels), airport ecosystems, and aircraft (Figure 3). Categorizing the numerous interconnections, subsystems, and energy-related influences is necessary to provide focus and prioritize the largest and most influential decarbonization pathways that minimize unintended consequences to adjacent activities and communities.

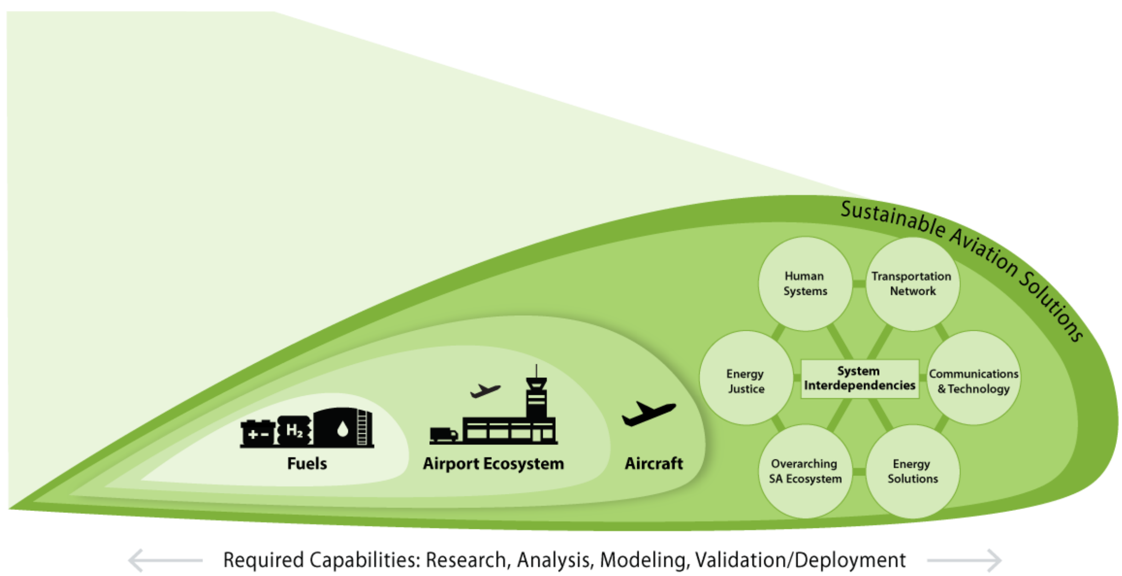

Figure 3. Sustainable aviation solutions

3.1 Sustainable Energy Carriers (Fuels)

Traditionally, fuels for the aviation industry have been petroleum-derived liquids delivered to on-site storage facilities at airports. The first pillar of aviation decarbonization focuses on fuels.

Decarbonized solution pathways for future fuels include SAFs—including electrofuels (e-fuels)[1]—hydrogen, and electricity to power aircraft. Each alternative energy carrier has its own challenges in production, distribution, and storage properties.[2]

SAF

As a drop-in replacement, SAF requires multilayered development and validation along the feedstock supply, pretreatment, intermediate stream production, technology validation, refiner, distribution, and customer value chain. Within supply, there are numerous feedstock pathways in limited form that need to be developed at scale to address the global utilization of local resources and the sheer volume required to meet global demand. Pretreatment and intermediary processes require physical collection, contaminant processing, and chemical manipulation of feedstocks to a form that is convertible into liquid fuel. Technology validation provides the necessary technical, environmental, and economic reassurances for refiners to scale up operations. Approval, distribution, and storage challenges arise in the transition timeline from Jet A to complete SAF usage and the blending of the two in the interim. Current challenges include maintaining necessary seal-swelling in existing "in-service" aircraft, while minimizing or preferably eliminating aromatics in fuels. Aromatics generate undesirable particulate emissions which affect air quality near airports (Holladay et al. 2020). ASTM International approval of drop-in SAFs is a lengthy, complex, and expensive procedure, eventually requiring up to 100,000 gallons of each candidate fuel despite recent process streamlining efforts. This can be prohibitively costly and risky for fuels that do not benefit from a well-established production stream. Final customer purchase commitments, whether through policy mandates or independent customer choice, are necessary to drive this transition toward industry SAF utilization.

Ongoing SAF research has included the work of the Commercial Aviation Alternative Fuels Initiative (CAAFI) since 2006 (CAAFI 2022), successful 100% SAF test flights for the U.S. Navy (Biofuels International 2016), and, beginning in 2016, significant federal and industry investment into research and certification of seven current pathways for SAF production at varied blend rates (Holladay, Abdullah, and Heyne 2020). Streamlined ASTM certification processes and other initiatives have contributed to advancements that include significant commitments for airline offtake agreements and the multiagency U.S. Department of Energy (DOE)-led "SAF Grand Challenge" seeking to have 35 billion gallons of SAF in place in the United States by 2050. Companion efforts by the FAA focus on improving aircraft efficiency and quantifying various elements to reduce emissions and increase aircraft operations efficiency under programs such as the Continuous Lower Energy, Emissions, and Noise (CLEEN) and ASCENT programs (FAA 2022; ASCENT 2022).

Despite challenges, SAFs present a major pathway to decreasing carbon emissions from air travel. SAF's ability to be used as a drop-in fuel makes it simpler and faster to implement than other fuel pathways, and the lower emissions of current SAFs in the short term provide the opportunity to further develop zero-emission solutions in the long term. Because SAFs still emit greenhouse gases and global aviation fuel use is on track to double from 106 billion gallons in

[1] E-fuels are low-carbon or carbon-neutral fuels containing hydrogen and CO_2 produced using electricity and a carbon source (Ramirez, Mani Sarathy, and Gascon 2020).
[2] See Figure 5 for more detail on fuel pathways.

2019 to 230 billion gallons in 2050, more carbon-neutral forms of SAF and other energy carriers must be a part of the solution to decarbonize aviation (Holladay, Abdullah, and Heyne 2020).

Producing e-fuels, a type of SAF, starts with hydrogen produced via water electrolysis (ideally from low-carbon power) and then combined with CO_2. The hydrogen and CO_2 can be processed in many ways, for example (1) conversion to e-methanol through methanol synthesis, followed by conversion to olefins ("MTO," or methanol to olefins), and (2) the Fischer-Tropsch process. The outputs of these processes are then further refined to create jet e-fuel (Ramirez, Mani Sarathy, and Gascon 2020). Benefits of e-fuels include their ability to combine clean electricity sources with carbon capture from other hard-to-decarbonize sectors, resulting in a drop-in replacement fuel with a lower carbon footprint. There are economic, technical, commercialization, and distribution challenges that are best addressed by a coordinated public and private initiative. For example, technical challenges for the use of e-fuels and thus the conversion of CO_2 into fuels involve the substantial energy required to create the product, as well as the compatibility requirements for e-fuels to fit within existing fueling infrastructure. In addition, although both Fischer-Tropsch and HEFA (hydroprocessed esters and fatty acids) fuels have been approved for use at a 50% blending rate, higher concentrations (as high as 100% SAF) have yet to be certified for use. So, although the technology has existed for decades, the industry needs further innovations to produce blendstock at scale, improve process efficiencies, and reduce costs.

Hydrogen-Based Fuels

Utilizing hydrogen as a primary energy source for aviation can offer the ability to refuel at rates equivalent to fossil fuels, potentially lower noise levels from engine operation, reduce or eliminate carbon emissions, and potentially leverage infrastructure across the ground, marine, and air transportation and industrial networks (Fuel Cells and Hydrogen 2 Joint Undertaking 2020). For example, hydrogen refueling rates can be comparable to Jet A refueling rates, with the National Renewable Energy Laboratory (NREL) recently making significant progress on its rapid delivery to vehicles. On April 26, 2022, NREL demonstrated an average mass flow rate of 14 kg/min (21-kg/min peak)—similar to those used by heavy-duty vehicles (NREL 2022). For comparison, a kilogram of hydrogen has approximately the same amount of energy as a gallon of jet fuel. Pairing localized renewable energy generation with hydrogen potentially provides energy storage capabilities and grid stabilization capabilities while also supporting transportation needs. Distance traveled is dependent on decreasing weight within the system, and currently, hydrogen is believed to offer longer distances than fully battery electric aircraft. However, the technology needs improvements to reach the current operational capabilities of traditional fossil fuels due to hydrogen's lower volumetric energy density in both gaseous and liquid form (Sharpe et al. 2015). Estimates show that hydrogen combustion could reduce aviation's climate impact in a measure similar to SAFs (Fuel Cells and Hydrogen 2 Joint Undertaking 2020).

Hydrogen economics, infrastructure, and storage on the aircraft present significant challenges for the two pathways currently under development—direct combustion and hydrogen fuel cell-generated electricity. However, efforts are underway to tackle these issues. For example, Airbus recently announced that hydrogen-fueled propulsion systems would be at the heart of a new generation of zero-emissions commercial aircraft (Airbus 2022). The first is a turboprop-driven aircraft capable of carrying around 100 passengers about 1,000 nautical miles. United Airlines and Alaska Airlines have publicly announced investments in hydrogen-based aircraft development with ZeroAvia for approximately 70-seat aircraft pervasive in regional aircraft travel. In addition, hydrogen benefits extend to the U.S. Department of Defense and the utilization of hydrogen within its transportation and logistical operations from an economic, fuel diversification, and environmental perspective. For example, in 2012, the U.S. Army launched 16 fleet vehicles powered by hydrogen fuel cells in Hawaii, fueled by hydrogen stations on Oahu (Garland, Papageorgopoulos, and Stanford 2012). It is noted that hydrogen offers somewhat unique economy-of-scale opportunities as an energy carrier for transportation, power, and industrial uses that converge in locations such as large transportation hubs, resulting in the opportunity for improved economics and shared infrastructure.

The cost of hydrogen is currently high compared to other sustainable energy sources. To address that challenge, in June of 2021, DOE announced a "1 1 1" Hydrogen Shot target to produce 1 kg of hydrogen at $1 in 1 decade (DOE 2022b). Another key challenge of hydrogen involves the emissions intensity of current production of hydrogen fuel. The most economic and common method of production uses steam methane reforming of natural gas. In order for hydrogen to be an effective contributor to the decarbonization of the aviation industry, whether as a direct energy carrier or a feedstock for liquid fuels, other production pathways such as clean electrolyzers and carbon capture technologies must become cost-effective, which includes the availability of necessary inputs such as access to water, low-carbon electricity, and sequestration sites for carbon capture.

Electric Flight

Electrified propulsion is the newest entrant into the aviation industry, introducing a significant opportunity to decarbonize travel for trips under 500 miles. Advanced air mobility encompasses a range of emerging technologies and propulsion types, including urban and regional air mobility, blending new technologies with the potentially disruptive benefits associated with alternative propulsion systems, nonconventional landing sites, and aircraft autonomy. Electric vertical take-off and landing (eVTOL), alternative-propulsion conventional take-off and landing, and larger short-haul aircraft are being pursued by various commercial ventures attempting to unlock tremendous mobility opportunities. Potential benefits include reduced noise, maintenance, and emissions; the utilization of existing energy infrastructure (although improvements may be necessary); and potential opportunities for local generation, storage, and improved operating economics.

At least seven manufacturers are currently in the certification process with FAA, along with multiple others actively developing propulsion systems, forming airline partnerships, and seeking certification through other ICAO-approved pathways. Multiple manufacturers have completed test flights, and initial deployments are occurring in flight training operations and the retrofit of short-distance seaplane services. Efficiency gains, lower operating costs, and potential to use existing general aviation airports and/or expanded vertiport locations offer new transportation options to expand access to underserved markets and/or subsidized routes such as the essential air service market.

The U.S. Department of Defense could integrate and capitalize on electrified aviation and coordinated electrification within future "electrification of the battlefield" scenarios both domestically and abroad with our key partners, who are currently considering hybrid-electric and fully electric logistics (National Academy of Sciences 2021). However, the industry is years away from mass certification, installing the necessary support infrastructure, and gaining passenger confidence to make a notable impact. Nonetheless, battery electric vertical take-off and landing capabilities are currently more established than hydrogen options as of 2022, based on aircraft currently known to be in certification with the FAA. This is particularly the case as it relates to the general aviation sector, which accounts for more than 90% of registered civil aircraft in the United States and where shorter-haul flights are more common (AOPA 2019).

3.2 Airport Ecosystems (Airports and Bases)

The second major pillar of the aviation ecosystem focuses on the airport, military base, and vertiport ecosystem. The future of these ecosystems will dramatically transform the energy landscape as they interact with ground-based transportation systems. The military is preparing for sea level rise, electrification of the battlefield, and logistics support for cargo and troops, as well as leveraging new technologies while also needing to adapt to changing energy availability in various locations around the world. Vertiports offer the opportunity to accelerate intracity or regional passenger and freight movement, but the energy demand and delivery will have to be optimized. Compounding these energy needs are real-time changes in weather, aircraft schedules, passenger demands, mechanical failures, and numerous other operational challenges that can impact energy optimization.

One issue is how nontraditional energy assets adjacent to airfields such as buildings, motors, charging equipment, controllers, and sensors can assist with energy planning and delivery while simultaneously reducing greenhouse gas emissions. A key element in reducing overall energy needs is optimizing existing infrastructure and facilities to support future loads by looking across transportation and building sectors for holistic solutions. Dallas/Fort Worth International Airport, for example, has realized this in its environmental, social, and governance efforts and is actively addressing facilities through transportation efficiency modeling and infrastructure modernization efforts, including distributed energy resources and evaluation of demand modeling efforts (DFW 2020). With the growing volume of future passengers and freight, these complex systems of ground and air-based transportation interdependencies will likely require higher levels of electrical energy usage, demand coordination, and cybersecurity, regardless of fuel type.

Optimizing the use of existing infrastructure while simultaneously planning for the future is a key first step in advancing the transformation of the overall ecosystem. For example, across much of the United States, many small general aviation airports, developed more than 50 years ago in support of post-World War II expansion, have available capacity, while congestion occurs at a small number of locations. Current trends indicate significant infrastructure deployment timelines lag the proposed delivery of aircraft. Charging standards are beginning to converge but have yet to be standardized across industry, resulting in limited guidance for facility operators. Hybrid-electric aircraft, smart management of charging profiles, and alterations of flight schedules can significantly reduce peak power demands at airports as part of the transition, reducing required grid infrastructure upgrades and peak demand costs for airports (Hou et al. 2021). The worldwide nature of aviation does not benefit from regional (e.g., not global) equipment standardization currently utilized in ground vehicles. Standardization would not only be helpful in planning infrastructure improvements, but would also offer greater efficiency for facility operators preparing to support all manufacturers and users.

As we think about energy carrier choices, how that energy arrives for use at an airport is also part of the ground infrastructure equation. New potential energy carriers and generation, delivery, and storage of those products require use/reuse of infrastructure to transfer this material to the point of flight. Liquid fuels are generally assumed to be able to utilize current infrastructure for delivery, and electricity generally has existing pathways that may require upgrades to meet projected demand growth. Hydrogen currently has limited pipeline capabilities in the United States and is generally generated close to point of use. Research continues on lower-cost solutions for the installation of new pipeline systems, along with blending and/or reuse of existing natural gas pipelines (Melaina et al. 2013), with the current HyBlend program a significant multi-lab effort to aid this sector (NREL 2020). The prevalence of the natural gas system in the United States—including in and around aviation facilities—provides a potential existing asset that could be repurposed for future energy carriers.

The aviation ecosystem extends beyond the physical ground equipment to include the systems and procedures for safely routing goods and passengers worldwide. Currently, there are efforts by the FAA to modernize the airspace and its subsystems to increase efficiency and reduce emissions through novel aircraft management solutions. FAA solutions for the next generation of airspace systems involve improvements in communications, surveillance, and routing procedures at airports. This effort is significant, and significant resources are applied to this component of the aviation infrastructure ecosystem. For example, voice-only communications can transition to faster digital communications, and radar-only surveillance can begin utilizing satellite-enabled, near-real-time surveillance (FAA 2020). The FAA's NextGen strategy has already accumulated $7 billion worth of benefits from 2010–2019: 5% from the reduction of accidents, 17% from fuel savings, 21% from aircraft operating cost savings, and 57% from passenger travel time savings. The solutions involved within this strategy are promising next steps toward a more efficient aviation ecosystem, with significant technological developments including wake recategorization, expanded low-visibility operations, enhanced flight vision systems, and trajectory-based operations. Wake recategorization redefines the separation standards used to separate aircraft from each other by using up-to-date research, making the standards more accurate. Expanded low-visibility operations reduce airspace ceiling and runway visual range minimums to improve airport accessibility during poor weather and low visibility. Enhanced flight vision systems also increase aircraft situational awareness by providing a display of real-time images of the surroundings using imaging sensors. All of these methods increase the efficiency and throughput at airports by reducing aircraft separation and wait times on taxiways and runways.

In addition to the focus on safely maintaining aircraft operations, sustainability can also be enhanced through better vertical route planning. Adjusting flight operations and how airplanes fly at the system level have great potential to improve aviation sustainability. Aircraft emit CO_2 and other climate-changing emissions such as nitrogen oxides and water vapor, which have different effects on our atmosphere based on the altitude at which they are emitted. This means that airports modifying flight altitudes can potentially reduce aircrafts' effects on our atmosphere. Current research shows that due to air drag, fuel consumption increases by about 1% if aircraft fly lower by 2000 feet (600 m) and decreases by 1% if aircraft fly higher by the same distance (Matthes et al. 2021). However, although CO_2 impacts from fuel consumption increase by 1% at lower altitudes, the radiative forcing of the non-CO_2 impacts decrease by about 33%, causing an overall reduction of climate impacts by 21% by flying lower. These data can help inform future flight operations at airports to take lower-emission routes when possible, within safety and capacity constraints.

As we look at efficient routing in the skies, it is also noted that there is opportunity to better couple aviation mode choice with other forms of transportation. The interdependencies or "coupling of systems" extend beyond the airport/base/vertiport ecosystems into the ground or intermodal transportation networks and throughout rural to urban communities. Moving people and goods between ground, marine, rail, and air transportation historically has been discussed but rarely coupled to understand the full mode choice opportunities from a customer, energy, and environmental perspective. Adding the significant energy intricacies among the ground, marine, and rail transportation systems via intermodal connection points compounds the analysis exponentially with competing needs for similar energy sources and concentration of energy sources at intermodal facilities from a geographically dispersed supply system.

3.3 Aircraft

The third major pillar for decarbonizing the aviation ecosystem focuses on the aircraft, specifically the parts, systems, and components that advance their energy contribution across all fuel types and propulsion pathways. Many different components come together for a successful aircraft certification and long-term use. Significant reductions in energy use have occurred in the past 30 years, focusing upon efficiency of the aircraft and keeping the energy source constant. Future high-performance, decarbonized aviation will require new energy systems, enhancements to existing technologies, and new aircraft and aircrew certifications and training standards. The energy-based systems include ultra-high-efficient motors and controllers, enhancements to existing powertrain components, next-generation propulsion/generator/powertrain systems based on new decarbonized "fuels," high-energy-density batteries, liquid/gaseous fuel tanks, advanced material composites, and power electronics. These energy-based systems may extend to the design of ground support vehicles, which include inductive charging, high-quality energy support for long-haul aircraft while parked, and emissions reduction with aircraft queuing.

When looking at future aircraft design, a key initial review is the energy source and method for converting that source to propulsion. This initial screening helps identify the areas in aircraft design for optimization of efficiency and reduced emissions, as differences in each energy source's characteristics such as energy density, propulsion, and efficiency affect the optimal design of an aircraft. Given that the majority of aircraft emissions result from long-distance transport, sustainable aircraft using fuel sources other than liquid fuel replacements need considerable energy storage and power output. For example, utilizing hydrogen fuel can lead to different, more efficient propulsion methods but will require significant aircraft modifications. Hydrogen fuel can be used to propel aircraft in two ways: combustion or fuel cells. Combustion of hydrogen can replace jet fuel in a turbine engine but will require modifications in combustor design and flame stability. In addition, nitrogen oxides and contrails are still emitted in combustion. An alternate approach involves hydrogen being used to produce electricity in electrochemical fuel cells to power electric motors and propellers. This method requires modifications of an electric powertrain and has significant weight consequences (ASCENT 2021). Liquid hydrogen's combustion power conversion is similar to that of jet fuel combustion and is currently feasible for longer-duration flights that aren't feasible for battery-electric or fuel cell planes. However, major changes to the fuel system to incorporate cryogenic storage and distribution of liquid hydrogen would be necessary.

In addition to hydrogen, a transformation utilizing electricity from batteries can help reduce emissions and noise pollution of traditional aircraft. Aircraft manufacturers have already begun incorporating electric technologies into their aircraft such as the Airbus A380 and Boeing 787 (Gnadt et al. 2019). Electrical systems are replacing mechanical, hydraulic, and pneumatic systems in order to improve reliability and decrease weight. Creative solutions to aircraft battery storage are being investigated, including NASA's studies on multifunctional aircraft structures that integrate energy storage into a concept design, allowing the structure to simultaneously serve as a battery and reduce the weight consequences of batteries. These modifications may help mitigate the limited range, payload, and speed of electric aircraft, further increasing the benefits of electric aircraft on the aviation ecosystem.

4 Research, Development, Demonstration, and Deployment

4.1 Outlook

Multiple elements within the sustainable aviation ecosystem are being addressed by federal agencies and industry groups, from work promoted by the FAA on aircraft efficiency to DOE collaborations such as the SAF Grand Challenge and Hydrogen Shot (DOE 2022b, 2022c). These influential efforts supporting aviation decarbonization could benefit from a systemic-level approach to the energy demands of the overall system. A holistic assessment across system interdependencies with goals under a coordinated, organized structure will help identify the greatest challenges ahead if true decarbonization across the aviation ecosystem is to be achieved. Developing a research roadmap to incorporate and coordinate these related aviation decarbonization efforts would provide key directions for accelerating innovative solutions. The intent would be to identify/address gaps or related additional areas of need under guidance from key public and private industry stakeholders, as well as critical synergies and technology gaps. Some of these research gaps include identification, acceleration, and de-risking new pathways for fuel certification (e.g., SAF, e-fuels, hydrogen, electrification); optimizing the dynamic energy needs across multiple fuel streams and sectors (transportation, power, buildings, and industry) at given locations and regionally; and providing new analytical tools or data sets to industry, regulators, or the military to evaluate new technology options and accelerate validation and adoption of new aircraft and use cases under a variety of new scenarios.

Leveraging prior experiences in other sectors, a coordinated public/private collaboration with a focus on RDD&D from both a national and global perspective can provide tangible opportunities to realize a decarbonized aviation ecosystem. Coordination and collaboration across federal agencies (e.g., DOE, Department of Defense, Department of Transportation/FAA, Department of Agriculture, Environmental Protection Agency, Federal Emergency Management Agency) will lay the foundation of targeted federal funding support for RDD&D roadmap targets across all three pillars. Consortia of industry partners (e.g., fuels providers, airports, aerial vehicles/aircraft, city planners, energy providers/utilities) can help prioritize industry needs and provide additional financial support and demonstration and deployment collaborations. Finally, energy-based research institutions (e.g., national laboratories, universities, NGOs) provide comprehensive capabilities of holistic analysis, research, configurable development, and demonstration and validation of in-field deployments to advance innovative solutions at scale and across the globe.

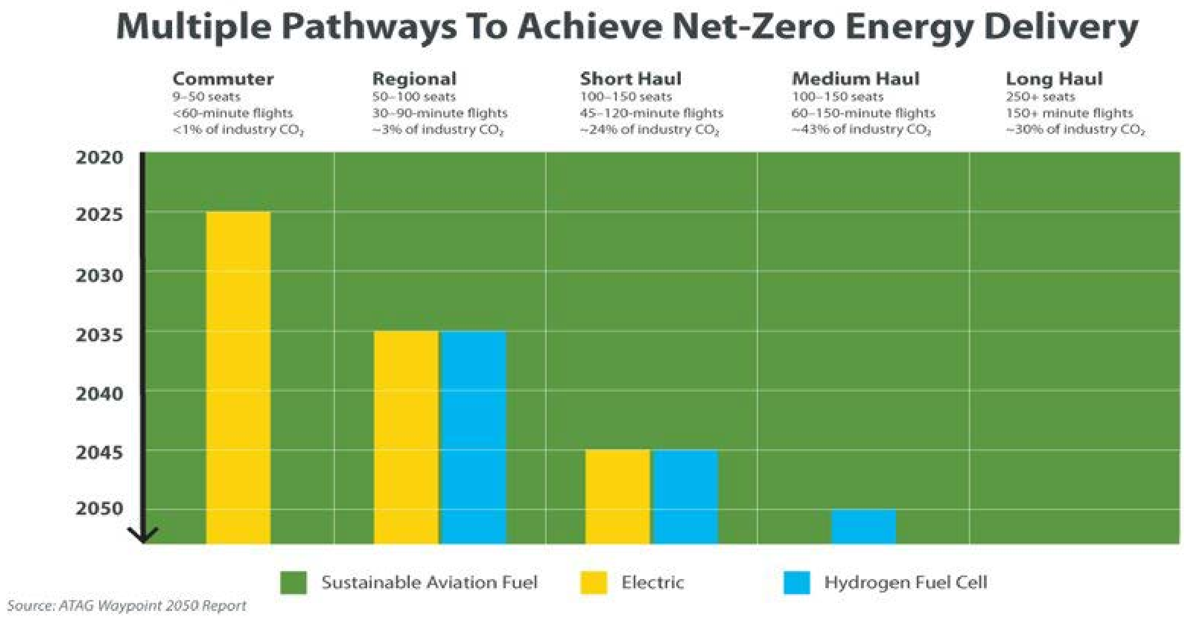

Figure 4. Estimated fuel types for aviation in future years

Figure 4 provides an estimation developed by the aviation industry of what fuels will support decarbonized aviation propulsion based on time frames, flight distances, passenger counts, and their associated CO_2 contribution within the aviation industry. Now and for the foreseeable future, SAF appears to be the dominant viable pathway for aviation, especially for medium- and long-haul routes (e.g., over 1,000 miles). Significant CO_2 emissions reductions are anticipated as SAF becomes increasingly economically competitive with widescale availability for global markets. The introduction of electric and hydrogen-based aviation propulsion offers alternative low-carbon solutions for select markets in the coming years and may penetrate other markets as technologies advance, costs decrease, and supply chains develop. Manufacturers, airlines, and cargo operators are partnering for SAF, hybrid-electric, electric, and hydrogen solutions. They have announced delivery targets for aircraft within this decade, while commitments are growing for large-scale offput agreements for SAF in the near term (Moriarty, Milbrandt, and Tao 2021). Public announcements backing emerging technologies, fuel offtake agreements, federal policy, and purchase orders for emerging aircraft are indicators of the direction aviation is looking to advance.

Energy needs are anticipated to change over time as technology advances in fuels, infrastructure, and aircraft. Transportation automation, an evolving sector, will influence energy intensities and communication protocols of ground and aerial systems and has the potential to alter routes and related protocols for the desired application. This nexus of mobility, communications, and energy will grow rapidly, and their interdependencies will require greater management.

4.2 Energy Carriers (Fuel)

Within the fuels pillar today, decarbonization of the aviation industry is strongly supported by DOE, Department of Transportation, and Department of Agriculture. The SAF Grand Challenge, announced on September 9, 2021, along with the Hydrogen Shot, are both relevant and significant initiatives (DOE 2022b, 2022c). These initiatives are examples of multiple agencies coming together to focus resources and goal-setting within the fuels pillar. In addition, FAA's ASCENT program and NASA's emerging technology programs contribute toward national and global goals. Building off these foundational efforts, robust analytics, both within the specific technical areas and holistically across systems, are poised to inform methodical, early-stage research that will provide cost-effective pathways toward viable energy solutions across all three pillars. Combining this analysis with research and viable solution pathways (Figure 5) can lead to repeatable, scalable, financially attractive deployment in a global context. Figure 5 also identifies the key steps in each value chain for focused RDD&D innovations.

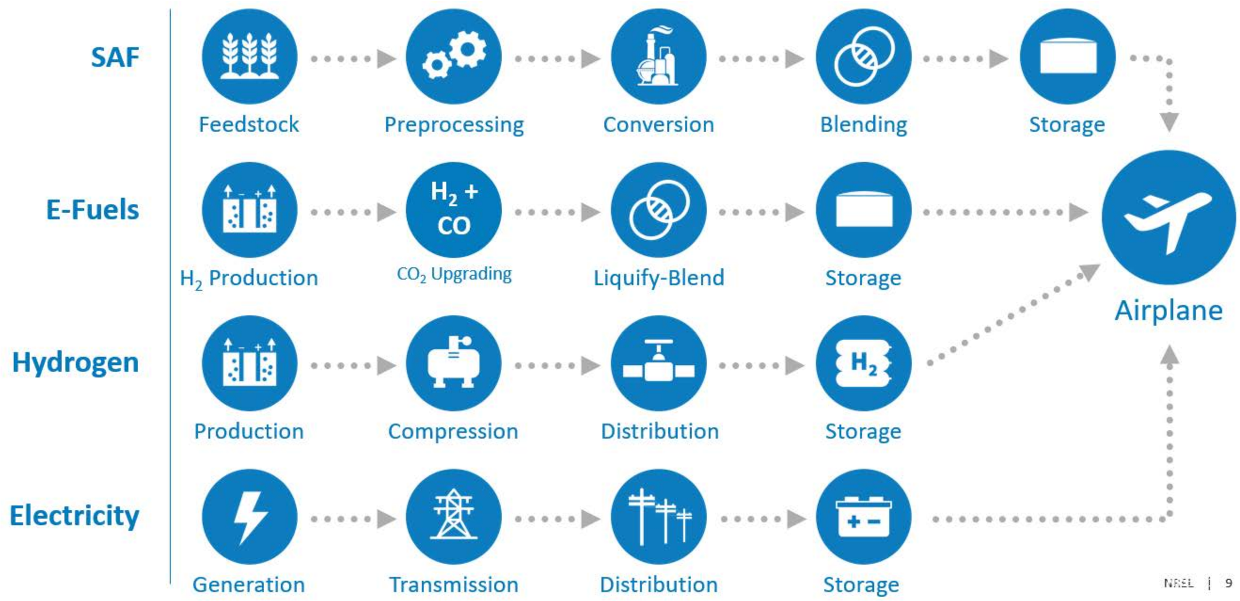

Figure 5. Simplified supply chains for sustainable aviation production

With the rise in airline CO_2 reduction announcements and commitments to SAF purchases, the demand for SAF has grown substantially, putting a spotlight on the limited options for technologically viable SAF production that are currently available. The predominant SAF production pathway involves using fats, oils, and greases as feedstocks utilizing hydroprocessed esters and fatty acids technology. Based on the limited feedstock availability of fats, oils, and greases, other SAF feedstock pathways must be accelerated to reinforce production at scale and within a global geography.

Along these lines, the United States is capable of producing up to 1 billion tons of biomass annually on a sustainable basis (DOE 2022a). This has the potential to produce approximately 50 billion gallons of biofuel per year. With continued pressure on feedstock for low-carbon fuels in multiple sectors, scalable approaches for SAF would be prudent to include wet and dry waste and algae feedstock. Given the breadth of wastes and multiple feedstocks available in various regions of the United States and around the world, multiple innovative conversion technologies are needed. Since there is some flexibility to choose the particular biomass that can be purpose-grown, solutions must account for the selection on the basis of cost, ease of conversion to SAF, compatibility with the soil, environment, stress on water supply, and ability of the plant to store carbon in the long term in the root system and soil.

Aviation industry economics are very sensitive to fuel costs, and therefore all opportunities to reduce and stabilize SAF costs should be explored and prioritized. Since feedstock cost constitutes typically about one-third of the cost of finished fuel, opportunities to produce fuel from low-value waste material (e.g., municipal solid waste and wet waste) should be further examined (Abdullah 2022). Hydrogen is required for hydrodeoxygenation, hydrocracking, and hydrotreatment for SAF production; the hydrogen can, in part, be supplied internally through process treatment of biofuels or supplied externally, ideally through low- or zero-carbon sources. Research in reducing low-carbon hydrogen costs via electrolysis or other processes (e.g., direct solar conversion) is critical to the development of low-carbon supply chains for some SAF pathways, e-fuels, and hydrogen-fueled aircraft.

Smaller but important steps within the value chain development—including feedstock collection, intermediary processing, and fuel distribution—will also greatly benefit from fresh approaches to strategic partnerships, economic incentives, promoting project permitting, and new business models. Development plans must include environmental and social justice considerations on selection of feedstock and conversion processes, as well as local or regional geographic and economic considerations or limitations.

E-fuels are synthetic fuels that can be utilized as carbon-neutral, drop-in, liquid replacement fuels that are made by storing energy in chemical bonds. The multistep chemical approach represents risk, collaboration, and validation challenges throughout the e-fuels development process: sourcing significant volumes of low-cost hydrogen; sourcing, capture, and utilization of CO_2; and technology aggregation, validation, and scaling. Much like other SAF, e-fuels will require multiple pathways or a portfolio of technologies to address growing volumetric demands and a global market. Testing and validation to meet strict certification guidelines must also be included in this holistic analysis of all energy carriers. New technologies and the nature of the multistep chemical process will need to be analyzed, vetted, and ultimately de-risked within the research community to accelerate commercialization.

Hydrogen presents different opportunities for coordinated research efforts across public and private partners. One of the biggest opportunities is the economical production, distribution, and storage of hydrogen being addressed by DOE's Hydrogen Shot initiative (DOE 2022b). Hydrogen can be generated by electrolysis, which splits water molecules into hydrogen and oxygen atoms using electricity. Cost-competitiveness, scaling, transportation, and storage of hydrogen remain significant barriers to widespread commercialization. Further, operational aspects, including safety standards and protocols, are also required for market adoption.

4.3 Airport Ecosystems

From an integrated systems perspective, viewing sustainable airports, military bases, and vertiports as an ecosystem can help to quickly identify critical RDD&D opportunities. Figure 6 provides a graphic representation of a node in an airport/base ecosystem. The figure highlights the high level of energy-related interconnections, subsystems, and influences across aviation facilities.

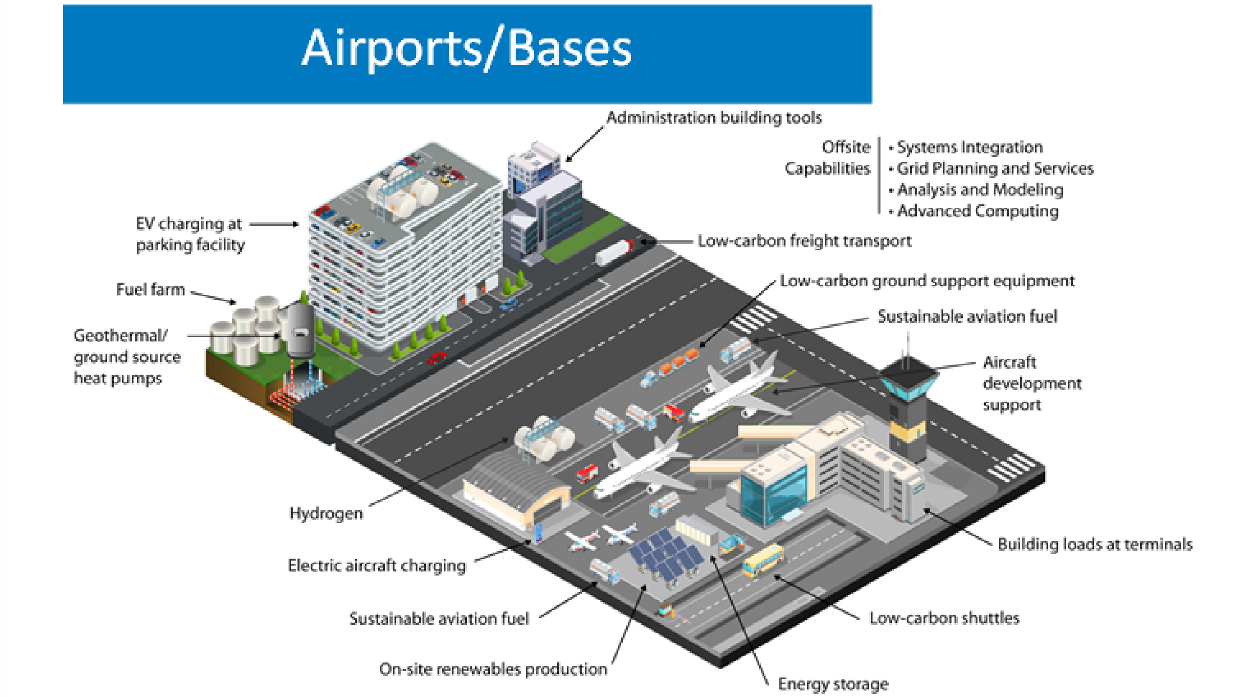

Figure 6. Airport/base sustainable ecosystem

Mimicking a small city, these aviation portals require coordinated energy delivery across various liquid, gaseous, and/or electrical forms to meet an ever-changing demand profile. Infrastructure supporting this energy demand must be scalable to meet growing needs, multimodally coordinated, responsive to maintenance and capital planning requirements, and flexible in approach to adjust to an evolving market. Currently, transportation sectors are primarily being evaluated on a sector-by-sector basis. However, there is a convergence of transportation sectors at airport facilities bringing last-mile delivery vehicles, light-duty vehicles, mass transit, aircraft, and, in many cases, rail to a concentrated location with the high energy needs of the airport facility at the center. Load management, resilience, coordination of energy supply at local and regional levels across all forms of energy (e.g., petroleum, natural gas, SAF, hydrogen, e-fuels, electricity), and new cyber challenges add to these ecosystem challenges. Research must also balance the paradigm of expanding passenger and cargo volumes in the future and look for opportunities to lower the needed energy demands. It is noted that much of current funding policy and initiatives for public facilities favor near-term capital cost reduction over long-term value, and/or precludes revenue generation from some funding sources. Should this situation persist, this results in higher ongoing costs for operations and likely less sustainable operations.

Support and advancement of existing efforts on en route economy and emissions reductions from a multimodal perspective is an area that has potential for additional benefits, including enhanced mode choice, route optimization, and related efforts. This is particularly acute on landside access and airport circulation, where rapid advancement in both light-duty vehicle automation and autonomy are bringing additional tools to the table in the near term, as well as long-term architectural possibilities that have significant potential to address energy, accessibility, and equity concerns. At most U.S. airports, landside access is dominated by individual vehicles, which must be parked, and then the user needs to navigate the airport and terminals, accessing flights and concessions through a number of systems. These systems will rapidly evolve with electrification and automation of vehicles. Low-speed vehicle automation technology enabling automated parking and valet services are being piloted for both after-market implementation and integration into new vehicles, opening the door to remote parking, charging services, and better charging management. In turn, a byproduct of an automated airport circulation system is enhanced efficiency of public transit and other shared modes, as "first-/last-mile" concerns are fully accommodated at the airport. Such advancements will come with additional challenges and pressures. Expectations of vehicle charging by travelers and employees will need to be met with sustainable resources. The ability to monitor and manage curb space, already stressed by the escalation of transportation network companies, will be needed when automated parking systems proliferate. In all, airport landside access presents many opportunities not only for increased energy sustainability, but also next-generation mobility access that addresses a broad array of urban mobility concerns.

4.4 Aircraft

Within the aircraft pillar, there is a different set of challenges for electrified aviation. The biggest is the energy density and weight of petroleum-based jet fuel alternatives such as batteries and hydrogen.

Current projected range for electrified aviation is 150 miles for electric vertical take-off and landing vehicles and 500 miles for electrified, conventional aircraft (Eviation 2022). If the energy density and/or weight of batteries is improved while maintaining safety, range can be greatly extended. Capital cost reductions, along with safety and range matching, will be important given that anticipated operating expenses, particularly energy, are anticipated to be economically attractive (Schwab et al. 2021). Additional challenges include charging standards and standardization of energy transfer rates, power electronics, charging cable management, inductive vs. conductive charging, new safety and emergency response standards, cyber protections, and energy transfer from the component to the grid level.

Advancements continue in utilization of hydrogen, both through combustion and hydrogen fuel cells. Work continues on modernizing hydrogen power turbines to improve upon concepts first flown more than 50 years ago, including work by Rolls-Royce in coordination with air carrier easyJet (Rolls-Royce 2022). Although hydrogen combustion has minimal carbon emissions, other greenhouse gas emissions and water vapor can be emitted, which are areas of concern. Work related to hydrogen fuel cell advancements continue to accelerate as manufacturers look to extend range, payload, and flexibility in energy delivery options (Walz 2020). Efforts by the Hydrogen Materials Advanced Research Consortium (HyMARC) provide mechanisms to improve energy storage through conventional liquid or gaseous storage and/or novel concepts such as alternative hydrogen carriers or storage within chemical structures such as metal hydrides (HyMARC 2022). Because of the legacy of attempts to utilize hydrogen for aviation, challenges are known and efforts are underway to attempt to improve upon methods to mitigate these concerns.

The aviation industry is accelerating with advancements in efficiency with each new aircraft design. Figure 7 provides a graphic representation of energy-related components within an aircraft. FAA-supported efforts are working to optimize existing aircraft, yet novel energy sources provide new opportunities to improve upon or potentially reimagine existing systems.

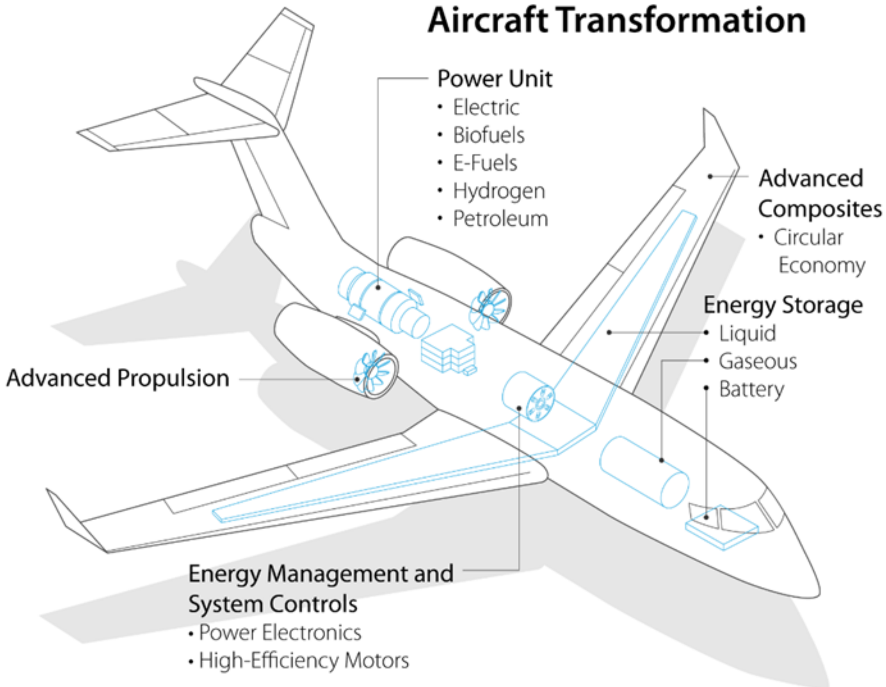

Figure 7. Aircraft transformation

As technology evolves, new aircraft and aerial vehicles are anticipated to serve myriad applications that will transform mobility and address customer needs. Holistic aviation decarbonization is envisioned to also incorporate autonomous flight, increasing communication needs, intermodal connections, and the associated energy for each. Research for accelerating key components within these aircraft related to electrification include battery energy densities and charge rates, power electronics, ultra-high-efficient motors, and conductors. Industrywide efforts could benefit from recyclability, reduction of rare earth elements, sustainable materials, and composites utilization. Further research is also needed for hydrogen fuel storage on aircraft to address weight versus range, tank design, pressure trade-offs, and transfer or refuel rates. New research could be directed toward hybrid propulsion systems (e.g., SAF/electric, hydrogen/electric, hydrogen fuel cell/electric) to capitalize on near-term industry transition.

5 Complementary and Integrated Analysis To Inform Strategic Roadmapping

To complete the holistic decarbonization assessment of the aviation ecosystem, research must include the interdependencies with other industries and their social, economic, and environmental impacts. These interdependencies include energy generation, transmission and distribution planning, ground transportation and other intermodal logistics, industrial and manufacturing needs, community energy and transportation planning from rural to urban locations, autonomous energy systems to facilitate incorporation of grid edge technology, energy and environmental justice. Currently, multiple federal agencies are addressing components of this system with the opportunity for additional collaboration in decarbonizing aviation at a system level in a resilient and sustainable manner. Leveraging coordination and industry, federal, and state collaborations will bring the necessary scale, impact, and transition management to achieve consistent solutions for the aviation industry and related interdependent systems to reach their decarbonization goal. Coordination of this type generally results in achieving goals more quickly and at lower costs.

This holistic approach is poised to identify additional options as the global aviation ecosystem moves toward decarbonization. For example, mobility options are anticipated to accelerate with the commercialization of electric and hydrogen-based aviation. Rapid intercity to regional transportation, point-to-point, or rural to urban flight options may offer better coordination for intermodal connections and provide new, lower-cost options for commerce. Emission, contrails, and other environmental pollutants will be reduced should greater volumes of decarbonized fuels integrate into the aviation industry. Cyber measures leveraged from energy sector efforts are available to raise the security and safety of new aviation options. As more airports across the spectrum from major airport hubs to small, rural airfields adopt on-site renewable electricity generation and energy storage, resilience of the energy supply and ability to meet demand may offer enhanced benefits for both aviation and local community energy needs. Carbon-negative SAF or e-fuels would assist with environmental efforts. Lower-cost mobility and freight/package delivery costs could provide an economic boom to the United States and around the world.

The immense effort to tackle aviation ecosystem decarbonization is indeed formidable. Challenges are significant within each pillar of the ecosystem—fuels, airport ecosystems, and aircraft. Fuels require economical solutions that can be implemented with lower risk and at a global scale. Airports, bases, and vertiports are complex, interdependent systems that are rapidly changing in their energy types, use cases, and demand models. Advanced research and analysis on an aircraft's energy components such as batteries, power electronics, hydrogen components, including fuel tanks, and material composites would accelerate new mobility applications, certification, and adoption. Holistic RDD&D offers the opportunity to maximize impact and accelerate decarbonization across the aviation industry. This initial outline of major areas for innovation across the ecosystem lays out a framework for significant future work that is necessary to develop detailed RDD&D roadmaps to deliver holistic, sustainable energy solutions throughout the aviation ecosystem.

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Appendix A. Carbon Sources From Aviation Ecosystems

Source: Airport Carbon Accreditation (2020)