By Phillip J. Ansell

Hydrogen-Electric Aircraft Technologies and Integration

Enabling an environmentally sustainable aviation future.

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AS THE GLOBAL COMMUNITY GRAPPLES with growing concerns of a changing climate, many eyes have turned to the sustainability of the transportation sector. In the United States, transportation is currently the leading category contributing to all greenhouse gas emissions, producing more emissions per year than the electricity generation, industry, commercial and residential, and agricultural sectors individually. As various transportation modes transition to more sustainable models, such as with the use of battery-electric vehicles, the aviation sector has struggled to identify effective solutions for future sustainability goals, largely due to the difference in power and energy requirements of aircraft, as compared to other vehicles. One solution currently being explored by a number of academic, government, and industry researchers is the use of hydrogen-energy systems on aircraft. Although practical challenges do exist in hydrogen adoption on aircraft, lightweight energy storage mediums remain appealing and technically viable solutions for future generations of air vehicles. More specifically to hydrogen-electric aircraft configurations, further significant developments are required in key technologies, such as high-temperature fuel cell power plants, electric machines, power electronics, power transmission systems, airframe designs, and propulsion system integration. However, there nevertheless remains a line-of-sight pathway to future zero-emissions aircraft capable of meeting or exceeding the performance of existing air vehicles. As described in this article, the advantages of future hydrogen-electric aircraft reside not in one specific technology but rather in the synergistic integration of a multitude of components into innovative aircraft configurations. These developments are explained using a candidate hydrogen-electric aircraft designed to fill the same mission-performance characteristics as a single-aisle reference aircraft, while producing zero carbon dioxide (CO_2) and nitrogen oxide emissions across the entirety of the aircraft's long-range mission.

Section 1—The Need for Sustainability

In 2018, CO_2 emissions directly attributable to the global aviation industry exceeded, for the first time, beyond an annual production rate of 1 billion metric tons. Although CO_2 emissions produced by the aviation sector have steadily increased throughout the lifetime of commercial aircraft operations, the overall efficiency and carbon intensity of aircraft has actually demonstrated significant improvements across previous decades. However, historical world air traffic has grown by between 3–5% each year, resulting in an approximate doubling of passenger miles traveled every 10–15 yr. This dramatic increase in commercial air traffic has consequently resulted in considerable growth of the climate impact produced by the aviation industry, which is anticipated to continue into future decades as fuel burn outpaces technological improvements. An example forecast of CO_2 growth due to international aviation and the continued use of fossil-derived kerosene fuels is shown in Figure 1, according to a 2019 International Civil Aviation Organization (ICAO) Environmental Report. However, despite these staggering CO_2 emissions metrics, overall, aviation has historically contributed between only 2–3% of annual global anthropogenic CO_2 emissions. In this way, the carbon footprint of aircraft operation is easily eclipsed by those associated with terrestrial energy and other transportation sectors.

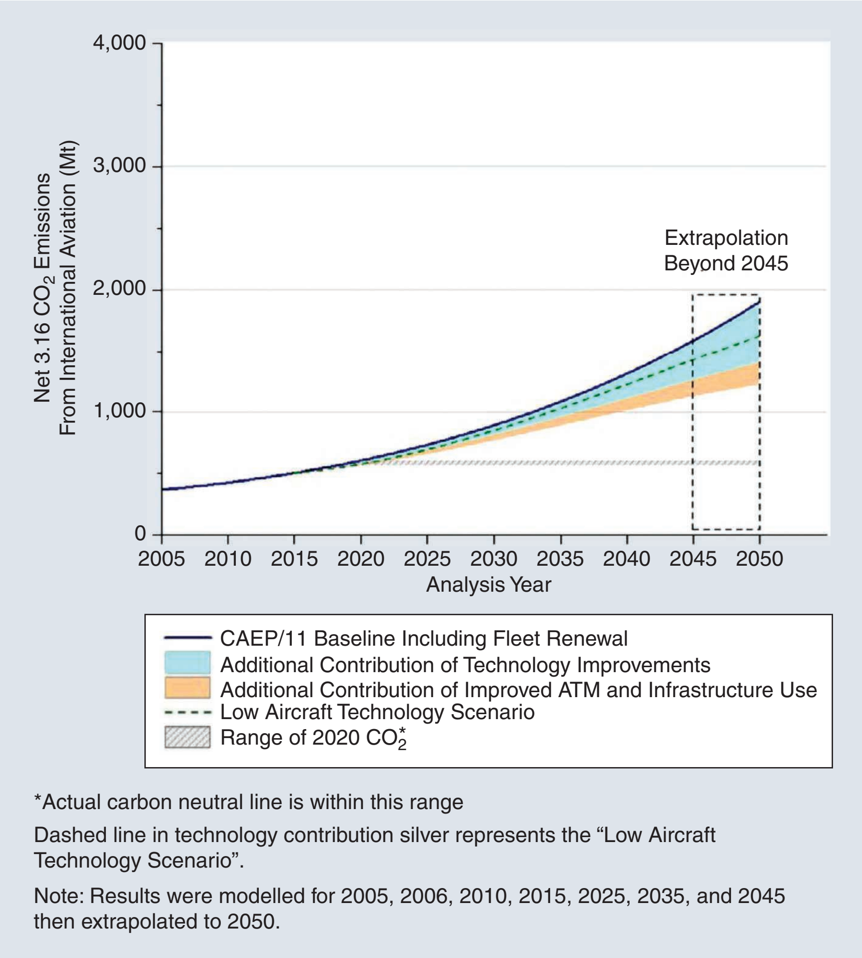

Figure 1. The CO_2 emission forecast for international aviation. ATM: Air Traffic Management; CAEP: Committee on Aviation Environmental Protection.

So why is it that environmental sustainability of the aviation industry should be appreciably considered when the impact of decarbonization is seemingly of small significance? One reason is that CO_2 is not the only greenhouse gas emission produced by the combustion of aviation fuels. Most of the general aviation aircraft today are fueled using a gasoline with a tetraethyllead additive, making it a leaded gasoline. Aviation turbine fuels, which are used on jet aircraft, are kerosene based. The combustion reaction of oxygen and nitrogen from the atmosphere and hydrocarbon fuel results in a broad array of emission components, including CO_2, water vapor, nitrogen oxides (NO_x), nitrous oxide (N_2O), carbon monoxide (CO), sulfur oxides (SO_X), particulate matter/soot, and unburnt hydrocarbons. Although CO_2 has a predominant effective radiative forcing impact, which represents an increase in the net energy trapped within Earth's atmosphere, other emission products also have significant influences on climate impacts.

The environmental impact of aviation is by far dominated by the fuel burn of commercial aircraft systems, which are responsible for approximately 93% of aviation-related fuel burn globally.

Note that nucleation and ice crystal formation around soot particles at high altitudes and low temperatures results in the production of contrail cirrus clouds. Similarly, NO_x products from aviation at high altitudes undergo a number of additional chemical reactions following emission from the aircraft, leading to an increase in production of ozone and other impacts. Although much work still remains to fully understand the role of these other emissions on the climate impact of aviation, recent studies have placed the net climate impact of contrail cirrus cloud formation and long-term NO_x, which have an overall impact on warming potential comparable to that of CO_2 emissions.

The environmental impact of aviation is by far dominated by the fuel burn of commercial aircraft systems, which are responsible for approximately 93% of aviation-related fuel burn globally. Given that the majority of this fuel burn for commercial aircraft occurs across the upper edge of the troposphere and into the lower edge of the stratosphere (i.e., approximately 30,000–40,000 ft), the environmental impact of fuel burn in aviation is unique when compared to the emission products produced at ground level. The perturbations to the natural atmospheric composition and chemical processes at these altitudes has remained a significant cause of concern, such that CO_2 or other emission products produced at these high altitudes cannot simply be viewed as being equivalent to those produced by other industries. The high altitudes used by commercial aircraft also contribute to the nonlocalized impact that aircraft operation has on global air quality and radiative forcing, while also complicating the bookkeeping of emissions "ownership" by global nations.

However, consideration of sustainable alternatives for future commercial air vehicles introduces several other challenges due to the unique operating configurations of aircraft as compared to other modes of transportation. Most notably, the efficiency and feasibility of an aircraft is far more sensitive to vehicle weight than ground transportation systems. As such, although battery-electric configurations have revolutionized much of the ground transportation market, the prohibitively heavy weight and large volumetric size of battery systems do not make them a viable means of displacing kerosene fuels for commercial aircraft. In particular, the specific energy (amount of energy contained per unit of mass) of kerosene is 12 kWh/kg, roughly 50–60 times that of a modern lithium-ion battery pack. As such, viable candidates for replacing aviation fuels for aircraft across short ranges and limited payloads are available or will be in the near future, but as mentioned previously, these platforms are not currently the predominant contributor to aviation-related emissions. Even though revolutionary improvements in battery system technologies are anticipated, it is unlikely that batteries will be capable of bridging this specific energy gap within the foreseeable future.

Although the use of hydrogen-energy storage has been considered in a number of other markets with mixed results, it is one of the lightest energy carriers known, having a specific energy 2.8 times that of kerosene. It can also be renewably produced through electrolysis or reverse fuel cell operation as long as the electrical power and other resources needed for the fuel production pathway are renewable. The chemical energy contained within hydrogen can also be released through a broad variety of means. When considering hydrogen as a drop-in fuel, it can be used in a thermal engine to produce mechanical power for aircraft propulsion, such as the one used in a conventional Brayton cycle to power a turbofan, or be used with a turbogenerator to produce electrical power. Hydrogen can also be used with a broad variety of fuel cells through an electrochemical process to produce electrical power directly.

The aforementioned features make hydrogen a highly attractive energy carrier for future aircraft systems. However, hydrogen integration into aircraft is not without significant technological challenges as well. Even in a condensed form, liquid hydrogen (LH_2) has an energy density (amount of energy contained within a given storage volume) roughly one-quarter that of kerosene. The requirement of large hydrogen volumes for aircraft platforms is further exacerbated by additional safety concerns related to the cryogenic temperatures of LH_2 and extreme flammability of hydrogen gas. Nevertheless, multiple government, academic, and industry research groups are actively considering LH_2 systems for future sustainable aircraft concepts.

The current article is intended to provide an introduction to methods for synergistically combining a broad variety of hydrogen-electric aircraft technologies to produce system-level benefits and meet future sustainable aviation goals. It is also intended to focus on single-aisle commercial aircraft and far-term developments. Relatedly, complementary discussions on smaller aircraft platforms of regional jet-class and nearer-term technologies can be found in a companion article of this special issue of *IEEE Electrification Magazine*.

Hydrogen can also be used with a broad variety of fuel cells through an electrochemical process to produce electrical power directly.

Section 2—Hydrogen-Electric Aircraft Integration

The discussions on hydrogen-electric aircraft are framed around the aircraft concept shown in Figure 2, which was developed by the Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA). This aircraft was configured with mission capabilities commensurate with a reference single-aisle aircraft (Boeing 737–800), matching the same range, payload, and cruise Mach number capabilities of the incumbent system. The concept is assumed to feature an entry-into-service date of 2050, and as such, improvements in several technological capabilities are assumed. The aircraft power system primarily consists of multiple high-temperature proton exchange membrane (PEM) stacks capable of meeting the 28-MW maximum power requirement of the aircraft. These fuel cell systems are combined with a battery system to improve coverage of transient loads across the aircraft mission.

Section 2.1—Considerations for Power Plant Configuration

In this particular aircraft configuration, fuel cells were utilized in lieu of turbofans or turbogenerators for multiple reasons. First, the underlying goal of the aircraft concept was to completely eliminate all CO_2 and NO_x emissions

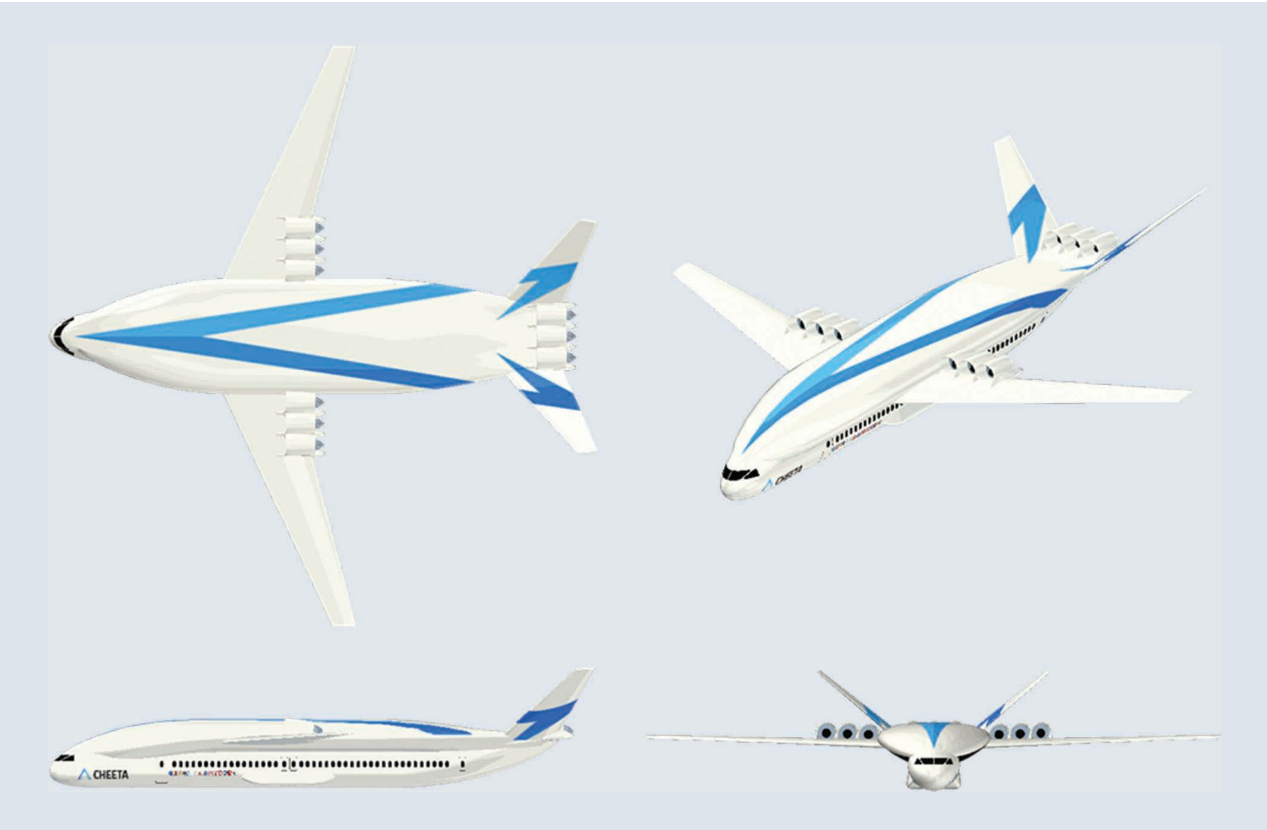

Figure 2. Three-view and isometric displays of a hydrogen-electric aircraft concept.

produced at the vehicle level. In the process of combusting hydrogen with ambient air for a conventional turbofan, a nonzero amount of NO_x is produced in the thermal reaction, which would not meet the underlying programmatic goals for this aircraft concept. Second, the electrochemical efficiency of modern fuel cell systems commonly exceeds thermal efficiencies of gas turbine systems. Although today's fuel cells feature a specific power (maximum power output per unit mass) significantly lower than that of gas turbines, fuel cell weights have decreased dramatically across the previous decade. As such, the aircraft concept was configured to address the question of what benefits may exist in aircraft operational efficiency if these trends in fuel cell light weighting continue. Third, it was also assumed that a direct electrochemical conversion process for hydrogen into electrical power would provide a lighter-weight and lower-loss solution to converting hydrogen chemical energy into electrical power, as compared to that which is produced by use of a turbogenerator.

For a turbofan, the energy release produced by combustion powers two turbine spools: one intended to power the compressor and another to power the fan.

A high-temperature PEM fuel cell architecture was also selected over standard PEM systems to better accommodate thermal management requirements of the high-power fuel cell system. To this end, configuration of the thermal management system for the power plant remains one of the most significant challenges of a fuel cell hydrogen-electric aircraft architecture. The operating efficiencies of lightly loaded PEM fuel cells on the order of 65–70% are not uncommon. However, the heat rejection required for these systems become extremely large, simply due to the power requirements of the aircraft operation. Additionally, electrochemical efficiency decreases at higher power ranges, exacerbating the production of low-grade waste heat. Even though heat exchanger systems can be configured to address these thermal loads, they negatively impact the overall aircraft weight and include a nonnegligible drag penalty. As a result, aggregate aircraft performance and efficiency is highly sensitive to how this thermal management system is integrated, and novel means for best accommodating large amounts of low-grade waste heat on aircraft is an area of active investigation.

The decoupling of power generation from thrust production on the aircraft also produces multiple benefits to the aircraft's operation strategy. For the aircraft concept presented in Figure 2, the power system is configured to provide fully redundant transmission pathways across propulsor modules in the event of failure in a given fuel cell power plant or single transmission line. Such a reconfiguration capability is practically infeasible for turbofan systems due to a mechanical coupling of the core and bypass flow systems. Another advantage of this decoupling is the ability to operate air-breathing inlet compression systems independent of the fan thrust. With air density significantly decreasing with altitude, additional compression is required to achieve the same mass flow of air into a gas turbine combustion chamber or fuel cell cathode. For a turbofan, the energy release produced by combustion powers two turbine spools: one intended to power the compressor and another to power the fan. In this way, however, the operation state of the fan is physically connected to the aerothermodynamics of the engine's core. For a fuel cell, the air inlet compression system can be operated across a broader range of pressure ratios independent of the operating state of the fan. Although this greater compression comes at a cost of increased parasitic power loss from the fuel cell system, it also reduces the lapse in maximum power that the fuel cell can produce with increased altitude. Since the top of climb, high-altitude requirements typically define the size and power of a turbofan propulsion system, the fuel cell power plant can be configured to meet the high-altitude power required with smaller-rated power requirements at sea level. These power reductions help partially compensate for the heavier weight of the fuel cell and thermal management systems.

Section 2.2—Cryogenic Fuel as an Opportunity

The use of hydrogen-electric configurations also offer several advantages in terms of propulsion-airframe-integration possibilities due to the delocalization of power production and thrust generation across the aircraft. In this way, distributed-electric propulsion concepts (see the "Section 2.4—Additional Benefits of Distributed Electric Propulsion" section) become a viable option, where aerodynamic surfaces, propulsion systems, and other airframe components are synergistically coupled in a fashion that produces system-level benefits. However, propulsion systems for conventional transport aircraft feature-rated power requirements range from several dozen to hundreds of megawatts. With these extreme power values, designing the electrical power system to be lightweight, spatially compact, and highly efficient is paramount. In pursuit of these three priorities, the use of cryogenic and superconducting technologies are areas of active exploration. With the boiling temperature of LH_2 fixed at 20 K (at atmospheric pressure), the additional use of the energy carrier as a cryogen is concept of active exploration. An example power system used for the aircraft concept in Figure 2 is displayed in Figure 3 and leverages a hydrogen-cooled transmission, motor, and inverter configuration.

Assuming ample LH_2 cryogen is available, the advantages of using superconducting materials for power transmission is clear. The superconducting state of several materials at LH_2 temperatures, such as magnesium diboride, yttrium barium copper oxide and others allows for high-power electrical transmission without ohmic losses. These materials are thus able to sustain extreme current density, which serves as an added advantage for allowing transmission voltages to be decreased relative to those envisaged for conventional conductors. This decrease in voltage alleviates some challenges of insulation and termination of power transmission components for aircraft operating at low-pressure environments at altitude. Additionally, the use of superconducting busbars for routing electrical power from the transmission lines to individual load paths allows for significant reductions in busbar weight, size, and heat production. However, the use of superconductors also requires the careful design and configuration of current leads, where the power transmission is converted from a conventional, high-temperature conducting state to a superconducting state. Additionally, ensuring the fault tolerance of superconducting transmission systems requires careful additional analysis as loss of cryogen flow may lead to the permanent damage or failure of power system components.

Clear advantages can also be leveraged when cryogenic LH_2 is used to bolster the efficiency and power density of power electronics and electrical machines. Additional technical information about cryogenic power electronics and superconducting machine systems can be found in companion articles to this special issue of *IEEE Electrification Magazine*. In brief, the low-temperature operation of some power electronics devices offers advantages of

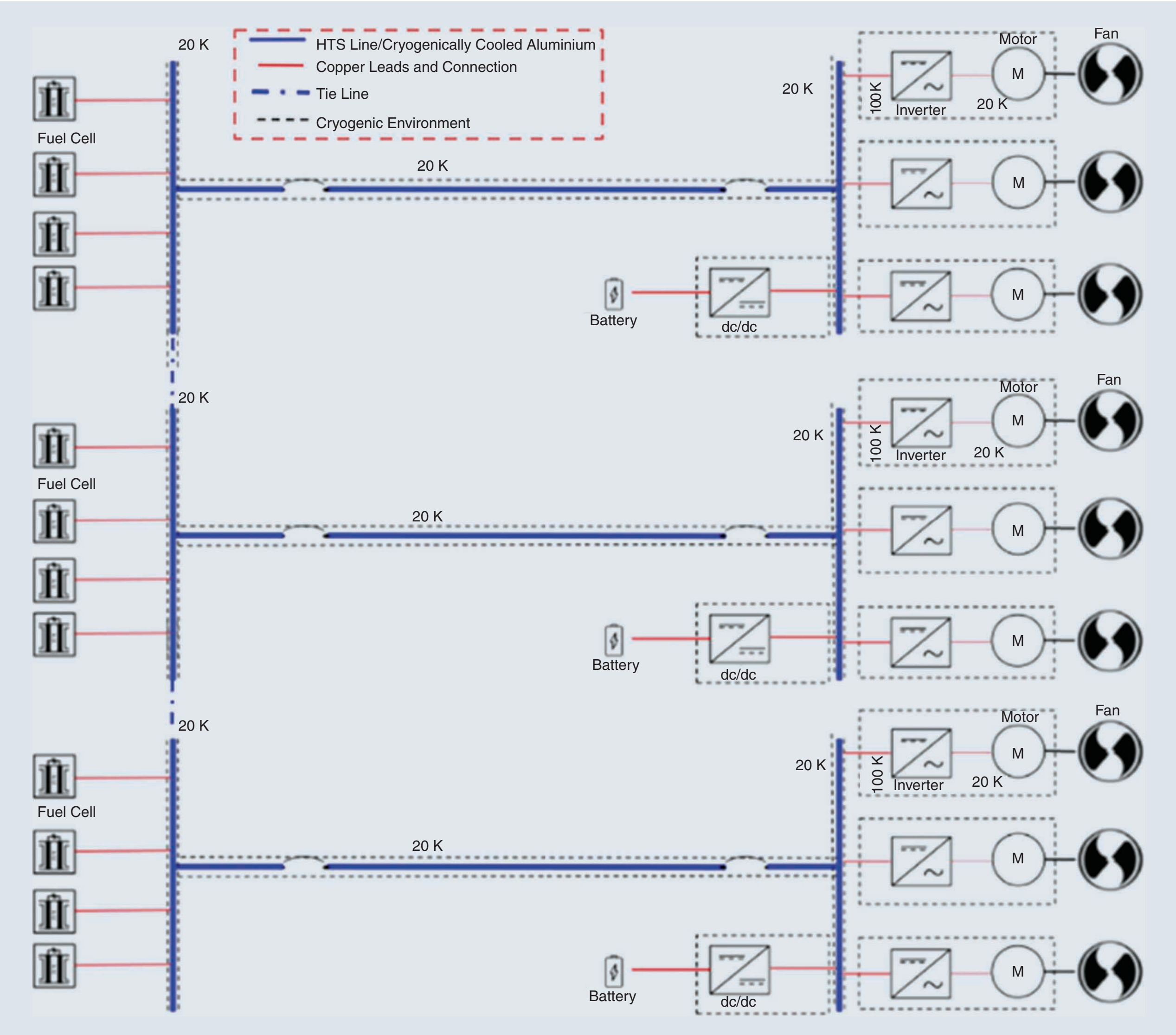

Figure 3. The power system architecture for a hydrogen-electric aircraft concept. HTS: high-temperature superconductor.

reduced losses and faster switching speeds, resulting in overall lighter and higher-efficiency systems as compared to conventional power converters. However, not all electronics components, such as gate drivers and power supplies, are able to robustly operate at cryogenic temperatures. This aspect thus requires the careful isolation of certain components to thermally insulated regions of converter systems outside of a cryogenic environment.

A careful design of the superconducting motor system is also required to prevent a system failure or thermal runaway in the event of a quench event.

Similarly, superconducting machines, which are enabled through the use of superconducting materials for motor windings, offer significant increases in specific power, power density, and efficiency. The extreme current density of these materials allow incredibly large induced magnetic fields to be produced in a very small form factor. Although the superconducting state eliminates ohmic losses in the motor coils, the presence of the coils within the induced field results in nonnegligible ac losses of the system. As such, thermal management of the machine becomes increasingly important as ample flow of cryogen is required in opposition to the heat generation associated with this ac loss component to maintain the superconducting state. A careful design of the superconducting motor system is also required to prevent a system failure or thermal runaway in the event of a quench event.

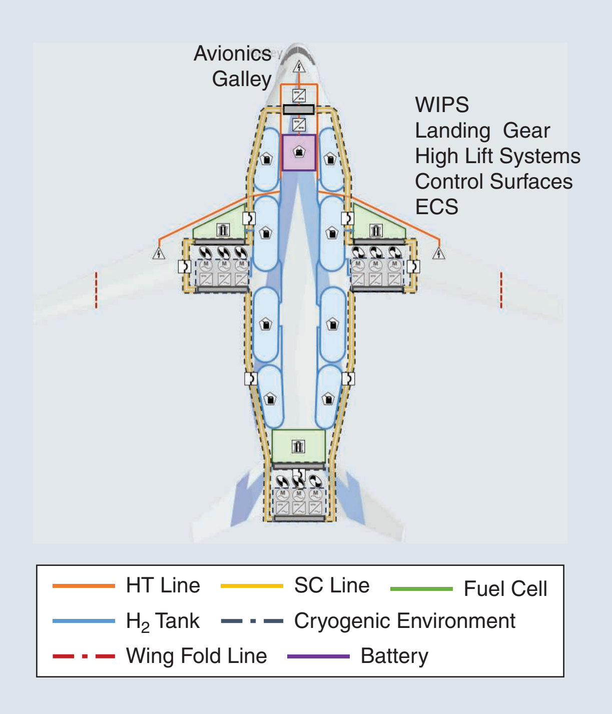

Figure 4. The internal layout of a hydrogen-electric power and energy system on the CHEETA configuration. ECS: Environmental Control System; HT: high temperature; SC: superconducting; WIPS: Wing Ice Protection System.

Therefore, it is clear that the extremely low temperature of LH_2 opens up many new possibilities for future hydrogen-electric aircraft but that a significant body of work is still required to address several inherent challenges associated with the feasibility and integrability of electrical system technologies. Simply because LH_2 is available does not necessarily signal that the flow of this cryogen is sufficient to meet the thermal loads of an entire electrical system across all instants of a flight profile and under off-design scenarios. The cases where LH_2 supplies are insufficient or in excess of those required necessitate careful consideration.

Section 2.3—Design for Volume Accommodation and Safety

When considering future hydrogen-electric aircraft concepts, the aforementioned challenges of cryogenic temperatures, fuel flammability, and storage requirements (including large volume and leaks) are predominantly referenced as the key technical barriers limiting future adoption of hydrogen as an energy carrier. The advances in hydrogen storage, fuel distribution, and cryogenics are necessary to address these concerns and make LH_2 aircraft solutions technically viable, and more information on these thrusts can be found in a companion article within this special issue of *IEEE Electrification Magazine*. However, additional methods for overcoming these technical challenges can also be made through purposeful and careful design approaches of aircraft systems. These features can be observed in the external diagrams depicted in Figure 2 as well as the internal layout of the hydrogen-electric power and energy system shown in Figure 4.

When considering a hydrogen system integration on an aircraft platform, one must always envision the worst-case scenario of failure modes that are possible for the aircraft to encounter, even if these situations are unlikely. Even though hydrogen is not nearly as prone to detonation as many other fuels, it is incredibly flammable, requiring very little external energy to ignite, even with limited concentrations of oxygen. Gaseous hydrogen is also incredibly buoyant, and integration efforts must be taken to avoid passage of hydrogen fumes across regions enclosing passengers, flight crews, or other safety-critical systems. Given this flammability risk and consideration for buoyancy, the CHEETA configuration was established with LH_2 tanks mounted high on the aircraft. In the event of a strike to the aircraft undercarriage due to failed landing gear or foreign object debris on runways, the risk of a puncture to the tanks is reduced. Similarly, in the event of a belly landing due to gear-actuation failure, the risk of ignition of fuel vapors in the vicinity of the aircraft undercarriage will be significantly mitigated. The high mounting of the hydrogen fuel system also accommodates upward venting of hydrogen vapor from the apex of aircraft structures and surfaces.

In addition to being mounted above the passenger cabin, the tanks are mounted laterally outside of the region occupied by the aircraft's pressurized main cabin. As such, the only regions where fuel flow pathways cross over the aircraft's centerline are within a forward firewall region and at the aft end of the aircraft. Limiting flow lines of cryogenic LH_2 to occur outside of passenger and flight crew occupancy areas ensures that large breaks or leaks in LH_2 flow will not pose frostbite hazards to occupants of the aircraft. A gap in the longitudinal placement of the tanks can also be observed near the trailing edge of the wing-body interface. The absence of tanks in this vicinity is motivated by the need to reduce the probability of tank puncture in the event of a propulsor fan-blade off event.

Another notable characteristic illustrated in Figure 2 is the wide centerbody blended into the aircraft's fuselage. On a conventional kerosene-based aircraft, fuel is typically stored within the wing structure. However, with the significant increase in volume required for an LH_2 system, increasing the wing area to accommodate this storage requirement would result in a wing configuration with a very low aspect ratio (AR). Small-AR wings typically have poor aerodynamic performance and, as such, would result in increased energy requirements of the aircraft's platform. Conversely, isolated external tanks alleviate these limitations on wing aerodynamic performance but also represent an appreciable drag penalty without significant lift benefits. Instead, for the CHEETA configuration, the large-volume centerbody is intended to serve as both an unpressurized fuel storage region and an intentional lift-generating component of the aircraft. This lifting centerbody can actually be configured to improve aerodynamic efficiency of the entire aircraft configuration, relative to modern tube-and-wing designs, by allowing lift distribution across the span of the aircraft to be more ideally configured. The quasi-cylindrical fuselages used today do generate a nonzero amount of lift during a typical cruising flight stage but also introduce a local decrease in the overall lift profile. The defect produced in this "carryover lift" of a typical fuselage reduces the aerodynamic efficiency of the configuration, relative to an ideal lift distribution. By utilizing the hydrogen storage centerbody region as an active lift producer, lift distribution can be returned to a more ideal state for maximum aerodynamic performance.

The quasi-cylindrical fuselages used today do generate a nonzero amount of lift during a typical cruising flight stage but also introduce a local decrease in the overall lift profile.

Section 2.4—Additional Benefits of Distributed Electric Propulsion

Utilization of the aforementioned lifting centerbody does result in improvements to the lift distribution, although volumetrically driven increases to the aircraft-exposed surface area (referred to technically as the *wetted area*) are unavoidable. This increase in wetted area is typically associated with undesired additional drag due to an overall increase in the aerodynamic skin friction applied across the aircraft's surface. For this reason, a bank of propulsors are configured across the downstream end of the lifting centerbody as this configuration allows the benefits of boundary-layer ingestion to improve propulsive efficiency and partially offset skin-friction drag penalties.

Stated broadly, boundary-layer ingestion leverages the low-momentum state of the slow-moving air present in a region immediately adjacent to the vehicle, known as the *viscous boundary layer*, to improve the efficiency of doing work on the flow by the propulsion system. In simplified terms, if the flow entering the propulsion system begins with a large flow velocity, a large increase in kinetic energy is required by the propulsion system to produce a given increment in flow momentum. Conversely, as the boundary-layer flow is already in a low-momentum state, a smaller increment in kinetic energy of the flow is required to produce a given amount of thrust. As such, boundary-layer ingestion can act to reduce the power required by the propulsion system to deliver a given thrust requirement. To be clear, the improvements in propulsive efficiency provided by boundary-layer ingestion do not indicate that momentum should be purposefully removed from the flow as much as possible, but rather that this serves as a useful approach to offsetting the undesired momentum decreases (i.e., drag) imposed by large surface-area regions like hydrogen storage volumes and fuselages.

In addition to centerbody-integrated propulsors, a series of wing-integrated propulsor banks are also presented in Figure 2. Although boundary-layer ingestion benefits can be expected for these wing-integrated propulsors, the associated reductions in power are appreciably less aggressive than those anticipated for centerbody-integrated propulsors. Instead, the primary motivation for wing integration of these propulsor banks is to allow a high-momentum nozzle flow of the fan units to be used for augmenting maximum lift characteristics of the wing system at low speeds. Blown flaps have been used on a number of aircraft platforms, such as the Lockheed F-104 Starfighter, McDonnell Douglas C-17 Globemaster, and numerous others. Coupling the propulsion system to the aerodynamics of the wing section allows sufficient lift to be produced during low-speed takeoff and landing segments of flight with a reduced reliance on heavy, high-lift flap systems. The partial removal of traditional high-lift systems results in a reduction of the additional aerodynamic surfaces, actuation, and track systems, alongside the additional structural weight required to support these devices.

Another benefit of utilizing a distributed electric propulsion system is the improved resilience to propulsor failure scenarios. For the internal power diagram depicted in Figure 4, it is assumed that a worst-case scenario of power failure would either include the loss of an entire fuel cell power plant module or loss of an entire bank of propulsors (e.g., due to loss of an entire dc bus). Current aircraft are configured to be capable of completing takeoff and landing procedures under a critical engine-out scenario, which often serves as the limiting factor when sizing the tail surface and takeoff field length requirement. As modern, conventional single-aisle jet aircraft utilize two turbofan engines, takeoff and flight-stability requirements are set by a failure scenario governed by a ~50% reduction in gross thrust and aggressive yawing moments induced by an imbalance of thrust generation across the aircraft's centerline. Using the distributed electric propulsion configuration shown in Figure 4, the critical failure scenario becomes more analogous to a three-engine system, with two wing-mounted engines and one tail-mounted one. This type of scenario produces more benign penalties to the empennage sizing and balanced field length requirements, as compared to a two-engine system. However, certification requirements and detailed studies into failure-mode scenarios for aircraft with highly distributed propulsion systems are still not fully established. As such, it is entirely possible that assuming the loss of an entire singular propulsor bank is overly aggressive, and the one-engine-inoperative rating (or equivalent) for distributed electric propulsion systems provide even further system-level benefits than those suggested here.

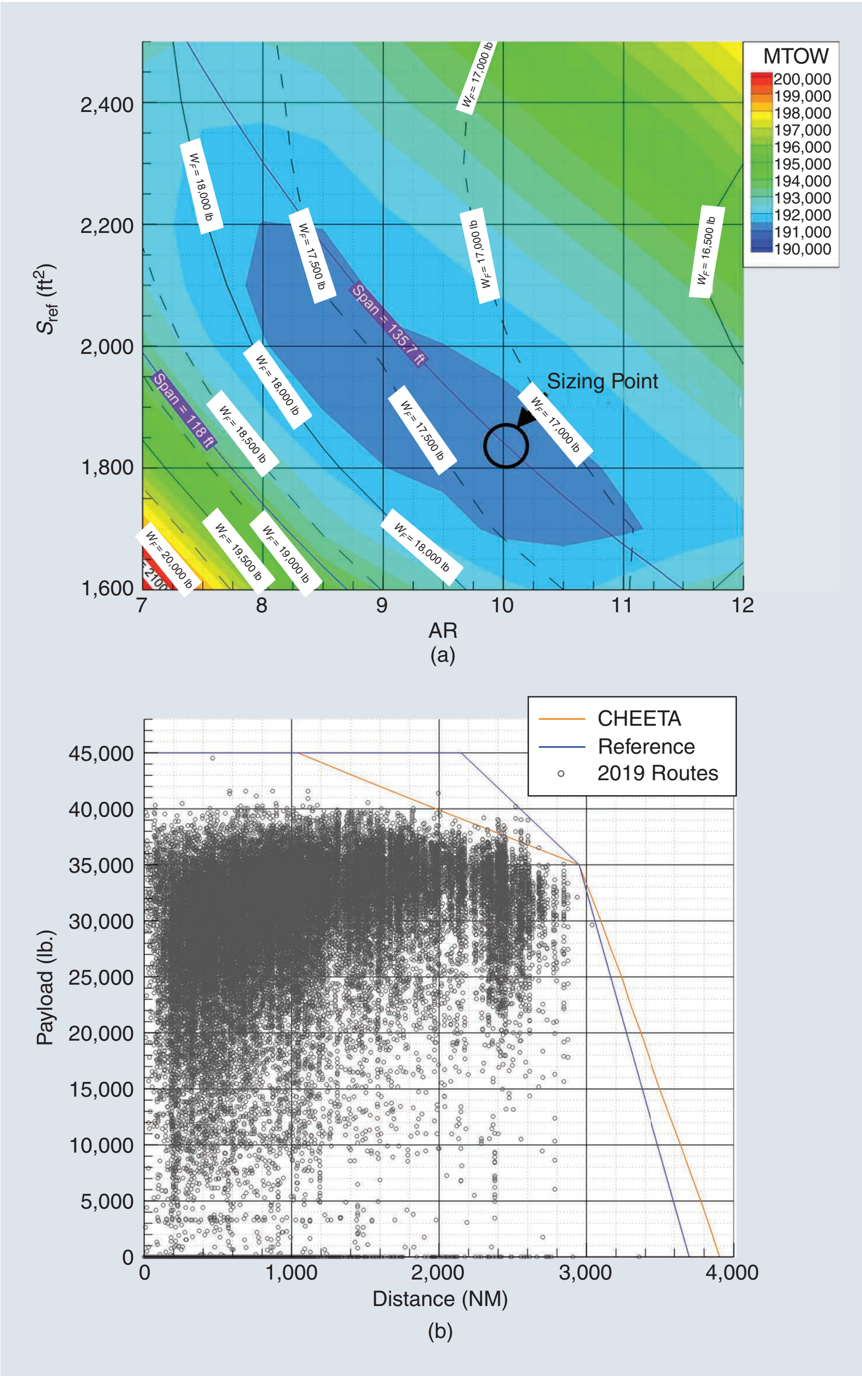

Figure 5. Hydrogen-electric aircraft sizing based on (a) primary wing design variables and (b) resulting payload-range capabilities.

Section 2.5—Resulting Performance for Novel Aircraft Systems

When incorporating various the integration considerations for a hydrogen-electric aircraft described in this article, the resulting concept is observed to close on a design capable of meeting the same mission performance of the reference aircraft with zero-CO_2 and NO_x emissions at vehicle level. Given the preliminary nature of the aircraft's concept, certain reductions in energy requirements due to boundary-layer ingestion, modern composite materials, powered lift, and optimized thermal management strategies are not included. Nevertheless, a comparison of the aircraft's maximum takeoff weight, with variations in wing design characteristics, is shown in Figure 5(a). This parametric comparison was used to perform the initial sizing of the aircraft's system. After establishing this baseline, it was identified that a further increase in the fuel cell's rated power led to significant decreases in the net energy requirements of the aircraft's mission due to improved electrochemical conversion efficiencies at lower current densities across the cruise stage. Additionally, mission capability of the integrated hydrogen-electric aircraft concept is displayed in Figure 5(b) as compared to the reference aircraft, alongside a scatter of all U.S. domestic flights flown by the reference aircraft. It can be seen that the hydrogen-electric aircraft concept studied here is capable of practically meeting all mission segments currently flown by the incumbent aircraft. The final conceptual design performance characteristics of the hydrogen-electric aircraft are listed in Table 1 as compared to the reference aircraft. It should be noted that the power of the reference aircraft system was based on an estimated rescaling of an aerothermodynamics analysis performed on a similar class of turbofan consistent with that of the reference aircraft. Furthermore, the hydrogen-electric concept requires a significant degree of successful future technological improvements to be viable, and such a configuration is far from feasible today. Nevertheless, this comparison provides a snapshot of one promising scenario for building a future zero-emissions aviation future.

Section 3—Lifecycle Considerations for LH_2 Fuel

The aforementioned discussions on vehicle-level integration of technologies for hydrogen-electric aircraft demonstrate how such a system could be configured to overcome the size, weight, and power challenges of other electrification strategies for transport-class configurations. However, the potential of hydrogen-electric systems as a sustainable alternative to kerosene-based fuels also requires a coupling to the broader power and energy ecosystem. As the energy and emissions requirements of the aircraft platform described in the "Section 2—Hydrogen-Electric Aircraft Integration" section were evaluated only at the aircraft level, there is an entirely separate set of contributions to sustainability that must be considered through fuel production pathways.

One advantage of hydrogen is that there are many production pathways to creating it because hydrogen is a fundamental building block of nature. However, not all pathways to producing hydrogen are equally sustainable, and often the most sustainable solutions end up being the most expensive. CO_2-equivalent (CO_2e) emissions, assuming a 100-yr global-warming potential produced by various LH_2 fuel production pathways and scenarios, are shown in Figure 6. Currently, steam methane reforming is a dominant approach to hydrogen production due to its relatively low cost and ease in production of hydrogen en masse and on demand. Without application of carbon-capture approaches, this production pathway produces significant carbon emissions, resulting in impacts greater

TABLE 1. The mission-performance parameters for a hydrogen-electric aircraft concept and a reference single-aisle aircraft.

Parameter	CHEETA (LH_2-Electric)	Reference Aircraft
Maximum takeoff weight (lb.)	196,794	174,200
Fuel weight (lb.)	16,189	46,131
Wingspan (ft)	135.7 (118 folded)	113
Energy carrier	LH_2	Jet A
Energy use (relative to reference aircraft) (%)	97.7	100
Time to climb (min)	23	22
Static sea-level peak power (MW)	28.4	~32
Vehicle-level CO_2 (lb./pmi)	0	0.2
Vehicle-level NO_x (lb./LTO cycle)	0	27

LTO: landing and takeoff.

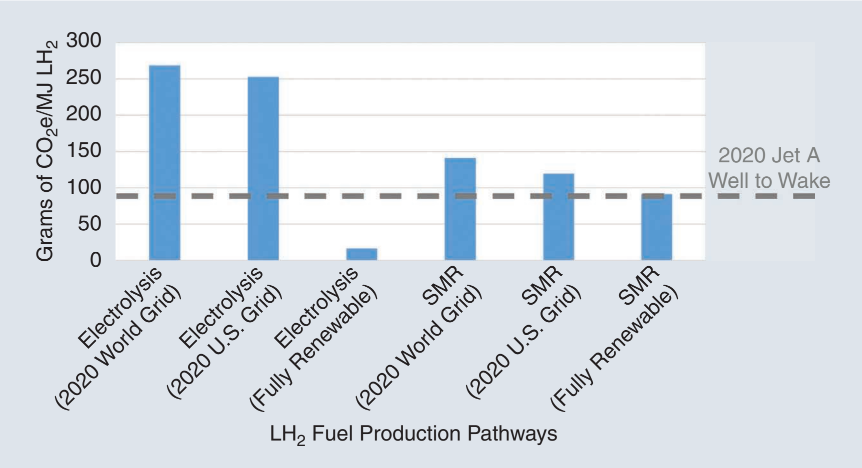

Figure 6. The CO_2-equivalent (CO_2e) lifecycle of LH_2 fuel production under different grid scenarios. SMR: steam methane reforming. (Source: Nicholas D. Applegate, Boeing; used with permission.)

than those associated with the use of kerosene jet fuels today. The current baseline emissions of Jet A fuels are 89 g CO_2e/MJ of fuel, as defined by the ICAO Carbon Offsetting and Reduction Scheme for International Aviation. This value includes contributions from oil extraction, transport, refining, and fuel combustion. In contrast, LH_2 produced using steam methane reformation and a current mix of the U.S. electrical grid produces 134.8 g CO_2e/MJ of fuel.

Electrolysis or reverse fuel cell use is commonly viewed as a renewable production pathway for hydrogen, even though the actual sustainability of this method will highly depend on the mix of power production methods and overall sustainability of the grid. Similarly, liquefaction is an energy-intensive process that requires significant energy input for hydrogen fuel to be appropriately packaged for aircraft use. It is not until the electrical grid extensively utilizes renewable means of electricity generation that hydrogen will become a sustainable option for aircraft into the future. For example, by using the current mix of power generation across the global grid, the well-to-wake greenhouse gas emissions of hydrogen would be 286.7 gCO_2e/MJ, roughly three times that of Jet A today. In contrast, assuming a fully renewable grid of 50/50 wind and solar power, these emissions drop precipitously to 16.6 gCO_2e/MJ of LH_2. As a result, the pathways may not yet be established for hydrogen to be a sustainable approach to aviation today, and the promise that hydrogen has for aircraft concepts is closely coupled with sustainability developments across the electrical grid in future scenarios. Thus, contingent on these necessary improvements, hydrogen-electric systems have the potential to revolutionize aviation into a compelling sustainable solution for the industry.

> ***Currently, steam methane reforming is a dominant approach to hydrogen production due to its relatively low cost and ease in production of hydrogen en masse and on demand.***

Conclusion

Hydrogen-electric systems demonstrate a great deal of promise for the future of aviation, although adoption is not without significant technical and integration challenges. The use of cryogenic LH_2 as a means for improving the performance of electrical systems is a significant enabler for high efficiency, specific power, and power density of high-power electrical components. Although a significant maturation of fuel cell technologies is required before these systems are ready for implementation in large-scale commercial aircraft, their flexibility in operation produces several system-level benefits that are apparent in aircraft sizing and energy efficiency. However, the thermal management requirements associated with PEM fuel cell adoption introduce a significant integration challenge as overall vehicle efficiency is highly sensitive to the parasitic losses associated with heat exchanger weight and drag. When integrating hydrogen storage systems, significant attention must be given to mitigating safety hazards during failure-mode scenarios, alongside the influence that large-volume requirements imposes on the aircraft aerodynamic performance. With proper integration, however, hydrogen-electric aircraft in the year 2050 are expected to be able to compete directly with modern aircraft systems while producing zero-CO_2 and NO_x emissions at vehicle level. For hydrogen aircraft to meet future zero-emissions goals, however, concerted attention must also be given to fuel production pathways. Most notably, average greenhouse gas emissions for hydrogen production today are greater than those associated with the continued use of kerosene-based jet fuels. However, driving toward a fully sustainable grid leads to a dramatic decrease in fuel-lifecycle emissions to near-zero values, making it a worthy goal for future aviation technology.

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For Further Reading

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