The Pragmatic Future of Hybrid-Electric Flight: A Technical Analysis of United Technologies Advanced Projects' X-Plane

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Executive summary

As the pace of technological change accelerates, large companies must be more focused and integrated while also embracing new approaches to innovation and risk disruption from new and more nimble competitors. That’s why United Technologies Corporation (UTC) recently launched United Technologies Advanced Projects (UTAP)—a startup-like organization at the heart of UTC that disrupts from within. UTAP moves at intense speed to build and pilot ambitious product and service demonstrators, while simultaneously distilling UTC’s curious and collaborative culture.

UTAP’s first project not only reflects UTC’s commitment to transformation and integrated aerospace innovation, it aims to pioneer a new chapter in aviation. Called Project 804, this unprecedented initiative will construct and fly a hybrid-electric X-plane in three-year’s-time. The X-plane is both a technology demonstrator pushing the boundaries of aerospace and a product demonstrator showcasing the economic viability of hybrid-electric propulsion. This marks the entrance of aerospace into the existing domain of large-scale public transit models, such as an intercity bus line, both high in efficiency and practicality.

With a dedicated technical team comprised of leading experts from Pratt & Whitney, Collins Aerospace, United Technologies Research Center and external institutions, the effort will primarily be based out of a Pratt & Whitney facility in Montreal, Quebec, and a Collins Aerospace facility in Rockford, Illinois. The number “804” refers to the straight-line mileage between those locations.

The Project 804 X-plane will be based on a Bombardier Dash 8 Series -100 aircraft, re-engined on one side with a 2 megawatt-class propulsion system. Its configuration will consist of an engine optimized for cruise efficiency augmented by a battery-powered electric motor to assist during the missions’ 20-minute take off and climb.

The engine and electric motor will each generate about 1 megawatt of power in a parallel hybrid configuration. While the battery cells are off-the-shelf, the packaging and battery management system (BMS) are custom-designed for efficiency and to meet necessary safety requirements. This approach could be suitable for a clean-sheet regional design as well as a retrofitted option for existing airframes. The demonstrator’s novel architecture is expected to provide an industry-leading total fuel savings of at least 30% during an hour-long mission, with some of the fuel savings attributable to the latest in engine technology, not just the added electrification.

At UTC, we believe the electrification of flight represents a significant opportunity for the industry, air travelers and the environment. By combining UTAP’s bold, risk-tolerant approach with UTC’s industrial roots and engineering expertise, Project 804 will make hybrid-electric flight a commercial reality with efficiency and speed.

This article presents the rationale behind why UTC, a leading electrical systems supplier and top propulsion company, is well-positioned to impel the aerospace industry toward improved efficiency through hybrid-electric propulsion.

Electrification in transportation

Electricity as a way of storing, distributing, and converting energy is an invention that dates to the late 19th century. While electricity has found applications in lighting and household appliances, other modes of energy storage, distribution, and conversion have prevailed throughout most of the 20th century. Hydrocarbon combustion, converted directly to mechanical energy for use in automotive and airplane propulsion, as well as hydraulics and pneumatics, supporting factory automation and onboard aircraft systems, have dominated the energy landscape. It was only earlier this century that the power and energy densities of various electrical systems, such as batteries, motors, generators, and power electronics, became truly competitive against other energy storage systems for size and weight-sensitive applications.

Over the last two decades or so, the automotive industry has experimented with hybrid-electric and fully-electric architectures for vehicle propulsion. Today, the base technology has advanced to a degree such that we can credibly discuss hybrid-electric and fully-electric propulsion for aviation.

Electrification in aviation

United Technologies has had substantial depth in aviation electrification for some time through its Collins Aerospace business. Collins Aerospace is an industry leader in producing electrical power systems. This expertise is demonstrated through its content on the most electric airplane in the sky today, the Boeing 787. This plane’s electrical system produces nearly 1.5 Megawatts (MW) of onboard electrical power using six generators, designed and built by Collins Aerospace, replacing many of the aircraft’s power systems historically powered by hydraulics or pneumatics. The “more electric” architecture demonstrated in the 787 is an example of what UTC is capable of, but is also distinct from the main topic of this paper, which focuses on architectures that use electric power for propulsion rather than for accessory systems.

Purely electrical architectures in aviation – those in which all the stored energy on the aircraft is in batteries or fuel cell – will be confined to smaller vehicles (~1-4 passengers) under a 200 km range for the foreseeable future, unless there is a fundamental breakthrough in electrical energy storage technologies. These types of vehicles, particularly those in a vertical take off and landing (VTOL) configuration, offer the tantalizing possibility of electric air taxis for urban air mobility missions – a market largely inaccessible to conventional helicopters due to issues of noise, (perception of) safety and cost. While the acceptance of widespread urban air mobility by the public and certification authorities remains to be seen, there is a moderate probability that electric VTOL will disrupt the conventional helicopter market.

Hybrid-electric propulsion is a more interesting proposition for business, regional, and large commercial aviation domains. There are two primary architectures for hybrid-electric systems: 1) serial hybrids, in which electrical energy (augmented via batteries) is used for propulsion but produced by combustion of hydrocarbon fuel on board, and 2) parallel hybrids, in which a hydrocarbon-powered propulsion system is augmented with electrical energy for portions of the flight.

The serial hybrid approach generally yields a slightly lower end-to-end efficiency of the propulsive energy chain but offers potentially significant advantages in terms of the efficiency of the overall aircraft design. This approach is contingent on the aircraft original equipment manufacturers’ (OEM) willingness to deviate from the conventional tube-and-wing configuration in future clean-sheet developments.

The parallel hybrid approach enables the downsizing of a conventional engine (in terms of thrust, operating temperature, and/or maintenance requirements) by augmenting it at peak phases of power usage, such as take off, with stored electrical energy. Low levels of augmentation, on the order of a few percent of total power, can yield notable reduction in combustor temperature requirements and improvement in parts life. Higher levels of power augmentation approaching 50% could allow an engine to be sized for cruise, which requires half the amount of power as take off in many regional applications, and could enable the use of a smaller and more efficient engine. This parallel hybrid, regional aircraft application is the focus of UTAP's technology acceleration and demonstrator efforts.

Trends in high-power electrical equipment

Electrical power demand has been steadily increasing as a result of the electrification of conventionally pneumatic and hydraulic accessory systems, as shown in **Figure 1**. The most electric airplane today is the Boeing 787 with electric power demand in the order of 1.5MW and voltages of up to ±270 Volts.

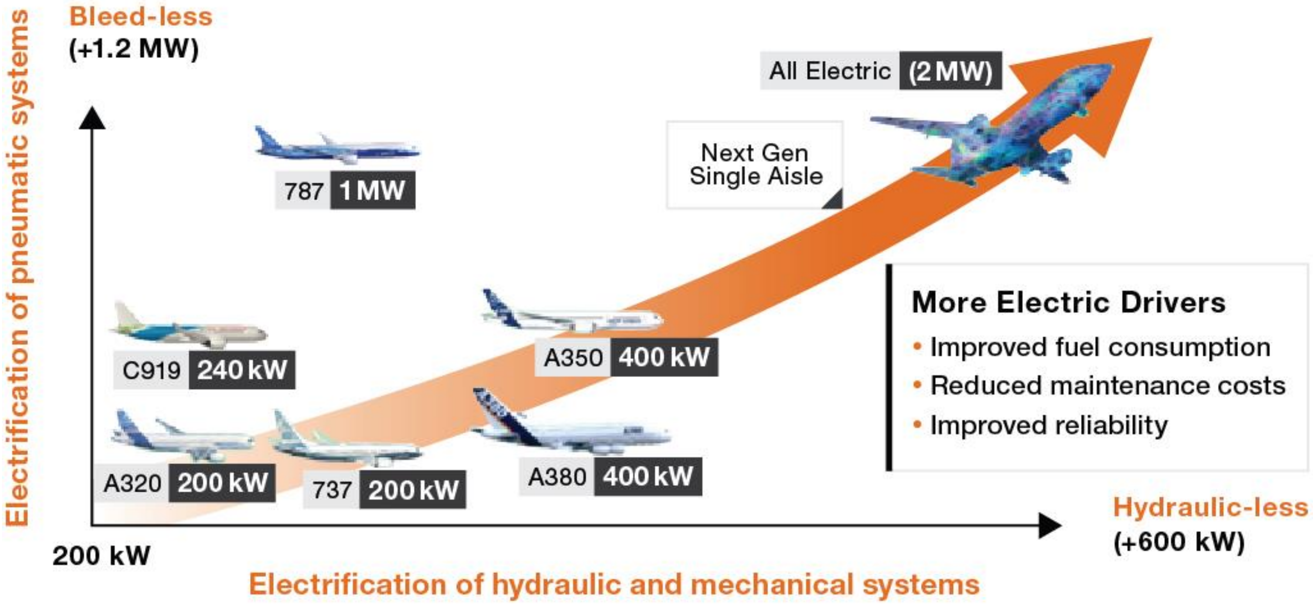


***Figure 1**- Increasing onboard electrical equipment demand in commercial aviation.*

As power levels continue to increase, so too does the need for higher power density motors, generators, and power electronics capable of reliably handling associated loads. Multi-phase and even multi-megawatt machines will require the use of advanced ceramic based semiconductors, packaging methods, thermal management, and manufacturing techniques in order to cope with the required power levels. Using these advanced methods, the Project 804 engineering team will develop products that approach, and sometimes even exceed, 20 kW/kg—surpassing the power densities available today.

Electrical energy storage

Figure 2 shows the Ragone plot for energy storage technologies available today and for the foreseeable future. Chemical energy storage devices suffer in that they must carry both the oxidizer and the reductor materials. Meanwhile, combustion devices only carry the fuel while the oxidizer is available in the environment at altitudes around 30,480m (100,000 ft) and below. Thus fossil or synthetic fuels will likely remain aviation's choice energy source for the near future. Project 804 does not intend to fully replace the fuel by an electrical storage device rather its intention is to supplement a fraction of the mission's energy with stored electricity to yield significant fuel consumption reduction.

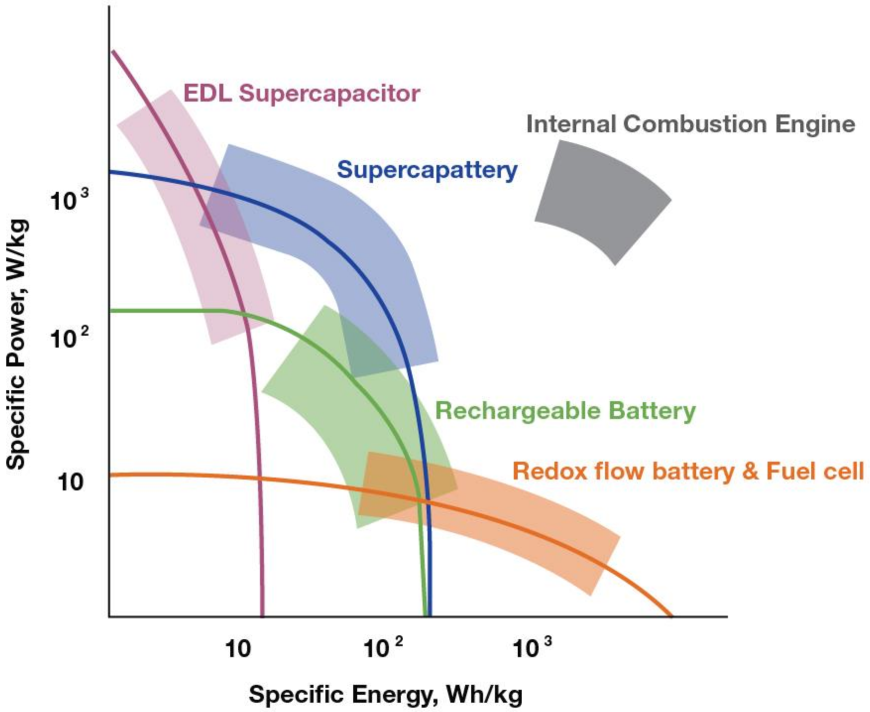
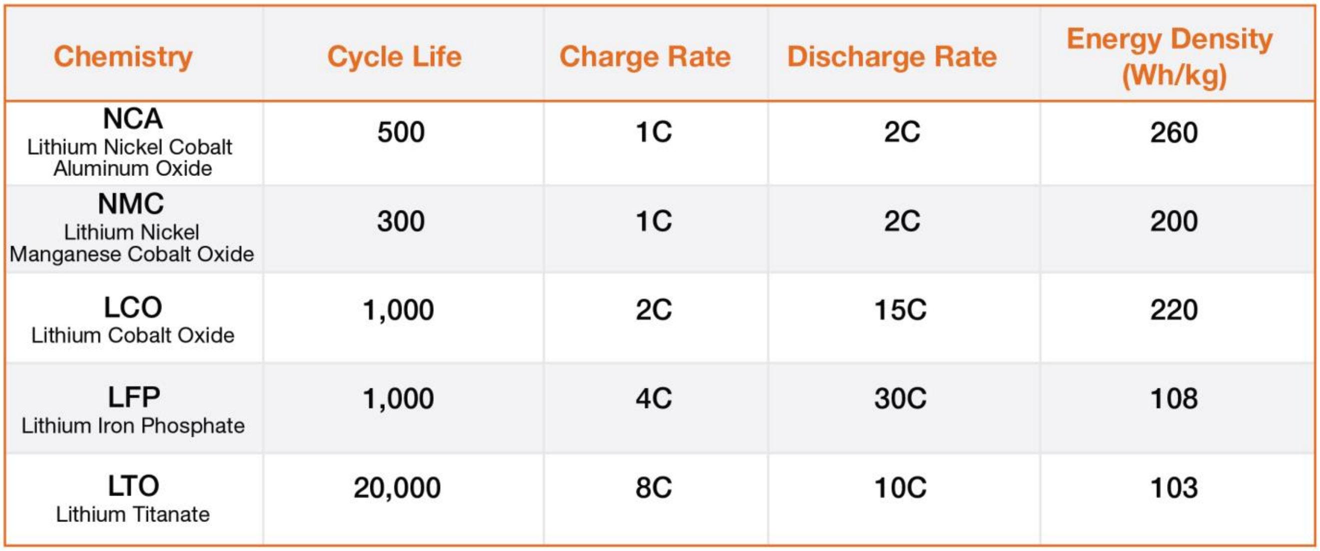


Figure 2 *– Ragone plot of energy storage technologies. Chen, George. (2017). (Open Access) Supercapacitor and supercapattery as emerging electrochemical energy stores. International Materials Reviews. 62. 173-202. 10.1080/09506608.2016.1240914.*

Due to their relative maturity and availability, lithium-ion (Li-ion) batteries are the most promising short to mid-term solution for the combination of power and energy densities that aviation's hybrid-electric systems will require.

Figure 3 shows the various chemistries available within the Li-ion family. Given the power draw of airplane propulsion, there is a limited number of viable chemistry options. At a given constant life, each reaches between 100 to 200 Watt-Hour/kilogram (W-hr/kg) of energy density at the cell level. Ongoing research, which Project 804 will contribute to, will continue to progress the capabilities of each base chemistry. For its initial flights, Project 804's demonstrator will consider both current performance as well as future promise when selecting cell chemistries.



Chemistry	Cycle Life	Charge Rate	Discharge Rate	Energy Density (Wh/kg)
NCA Lithium Nickel Cobalt Aluminum Oxide	500	1C	2C	260
NMC Lithium Nickel Manganese Cobalt Oxide	300	1C	2C	200
LCO Lithium Cobalt Oxide	1,000	2C	15C	220
LFP Lithium Iron Phosphate	1,000	4C	30C	108
LTO Lithium Titanate	20,000	8C	10C	103

***Figure 3** – Li-ion available chemistries and key characteristics.*

There are other important considerations as well, such as the operating temperature, which must be respected in an optimized design. In theory, Project 804 could consider any cell chemistry as the environment can be fully controlled in the demonstrator project. In practice however, Project 804's objective is to test an energy storage configuration that has good traceability to productization, and considers future operational environments, and this will influence the ultimate battery chemistry selection.

The regional aircraft mission

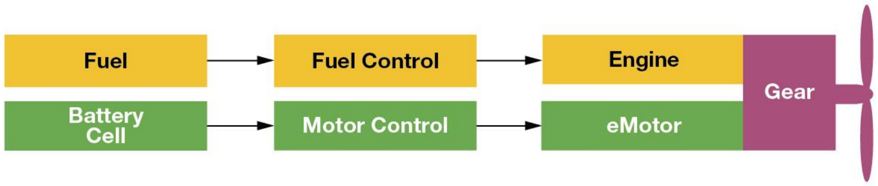
A regional turboprop aircraft requires approximately 2MW to fly at cruise speed. The typical 200-250 nautical mile mission lasts about one hour, including its climb, cruise, and descent, with an average of 2,000 kW-hr of energy required to complete the mission. Adding the usual reserve, the aircraft needs to carry about 3,500 kW-hr of energy per typical flight. Current engines convert about 30% of the fuel energy in useful work therefore the minimum fuel energy on board is around 12,000 kW-hr. To power this mission on stored electricity alone, assuming an electrical conversion factor of 85% and a cell packaging weight burden of 35%, a 200 Wh/kg based battery cell system would weigh in excess of the aircraft's maximum take off weight (MTOW).

$$\frac{\textbf{Onboard Energy (Mission + Reserve) x Cell Installation Burden}}{\textbf{Battery Cell Energy Density x Electrical System Efficiency}} = \textbf{Total Battery Mass}$$

Given the large energy needs of even short-haul missions, and near-term energy storage densities, a fully electric solution to propel a regional turboprop-sized aircraft is out of reach for the short to mid-term future. However, a hybrid-electric solution may be viable, provided it can enable significant fuel savings and justify its onboard presence without limiting overall aircraft capabilities. If a hybrid-electric engine converts 40% of the fuel energy into useful work (as opposed to 30%), it would enable 25% of the fuel energy to be replaced by electrical stored energy in the form of batteries. This stored electrical energy is used for only a short period of the mission time, like during take off and early climb. Additional benefit can also come from using renewable sources for the stored electrical energy.

Application example - regional turboprop

A regional turboprop requires high take off power to carry large payloads but flies relatively slowly under relatively low power. Project 804 leverages this large ratio between peak power and steady-state power to create significant total energy savings. The propulsion system uses a 50/50 power split, parallel-hybrid configuration between an engine and an electric motor that is shown in **Figure 4** below. The electrical assist is high-power and short-duration allowing the size and weight of the energy storage device to be manageable within the aircraft maximum take off weight. The configuration also allows the engine to be optimized for the cruise portion of the flight only. Full system capability is within the 2MW power class for the 30-50 passenger regional turboprop market.



Key attributes:
- Fault-tolerant architecture
- Electrical assistance up to 50%
- Optimized engine for cruise operation
- Reduced weight/losses compared to series architecture

Figure 4 *– Project 804's hybrid-electric propulsion architecture.*

Figure 5 below shows the intended flight mission profile and typical use of the hybrid-electric propulsion system where take off and climb is conducted with the electric motor and engine and the remaining climb, cruise and descent are powered by the engine only.

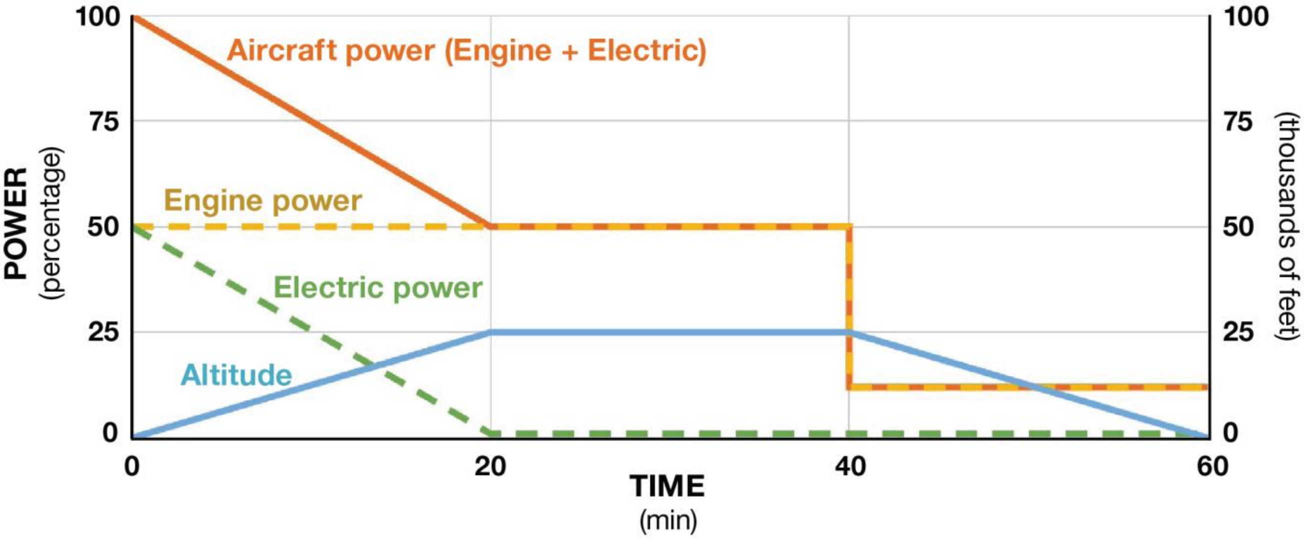


***Figure 5** – Typical mission profile and power sharing. Electric assist in high-power region only.*

The hybrid-electric system increases the aircraft Operating Empty Weight (OEW), and the aircraft's fuel capacity is reduced by about 50% to allow for the electrical equipment and energy storage. The remaining fuel mass, combined with the more efficient hybrid-electric system gives the re-engined aircraft a range of approximately 600 nm (as compared to the base 1000 nm range). Given that 99% of this airframe's missions are shorter than 500 nm, and that the hybrid-electric system provides an average 30% increase in fuel economy over the missions mix, this is a tradeoff that makes both technical and economic sense.

It is important to note that this preliminary study is carried out with the assumption of a re-engine in an existing aircraft. Incorporating the proposed hybrid-electric solution in a clean sheet new design aircraft could significantly reduce the weight and range penalty by better integrating the system with the airframe structure and required secondary systems. The architecture also decouples the aircraft field and flight performance to a point that new vehicles can be optimized to bring the fuel consumption per seat mile closer to an inter-city coach than the baseline airplane for typical short haul (around 400 km) and similar maximum passenger count.

More generally speaking, UTC's hybrid-electric system is a very competitive solution wherever the peak load is of short duration and significantly higher than the normal load. The regional turboprop case was discussed here but similar benefits are expected for category "A" helicopters, APUs and some turbofans as well.

Technology acceleration – UTAP's Project 804

The project will accelerate the technology readiness level of key components, sub-systems and power management systems for hybrid-electric propulsion. The program will deliver a technology platform that is scalable across a range of aircraft sizes, from general aviation to large commercial jets, and applicable to a broad section of aerospace applications.

Through the development of its hybrid-electric propulsion system, Project 804 accelerates the readiness of the following key enablers:

- Hybrid-electric propulsion system eligible for systemwide certification
- Engine within 1 MW power class
- Integration of significant amount of on-board batteries to support the main propulsion take-off and climb phases of the flight
- High-power / voltage electrical system (1MW / 1kV)
- Power management system
- Low-loss high-power electronics integration
- High-power density electric motor
- Efficient heat management systems and minimized drag penalties

On top of enabling hybrid propulsion systems in aviation, P804 will accelerate the sub-systems and components technology readiness to support faster time to market of new technologies. Examples range from high voltage distribution systems, high-power density and efficiency motors and generators, general aviation turboprop and helicopter engines to high efficiency auxiliary power units enabling their in-flight usage. Additionally, Project 804's technological solutions are equally viable for new platform applications and retrofitted upgrades to existing aircraft.

Figure 6 shows a high-level illustration of the proposed demonstrator. The battery, its power management system, and the power electronics will be installed in the cabin. The hybrid-electric propulsion system will be mounted in a modified nacelle.

Figure 6 *– The project team proposed demonstrator.*

Conclusion

UTC is continuing its leadership in electrification of aviation journey with a unique solution that could lead to multiple viable products and systems. **Our unique hybrid-electric propulsion system is expected to provide a total fuel savings of at least 30% during an hour-long mission.** The project leverages UTC's world-class expertise in engine propulsion and high-power electrical systems. Several technology off-ramps will be derived along the way that will benefit UTC's existing businesses and offerings. UTAP's Project 804 technology is writing the next chapter of aviation, by fundamentally creating a new design space for aviation. On top of the significant carbon footprint reduction for the industry, new operational spaces and missions will now become possible, enabled by the propulsion system's novel architecture.

The project is tracking as scheduled and its aggressive plan is receiving UTC's full support. The program is run throughout UTC-wide teams and the progress has been phenomenal.

In summary, UTC is leveraging its full engine, electrical, and subsystems integration capabilities to open a new paradigm in aerospace propulsion. The company's unique and novel approach yields significant fuel burn savings, of approximately 30% over the missions mix, and unlocks a new operational working space that fits within the aircraft's MTOW. UTC's experts in propulsion, thermodynamics, aerodynamics, aerostructures, electrical machinery, controllers and aircraft operations are joining forces to lead aviation's next steps in electrified propulsion for aviation.

At UTC, we are defining what hybrid means for aviation.

About the Authors

Jean Thomassin is the Project Director for Project 804. In this role, Jean oversees the effort to build and fly the hybrid-electric demonstrator, bringing to bear the expertise of UTC's portfolio companies and other partners to further UTC's capabilities in future propulsion systems.

Jean comes to this role after 20 years of experience at Pratt & Whitney Canada, most recently serving as the Senior Director of Systems Engineering. In addition to these responsibilities, Jean has played key roles in the development of several innovative engine programs, clearly demonstrating a forward thinking mindset and technical expertise that make him a natural fit for the role.

Jean holds a bachelor's degree in electrical engineering from the University of Sherbrooke, a master's degree in mechanical engineering from Concordia University, and a Ph.D. in mechanical engineering from the University of Montreal. Additionally, he has participated in UTC's Emerging Leader Program hosted at the University of Virginia's Darden School of Business.

Greg Winn is the Director of Program Management for Project 804. He is an engaging leader with a proven skillset in both business and technical development capacities. In his current role, Greg oversees Project 804's overall progress including its technology integration, partner sourcing, and business collaboration; ultimately helping UTC to impel the future of hybrid-electric flight. Greg joined the team after having spent 15 years at Collins Aerospace, where he was most recently the Director of Business Development for Electric Power Systems.

Greg served in many integral roles during his time at Collins Aerospace. Of note, he oversaw all Boeing commercial platforms and several major milestones including the development of the 777X electrical system and the delivery of the Embraer E2 and KC-390 electrical systems. Greg holds a bachelor's degree in mechanical engineering from the University of Iowa and a Master of Business Administration from Cardinal Stritch University.