HYBRID ELECTRIC PROPULSION

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This article is part of an ongoing decarbonization series (see the Sept 2019 issue for details).

Architectural Design Space and Potential Benefits

ABSTRACT

Electrified propulsion holds the promise of reducing aviation's CO_2 emissions footprint through three means: access to green grid electric energy, improvements in aircraft performance through new airframe and propulsion system architectures and enabling further optimization of the gas turbine cycle. Charging an aircraft battery pack with green electric energy and using this energy to drive electric propulsors results in a zero emissions vehicle. This is practical for light aircraft and short missions. Boosting a Jet-A burning gas turbine with green electric energy (again stored in a ground charged battery), in either a parallel or series turbo-electric architecture can yield a net reduction in CO_2 emissions, as long as the fuel burn required to carry the weight of a discharged battery pack does not overcome the reduction in fuel burn afforded by the ground charged battery. Several studies have indicated that a net savings is possible with cell level energy densities approach ~ 500 whr/kg, a reasonable target for the 2030 time frame. Electrified propulsion can also enable unique aircraft configurations, employing a very high efficiency prime mover (gas turbine) designed for running only a generator at peak efficiency, and/or distributing the propulsors throughout the aircraft, for improvement in L/D and propulsive efficiency.

Airliners (aircraft of > 100 pax), consume over 90 percent of aviation fuel [1]. Absent a major shift from the hub and spoke system, efforts to reduced aviation's emissions footprint must focus on airliners. Carbon-neutral liquid fuels (CNLF [2]) are clearly one pathway to lowering emissions, thus efforts to develop CNLF production methods should clearly continue. Improvement in aircraft performance, both airframe and propulsion system represent the other major pathway to reduced emission. Further advancements in gas turbine (GT) technology will continue to provide GT performance improvements. In addition, with recent improvements in electric machine performance (weight and efficiency), propulsion system electrification could provide aircraft performance improvements beyond what is possible with conventional GT technology.

Airliner propulsion electrification architectures have been extensively studied within the aviation research community. Figure 1 provides the continuum from the conventional gas turbine (GT) to the battery all-electric. Between these two extremes lies the series turbo-electric, the partial turbo-electric and the parallel hybrid. In the series turbo-electric, a prime mover converts fuel energy to electric power to drive a set of electric propulsors. A battery may be included for peak shaving or access to green grid energy. With the partial turbo-electric, the GTs provide propulsive thrust and electric power to drive a set of auxiliary electric propulsors. A battery may also be included. Finally the parallel hybrid integrates an electric machine onto the GT fan drive shaft with the electric power sourced by a battery charged with (green) grid energy.

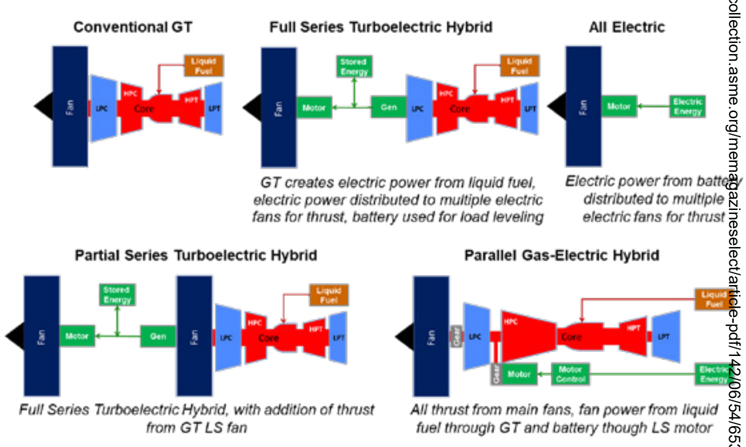
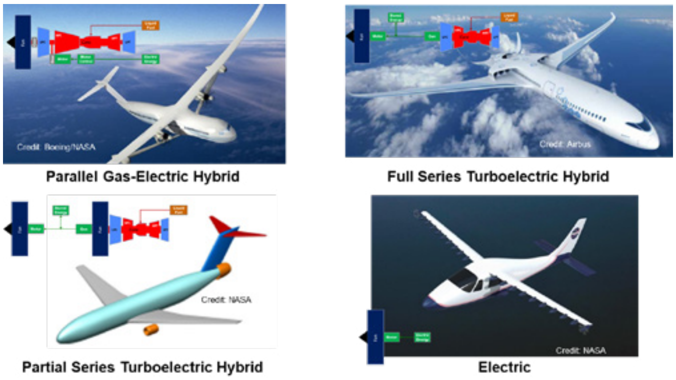


Figure 1. Electrified Propulsion Architectures

Some aircraft concepts that have emerged based on these propulsion system architectures are provided in Figure 2. The upper left Boeing SUGAR-VOLT employs a parallel hybrid propulsion system, injecting battery energy during cruise to decrease Jet-A consumption. The upper right Airbus E-Thrust employs six distributed over-wing electric propulsors, sourced by a turbo-generator and battery pack, that ingest the aircraft boundary layer for improved aircraft performance. The bottom left partial series turbo-electric NASA STARC-ABL leverages a tail boundary layer-ingesting electric fan, driven by electric generators on the two main underwing GT propulsors. Finally the bottom right battery electric NASA X57 employs distributed blown-wing electric propellers enabling a smaller wing and maximum power reduction.

Battery All-Electric

The X57 offers a battery electric configuration example. Small, low passenger-count aircraft have been shown to



be feasible at short range with battery energy densities achievable in the next five years (~ 300 whr/kg, packaged) [3]. However, multiple studies have shown that all-battery electric flight for airliner aircraft is not feasible [4] at current battery energy density. At 500 to 1000 whr/kg an airliner may be able to reach ranges of ~ 300 nm, but the demand for such a range-limited aircraft is unclear. Improvements in battery cell and pack specific energy will help. Current packaged battery energy density is approaching ~ 250 whr/kg, there is general agreement that 400 whr/kg (packaged) is possible in 5-10 years, and while the theoretical energy density of some chemistries reaches almost 3000 whr/kg, the path to a practical battery at > 500 whr/kg [5] is challenging.

Parallel Hybrid

Green grid energy can be accessed, without full electrification, through the parallel hybrid, where battery energy is used to inject power into a GT during some operating points. With power coming from an alternate source, less Jet-A is needed to make the same thrust. However the parallel architecture adds electric component weight to the system, thus more thrust is required at any given mission point. The parallel hybrid architecture may provide an energy decrease or increase depending on these two opposing effects. Four single aisle aircraft studies illustrate the range of results. The Boeing SUGAR study [6] of augmented takeoff and cruise operation predicts a 20 percent Jet-A reduction but a 17 percent energy consumption increase. UTRC explored a core sized for cruise [7], predicting a 6 percent Jet-A reduction and a 2 percent energy consumption increase. A Rolls Royce study [8] considering fleet operations, showed a 20 percent Jet-A and 10 percent energy reduction for the short (<300 nm) missions. Finally, NASA has studied use of electric machines for GT stability control [9], showing significant efficiency improvements could be realized.

Series Turboelectric

As described above, even with unknown battery technology approaching 1000 whr/kg, batteries can't provide the energy density necessary to enable an all-electric airliner with meaningful range. A GT based turbo-generator burning Jet-A however, easily achieving > 1500 whr/kg (2-hour cruise) to 3000 whr/kg (5-hour cruise), could feasibly provide the electric power for an electric propulsion system. However, with an electric drive train (EDT) of generators, distribution cable, motor drives and motors between the GT and the propulsors, such a propulsion system would be heavier and less efficient than a conventional underwing GT propulsion system and thus result in increased fuel burn and CO_2 emissions. The series electric propulsion system cannot provide a benefit by simply replacing conventional GTs on a conventional tube and wing aircraft with a conventional GT driving an EDT with two underwing electric propulsors. The prime mover thermal efficiency must be improved through cycle improvements and/or the electric propulsors must enable an aircraft level performance benefit through propulsion airframe integration that overcomes the EDT weight increase and efficiency decrease. A parametric analysis of EDT specific power and efficiency required to provide a fuel burn reduction with assumed benefits of propulsion airframe integration has been conducted by NASA [11, 12]. This study shows a partial series turboelectric like the NASA STAC-ABL could provide a fuel burn benefit with near term realizable EDT efficiency of 80 percent at 4 kW/kg specific power.

Conclusion

There is potential for reducing airliner emissions through aircraft electrification, with the parallel hybrid showing the most mid-term promise and the partial turboelectric incorporated on an advanced airframe showing longer term promise. However, there is a large design space that has only been cursorily described above. A survey study executed Isikveren [12] provides a good review of the design space, and introduces the degree of energy and degree of power electrification parameters in describing this design space.

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