HE AERONAUTICS INDUSTRY HAS BEEN challenged on many fronts to increase flight efficiency, reduce greenhouse gas emissions, and decrease dependence on traditional hydrocarbon fuels. Each year, aviation produces more than 900 million metric tons of CO$_2$, which, without new interventions in policy, technology, and business practices, will further increase alongside the growing air transport market. Currently, aviation accounts for 4.8% of U.S. contributions to CO$_2$ emissions, and the global aviation industry constitutes about 2% of all human-induced CO$_2$ emissions. While this contribution may appear to be small when compared to other sources, it is likely to become more prominent in the years to come.

Forecasts by the U.S. government and global agencies have predicted growth in air travel by 4–5% per year. With the effect of compounding, this growth rate leads to an approximate doubling of global flight demand every 15 years, which is consistent with previous historical data (Figure 1). Aside from the sustainable biofuels currently under development, the air transportation industry does not have economical and carbon-neutral alternatives for power and energy as other markets do, such as the renewable energy sources found in ground-based power...
In this way, as more wind, solar, nuclear, hydroelectric, and geothermal power plants come online in the terrestrial grid, the proportion of greenhouse gas emissions directly attributable to aviation may see a rapid rise over the coming decades.

In response to this need for greener aviation, several U.S. and international organizations have set aggressive benchmarks for future aircraft systems. The International Air Transport Association has committed to reducing CO₂ emissions of commercial aircraft by 50% relative to values produced in 2005. The International Civil Aviation Organization similarly committed to ensuring carbon-neutral growth in aviation beyond 2020. NASA has also established goals of reducing landing and takeoff nitrogen oxide emissions by more than 75%, reducing fuel burn by 70%, decreasing the noise impact of aircraft, and ensuring the use capability of future aircraft to operate across a range of airport runway classes and infrastructures.

Recent efforts in aircraft propulsion electrification seek to disrupt the current paradigm and decrease community dependence on fossil fuels by developing novel means of aircraft energy storage, power generation and management, and integration. Before describing propulsion electrification efforts, however, we must discuss the current systems used for air transportation and their associated fuel burn impact.

Electric flight is already possible across certain types of aircraft platforms and is even common for certain unmanned aerial systems. Recent developments by a number of aircraft manufacturers have paved the way for small, one- and two-passenger experimental aircraft that operate solely on battery energy storage and a fully electric drivetrain. These developments for small-scale aircraft serve as a noteworthy start to the aircraft propulsion electrification process, though several key challenges exist when moving toward larger, commercial aircraft platforms.

Despite these difficulties, the electrification of propulsion at larger-aircraft scales is necessary to see the greatest impact on the environmental sustainability of aviation into the future, as these platforms are associated with the greatest CO₂ emissions (Figure 2). A total of 93% of commercial aviation-related fuel burn is directly attributed to aircraft that are designed to carry more than 150 passengers or feature a maximum takeoff mass of greater than 45 t. Across category, 36% of global fuel consumption is associated with single-aisle transport aircraft, and 57% is attributed to twin-aisle transport aircraft. The remaining 7% of fuel burn is associated with business jets (1%), turboprop aircraft (1%), and regional jets (5%).

While the electrification of aircraft propulsion can act to displace the greenhouse gas emissions associated with fuel burn by changing the energy source used for propulsion, there are other benefits to using electrically driven propulsion systems as well. Depending on the energy storage scheme, electrified propulsion systems offer an ability to reduce direct operating costs. Previous decades have demonstrated a great deal of volatility in jet fuel prices, while electrical energy costs have increased only at a rate proportional to inflation. A comparison of equivalent energy costs between jet fuel and electricity from the U.S. national grid is shown in Figure 3, which takes into account estimated differences in overall drivetrain efficiency between these two approaches.

Distributed electric propulsion can also be used with many electric drivetrain architectures to produce large system-level benefits on the vehicle. These concepts permit improvements to aerodynamic efficiency, decreased noise, and increased tolerance to failure scenarios of one or more propulsors. This role of distributed propulsion in the design of electric aircraft will be further described in the “Electric Aircraft Architectures” section. In addition, electric machines are known to have superior reliability, reduced maintenance, and lower operating costs as compared to most combustion engines. Noise generation from electric motors is also significantly lower than that.
associated with the compressor, combustor, and turbine components of a traditional turbofan. While these general advantages offer compelling reasons to explore electrified aircraft propulsion, there are numerous technical challenges that must be overcome before these concepts can be realized.

**Challenges**

Electric flight at scale is not yet a reality due to a number of technological barriers. One of the key bottlenecks is the limited specific energy, or the amount of energy carried per unit mass, of modern battery systems. Fundamentally, an aircraft can be only as efficient as it is light, so a direct replacement of kerosene-based jet fuels with modern battery systems is infeasible. This is particularly true for commercial aircraft that feature much higher fuel fractions, and small enough form factor has proven to be a challenging technical task. While systems rated for these power levels certainly exist in several industries, these power requirements of today’s commercial aircraft span a wide range of values, from approximately 20 MW for small, single-aisle transport classes to upward of 300 MW at the largest scale (Figure 5). Achieving these rated power levels with acceptably low weight and small enough form factor has proven to be a challenging technical task. While systems rated for these power levels certainly exist in several industries, these components are often not packaged in a way compatible with integration into aircraft. The aforementioned technical challenges are currently high-priority items of

Commercial aircraft rely on the high specific energy of fuel sources to complete long-range missions, so large reductions in specific energy of the storage medium will result in significant reductions in range capability and, potentially, even be insufficient for the aircraft to be capable of climbing to a reasonable cruise altitude. An example is shown in Figure 4 of the estimated range capability for a hybrid electric single-aisle transport aircraft concept across a series of pack-level battery specific energy values, where $H_P$ represents the proportion of propulsive power delivered by an electric machine.

Conventional gas turbines for aircraft are configured to burn kerosene-based fuels, such as Jet A (commercial) or JP-8 (military), which feature a specific energy of approximately 12,000 Wh/kg. After the thermal efficiency of the turbofan core and losses across different stages of the turbofan are factored in, just more than one third of that energy is actually utilized toward propelling the aircraft. The “useful” specific energy of jet fuel is, thus, closer to 4,500 Wh/kg. By comparison, the cell-level specific energy of modern lithium-ion battery systems is more than an order of magnitude lower, at roughly 250 Wh/kg. Factoring in the additional requirements of configuring these battery cells into packs that are usable on an aircraft platform reduces the effective specific energy to less than 200 Wh/kg.

Similar to the turbofan, the electrical system also has associated losses, though, since these systems are still very much at a conceptual stage, there are no definitive efficiency metrics for the drivetrain. However, a reasonably assumed efficiency of 75% across the entire system, from stored energy to thrust output, would, thus, place the useful specific energy of modern battery packs on the order of 150 Wh/kg. While many active research programs globally are developing advanced battery systems that push the state of the art, there is not currently a battery system in the foreseeable future that can directly meet the specific energy requirements to displace kerosene-based jet fuels and still result in similar overall mission capability.

In addition to energy storage, another significant challenge for electric aircraft resides in the development of flight-weight electrical components suitable for the high-power requirements of commercial platforms. Example components include motors, inverters, energy management systems, power transmission, and circuit protection systems. The net power requirements of today’s commercial aircraft span a wide range of values, from approximately 20 MW for small, single-aisle transport classes to upward of 300 MW at the largest scale (Figure 5). Achieving these rated power levels with acceptably low weight and small enough form factor has proven to be a challenging technical task. While systems rated for these power levels certainly exist in several industries, these components are often not packaged in a way compatible with integration into aircraft. The aforementioned technical challenges are currently high-priority items of

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**Figure 3.** The historical trends in equivalent propulsive energy costs for jet fuel and electricity for the U.S. energy grid. Data are from the U.S. Energy Information Administration (see https://www.eia.gov/electricity/data/browser/#/topic/?agg=0).

**Figure 4.** The estimated range capability of hybrid electric commercial aircraft across varying hybridization power factors and battery specific energy values. Data are from Wroblewski and Ansell (2019).
research by global experts across a broad range of technical fields.

**Electric Aircraft Architectures**

Fundamentally, propulsion electrification allows the power-producing and power-expending components of the aircraft to be operated with a degree of independence from one another. For conventional turbofans, mechanical power is produced across the turbine stage by extracting the energy produced during fuel combustion, which is then mechanically routed to nearby fan and compressor components through a spool system. When using electrically driven propulsors, this mechanical link becomes unnecessary, and propulsors can, instead, be operated independently from power-generating devices, so long as sufficient electrical power can be supplied to the motor system from one or more sources. This decoupling also implies that different approaches can be used to combine electrical and/or mechanical power to meet the propulsion requirements of the aircraft, and, as a result, electrified propulsion systems come in a number of different architectures (Figure 6).

**Figure 6.** The electrified aircraft propulsion architectures. (Source: NASA.)
Naturally, a fully electric architecture consists of one or more motor-driven propulsors, which are powered by one or more electrical energy (e.g., battery) or electrochemical power conversion (e.g., fuel cell) systems. Given the aforementioned limitation in specific energy of available electrical energy storage systems, many recent efforts have focused on hybrid electric configurations, in which gas turbines are utilized in conjunction with energy storage systems and electric machines. The inclusion of conventional fuels provides a stepping stone to leveraging the beneficial aspects of electrification, such as reduced operating costs and reduced greenhouse gas emissions, while making fewer compromises in aircraft performance, such as range, weight, and turnaround time.

A relevant example includes the series hybrid configuration, where the gas turbine power is converted to electrical power through a generator, which is combined with stored electrical energy to power one or more electrically driven propulsors. This series hybrid configuration offers a means to enabling distributed electric propulsion, for example, with the reduced impact on range that naturally comes from the lower specific energy of most electrical energy storage systems. In contrast, a parallel hybrid configuration utilizes stored electrical energy to drive an electric machine, which is coupled to the mechanical power of a turbine-driven propulsor. Such an architecture allows electric boost motors to augment the peak power demands during the takeoff and climb flight phases and permits the use of smaller engine cores that are better tailored for cruise requirements. These systems would be very familiar to those working on hybrid electric automotive powertrains.

Concepts have also been developed for turboelectric drivetrains, for which conventional kerosene-based fuels are used to power a gas turbine and nearly all (fully turboelectric) or part (partial turboelectric) of the associated shaft power is extracted by a generator. This power is then used to operate one or more electrically driven propulsors. Turboelectric configurations permit the power generation process to be centralized into a smaller quantity of high-power, efficient turbine cores. The thrust contribution of electrically driven propulsors can then be spread across a larger region of the vehicle and allow avenues for larger effective fan areas.

In the pursuit of improved propulsive efficiency, many ultrahigh bypass turbofans also feature increasing fan areas but are limited by a required minimum clearance distance between the ground and the turbofan nacelle. By providing flexibility in the placement of individual propulsors, series hybrid and turboelectric architectures alleviate some of these challenges. However, a disadvantage of turboelectric configurations is the associated reliance on conventional jet fuels with no immediate path for carbon-neutral energy storage. Such a system would be familiar to those working on diesel-electric locomotives or ships.

**Electrified Aircraft Design**

Since the challenges of electrical energy storage are exacerbated by an increase in the scale of the aircraft platform, a number of researchers are turning toward battery hybrid electric architectures for regional-class aircraft that are typically designed to carry between 48 and 86 passengers across short-haul flights of 600 nmi or less. These efforts offer a near-term approach to reduce fuel burn and, for some missions, operational costs. The global average passenger flight has a range just above this 600-nmi capability, suggesting that hybrid electric aircraft designed with this range in mind would capture a great portion of air travel demand. Example range profiles from notable airport hubs are shown in Figure 7 for reference.

This approach would require that air carriers make modifications to their typical concept of operations and means for allocating aircraft to associated routes, though the prospect of reduced operating costs offers an appealing reason to deviate from current business practices. This class of regional aircraft also features lower-power propulsion systems than single- and twin-aisle aircraft, which decreases the aggressive improvements in rated power required from electrical components, permitting nearer-term viability. It should be noted that this class of aircraft currently does not contribute significant portions of aviation-related fuel burn, potentially limiting the impact of electrified propulsion solutions at this scale. This trend, however, could change if new operations models are adopted with regional hybrid electric aircraft.

With increasing vehicle scale, passenger capacity, and range, trends in propulsion electrification are observed to shift toward lightly hybridized configurations and kerosene-fueled turboelectric or alternative energy–driven fully electric systems. While single-aisle and twin-aisle aircraft concepts better target the classes associated with the greatest fuel burn and emissions, they also rely on technologies and developmental improvements that give them an entry into service timetable further into the future. In essentially all circumstances, key technological...
improvements in electrical components, power conversion devices, or battery systems are required to make these single-aisle or twin-aisle aircraft concepts feasible.

In many concepts for larger aircraft, distributed electric propulsion is extensively utilized to reduce the overall burden of developing direct electric machine replacements that have the rated power equivalent to existing gas turbine engines. Distributed propulsion concepts also are used to exploit propulsion-airframe integration benefits. The use of electric cables to distribute power across an aircraft, rather than fuel lines, allows greater flexibility in the placement and number of propulsors. In this way, propulsors can be strategically and intentionally designed to interact with other aspects of the vehicle to produce a net system benefit. One such advantage of distributed electric propulsion is boundary-layer ingestion, where propulsors are configured to draw in the low-momentum flow adjacent to aircraft surfaces (e.g., wing, fuselage, tail), which can improve propulsive efficiency.

Additional benefits of distributed electric propulsion include more inherent coupling of the propulsive device to the designed aerodynamic performance of wing and tail surfaces, which permits improved tailoring of the coupled system for aeropropulsive performance across all phases of flight. As an example, distributed propulsors can be set to variable thrust levels across an aircraft to augment standard methods for attitude control. Distributing the thrust load across an array of propulsors also decreases the criticality of failure in one propulsor unit, making design decisions to handle these scenarios simpler than is required in current systems. Stretching the net propulsive thrust requirement across a larger area around the aircraft can improve propulsive efficiency and decrease noise by decreasing the fan pressure ratio required from each propulsor.

A similar approach is commonly used for turbofans, where a larger bypass ratio, or fan-to-core area, can be used to improve propulsive efficiency. However, the decoupling of power production and expenditure enables ultrahigh effective bypass ratios to be achieved, since many geometric constraints of the fan design are relieved.

**Enabling Technology**

Continued research into electrical components is necessary to produce systems that are appropriate for aircraft propulsion. The limitations of current energy storage technology have been belabored in discussions of future aircraft propulsion electrification, though for good reason. As stated previously, current battery systems provide insufficient specific energy capability that would be needed to displace hydrocarbon fuels as a primary energy source, though significant and rapid improvements in battery capabilities are emerging with new chemistries.

While it is not envisioned that battery cells exceeding a specific energy of 1,000 Wh/kg will be realized within the next one to two decades, future hybrid electric aircraft architectures are highly sensitive to near-term improvements in these battery technologies, as seen in Figure 4. In this way, the response to specific energy improvements is
Regarding energy storage, battery systems are not the only medium that can be utilized to provide electrical power. As mentioned previously, turboelectric configurations have been proposed to take advantage of the dense chemical energy found in hydrocarbon fuels, which can be converted to electrical power through a turboshaft-driven electric generator. Other gaseous or liquid fuels can also be used, due to their relatively high specific energy, and converted into electrical power through other means. For these cases, fuel cells are often used due to their high electrochemical conversion efficiency, which varies as a function of output power (current density).

For example, the peak conversion efficiency of modern proton exchange membrane fuel cells operating on hydrogen have reached values of approximately 60–70%. While these systems are canonically envisioned for use with hydrogen, some fuel cell systems are also compatible with other energy carriers, such as methanol, ammonia, ethanol, and even some heavier hydrocarbons. Some of the disadvantages of fuel cell systems, though, are the high weight these power conversion devices have and the significant cost of certain materials (e.g., platinum) often used in their production. Rapid improvements have been made in both of these areas in recent history, but further development is still necessary before the integration benefit of fuel cells becomes clear.

Certain types of fuel cells may also have long startup times and generally are unable to respond to rapid changes in power demand. For this reason, many fuel cell architectures are designed with a supplementary battery and/or ultracapacitor system, both to handle dynamic changes in power and shave peak power demands during takeoff and climb, permitting reductions in the required weight/sizing of fuel cell stacks.

The aforementioned limited availability of high-power, flight-weight motors and generators has been met with a recognized need for improved rated power and specific power of electric machines. The Boeing 787 defines the current technology in aviation-rated electrical machines with four 250-kW electric generators, each with a specific power of 2.2 kW/kg. The electrical power produced by these generators is not intended for propulsion but, rather, the auxiliary systems and hotel loads on the aircraft. These capabilities are quite far from the multiple megawatt-class electric machines that are required to meet the demands for aircraft propulsion with suitable specific power above roughly 6.5 kW/kg. To address this need, researchers are turning to novel machine architectures and topologies. For particularly high-power applications, superconducting machine systems are being considered to meet aggressive weight and size constraints.

In a similar fashion, high-power, lightweight, high-efficiency power electronic converters are also required for the motor drives and energy management system. Systems of varying levels of power electronics integration have been explored. In one extreme, the frequency is controlled at the generator, and power is distributed at the same frequency to multiple electric propulsors. At the other extreme, rectified power from generators or energy storage, or a combination of both, is processed with an energy management system and distributed in dc form to multiple inverters that independently drive individual propulsors.

Intermediate solutions are also possible with a few inverters driving a collection of motors. In vehicles with ac distribution, doubly fed induction machines could be employed to reduce the rating of the power converter, especially if only a limited range of fan speed is needed. With the rapid advance in power electronics technology, especially with wide-bandgap devices, such as silicon carbide and gallium nitride, the use of full power conversion combined with compact, highly efficient synchronous machines tends to be the most attractive. In addition to the power density and efficiency improvements being sought, such converters are also expected to incorporate fault tolerance and protection functions.

New approaches for the distribution of high electrical power in the flight environment have been recently studied. The overall weight and reliability of power distribution systems have been shown to vary substantially depending on the distribution architecture, protection scheme, component redundancy, operating voltage, and management approach. Since commercial aircraft operate at high altitudes where the atmospheric pressure decreases, partial discharge can occur across transmission lines at lower voltages than would be observed in ground-based systems. If lower voltages need to be utilized, the conductors must then be sized to carry a larger current to meet power requirements and, as a result, become heavier.

Furthermore, the protection system must be sized to interrupt larger currents. The inclusion of new insulation materials and terminating schemes may assist with preventing partial discharge at altitude, and novel conductor designs could reduce the associated weights of these systems. The importance of effective thermal management has also become apparent as the field of electrified aircraft propulsion has progressed. In terms of the propulsive power requirements at scales in the 10s and 100s of megawatts, efficiency losses of 10–15% across the entire electrical system can result in enormous thermal sources that
must be dispersed. This thermal load, typically, will require some parasitic power draw for the drivetrain and aerodynamic drag due to heat exchangers to function appropriately, which increases the overall challenge of storing sufficient energy for long-range missions.

**Electrified Commercial Aircraft Programs**

Driven to make electric flight for commercial transport a reality, researchers have developed a number of visionary aircraft concepts under previous and ongoing efforts. While there are a number of notable concepts, only a select few will be described here for brevity. Renderings of these concept aircraft are shown in Figure 8.

For small, single-aisle aircraft, several turboelectric, hybrid electric, and fully electric concepts have been developed. The NASA STARC-ABL aircraft is designed as a partial turboelectric concept, where power extraction from a pair of turbofans is used to drive a tailcone thruster. By placing the propulsor at the aft end of the aircraft, the boundary layer produced by the fuselage is directly ingested into the electrically driven fan.

The ECO-150 concept developed by Empirical Systems Aerospace is another turboelectric configuration with a distributed electric propulsion system. Two large turboshaft generators are used to produce electrical power, which is then routed to a series of electrically driven ducted fans mounted within the wing surfaces. This split-wing configuration offers several aerodynamic benefits for the platform in addition to a substantial aeroacoustic improvement from having the propulsors embedded.

The Boeing SUGAR Volt is configured with two electric motor-boosted turbofans in a parallel hybrid architecture, reducing fuel burn of the propulsion system, and a truss-braced wing for improved aerodynamic efficiency. The Airbus E-Thrust has also been proposed as a series hybrid, in which a large engine core drives a turboshift generator. This electrical power is combined with a battery system to run a six-fan distributed electric propulsion system over the main wing of the aircraft.

Projecting to technologies further in the future, researchers from Bauhaus Luftfahrt have developed the Ce-Liner concept, which is a fully electric single-aisle transport aircraft. This concept uses an advanced battery system assumed to emerge with future research developments as well as high-temperature superconducting electric motors to meet rated power and specific power requirements.

**Figure 8.** The commercial electrified aircraft propulsion concepts. (a) The NASA STARC-ABL (Source: NASA). (b) The ESAero ECO-150. (Source: Empirical Systems Aerospace; used with permission.) (c) The Boeing SUGAR Volt. (Source: Boeing; used with permission.) (d) The Airbus E-Thrust. (Source: Airbus; used with permission.) (e) The Bauhaus Luftfahrt Ce-Liner. (Source: Bauhaus Luftfahrt; used with permission.) (f) The Center for High-Efficiency Electrical Technologies for Aircraft. (Source: University of Illinois Urbana-Champaign; used with permission.) (g) The NASA N3-X. (Source: NASA).
Taking a different approach, a team from the Center for High-Efficiency Electrical Technologies for Aircraft, led by the University of Illinois at Urbana-Champaign, is currently developing concepts for a fully electric aircraft. This concept uses hydrogen energy storage and a fuel cell/battery hybrid system to achieve payload and range capabilities commensurate with modern single-aisle transport aircraft. Since the hydrogen is stored as a cryogenic liquid, this medium is also used as a means to achieve superconducting power transmission and motor systems. The aircraft is configured with a distributed overwing ducted fan system to promote the benefits of boundary-layer ingestion, improve robustness to component failures, and improve takeoff and landing performance.

Due to the aggressive power requirements of a twin-aisle aircraft configuration, very few concepts have broached this large class of aircraft. However, the NASA N3-X is one concept where distributed-electric propulsion was used at this scale. The N3-X is fully turboelectric and utilizes a superconducting electrical system with a blended wing body configuration. The aircraft features two 30-MW turbogenerators, one at each wingtip of the aircraft, and 14 motor-driven ducted fans mounted overwinging on the fuselage surface.

Conclusions

Electric propulsion offers a new paradigm for aircraft design and operations not offered under previous configurations. While a number of technological challenges exist to making electric propulsion realizable at commercial scales, the benefits of reduced costs, decreased emissions, and improved flexibility of operation serve as attractive motivations for developing these new technologies. Advancements in energy storage systems, high-power electrical systems and components, and matured methods for synergistic propulsion integration will pave the way for the electric aircraft of the future.

It is worth noting that scaling existing technologies to higher-rated power capabilities is not the only consideration when introducing electric aircraft into the aviation community. To date, no electric aircraft has been certified for commercial use with passengers. This certification process is already time intensive and costly for conventional aircraft, but it is expected to be particularly laborious for cases of electric aircraft propulsion systems due to the lack of precedent and data on reliability and safety. For airlines to make a strategic shift to electric aircraft, there must be an economic viability in this operation model. If this viability is achieved, then a fundamental shift to fleets of electric aircraft could change the economic model that is used in aircraft acquisition, scheduling, and profitability.

Readiness of electric aircraft would also require developments in the international power grid. Recent studies have indicated that displacing aviation energy usage to the ground would result in a required 26% increase in global electricity production, and airports will have to be equipped with appropriate charging infrastructure. These indications demonstrate that air transportation is an interconnected aspect of modern life. Fostering the development of electric aviation in a fashion that is environmentally responsible, economically sustainable, and technically viable requires extensive coordination across international communities as well as creative thinking that goes beyond conventional wisdom.

For Further Reading


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