NASA Electrified Aircraft Propulsion Efforts

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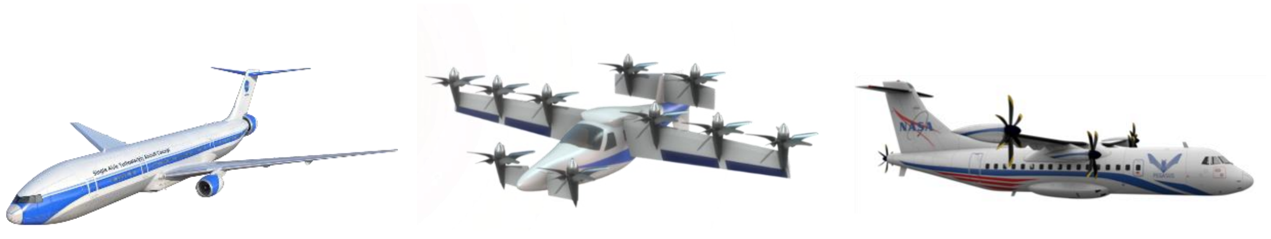
ABSTRACT

NASA's broad investments in Electrified Aircraft Propulsion (EAP) are reviewed in this paper. NASA investments are guided by an assessment of potential market impacts, technical key performance parameters, and technology readiness attained through a combination of studies, enabling fundamental research, and flight research. NASA has determined that the impact of EAP varies by market and NASA is considering three markets: national/international, on-demand mobility, and short haul regional air transport. Flight research is underway to demonstrate integrated solutions and inform standards and certification processes. This paper focuses on the vehicle related activities, however there are related NASA activities in air space management and vehicle autonomy activities as well as a breakthrough technology project called the Convergent Aeronautics Solutions Project. A key finding is that sufficient technical advances in key areas have been made which indicate EAP is a viable technology for aircraft. Significant progress has been made to reduce EAP adoption barriers and further work is needed to transition the technology to a commercial product and improve the technology so it is applicable to large transonic aircraft. This paper will review the activities of the Hybrid Gas Electric Subproject of the Advanced Air Transport Technology Project, the Revolutionary Vertical Lift Technology Project, and the X-57 Flight Demonstration Project, and discuss the potential EAP benefits for commercial and military applications.

1.0 INTRODUCTION

NASA is investing in research to enable Electrified Aircraft Propulsion (EAP). EAP is the use of electric motors to drive some or all of the propulsors on an air vehicle. The energy source for the system can be electric (electric energy storage), hybrid (a mix of electrical and fuel based energy storage), or turboelectic (fuel based energy storage only). NASA is working across a range of markets from urban air mobility to subsonic transport; each market has differences in vehicle sizes, ranges, and speeds. The overarching strategy is to create enabling technology, demonstrate this technology in flight-test vehicles, and transfer the knowledge to industry for future products. This paper focuses on vehicle related activities, however there are additional ongoing NASA activities covering air space management and vehicle autonomy, as well as a breakthrough technology project called the Convergent Aeronautics Solutions Project. In this paper the following topics will be reviewed: the activities of Hybrid Gas Electric Subproject of the Advanced Air Transport Technology Project, the Revolutionary Vertical Lift Technology Project, and the X-57 Flight Demonstration Project. Additionally, the potential EAP benefits for commercial and military applications will be discussed.

Electrified aircraft propulsion has varying impact on air vehicle design depending on the key requirements of the market that the vehicle is intended to serve. NASA Aeronautics considers market impact in making technology investment decisions. Three markets under consideration are: the existing national and international commercial transport aircraft market, a potentially emerging market of on-demand mobility characterized by vertical take-off vehicles with relatively short range, and the short range regional transport market (Figure 1-1). The national / international market is typified by transonic operation with design ranges greater than 3000 miles, served by aircraft of the single aisle size and larger. The on demand mobility market is an emerging market where air taxi services could be used to provide transport around large urban areas, and would likely be served by vertical takeoff, short range aircraft which will be partially or fully automated. The regional market is a small existing market featuring lower passenger load and shorter routes, operating into smaller airports and usually serviced by turboprop aircraft. Studies have been conducted to determine potential benefits of EAP and in some cases autonomous flight operation in these markets. Benefit assessments are largely dependent on the underlying technology assumptions. NASA technology investments are guided by key performance parameters determined from these studies. Fuel burn reduction and corresponding emissions reductions are potential benefits from EAP for the national/international air transport market. The combination of EAP with autonomous flight operation has the potential to enable the on demand mobility market which would be a new paradigm for local transportation. EAP combined with autonomy to reduce pilot operations has the potential to revitalize the economic case for shorter, more lightly loaded regional routes.



Market: National/International

Impact: Fuel Burn/Emission Reduction

Market: On demand mobility

Impact: New mobility capability

Market: Regional

Impact: Revitalization of smaller routes

Figure 1-1: Benefits of Electrified Aircraft Propulsion by Market

2.0 OVERVIEW OF NASA ELECTRIFIED AIRCRAFT PROPULSION (EAP) PROJECTS

2.1 Hybrid Gas Electric Subproject of Advanced Air Transport Technology Project

The NASA Advanced Air Transport Technology (AATT) Project continually challenges the technical community to improve the noise generation, emission output, fuel burn, and overall efficiency of commercial transport aircraft. This project traditionally invests in a broad research portfolio that includes fundamental improvements in gas turbine engines, advanced airframes including radical improvements in propulsion-airframe integration, and improvements in aircraft safety through icing research as well as engine and airframe acoustic remedies. This NASA project focuses on the commercial transport market with emphasis on narrow-body size aircraft. The Hybrid Gas Electric Propulsion subproject (HGEP) was created in 2014 within the AATT Project to find a viable transport-class EAP aircraft concept, identify barrier technologies, and advance the technology readiness level of those barrier technologies. The HGEP team used a three tiered approach to 1) study aircraft concepts and identify potential aerodynamic efficiency gains, 2) investigate powertrain architectures, and 3) develop the fundamental components that will enable broad improvements in aircraft power systems. Elements of each of these three tiers will be reviewed in this paper.

Key concepts of several NASA sponsored aircraft designs are summarized here with further details available (Bradley, 2012; Lents, 2016; Perullo, 2017; Bowman, 2018). Boeing, United Technology Research Center and Rolls-Royce North America have performed detailed designs hybrid-electric propulsion systems that added battery energy storage and incorporated minimal changes to the narrow-body aircraft outer mold-line. These studies showed that sufficiently advanced battery management systems (750~1000 W-hr/kg) combined with optimization of the turbine engine operation could provide narrow-body aircraft with improved total energy usage. When the Rolls-Royce North America team did their assessment for a 90-passenger aircraft using 1.5 MW electric machinery and 400 w-hr/kg batteries, they found that the hybrid system provided a two percent energy benefit for a 926 km mission, and fuel benefits approaching 14 percent for shorter range missions (O’Brien, 2018). Significant progress in several technologies are required to realize the gains projected from these hybrid electric propulsion studies, with the most noticeable challenge being the need for improved battery management systems.

Other early EAP configurations such as the N3-X and ECO-150 considered fully turboelectric propulsion, in which all of the turbine shaft power is converted to electricity and distributed to numerous motor-driven fans (Felder, 2011; Schiltgen, 2016). Fully distributed concepts can take advantage of the propulsion efficiency benefits of distributed fans and advanced boundary layer ingestion, but require extremely efficient electrical machines and power distribution to handle the large electrical power loads. NASA has evaluated a tailcone thruster concept called Single aisle Turboelectric AiRCraft with Aft Boundary Layer ingestion (STARC-ABL) as one minimalist approach to partial turboelectric distribution (Welstead, 2016). The advantage of partial turboelectric distribution is that it opens the door to new propulsion-airframe-integration efficiency while using nearer-term technologies. The projected fuel savings of “revision B” of this aircraft were 2.7 percent for a typical economic mission (1667 km or 900 nm), and 3.4 percent savings for the full design mission of 6482 km (3500 nm) (Bowman, 2018). The fuel and total energy savings are the same in this case, because fuel is the only energy source used in a turboelectric concept. The fuel/energy savings of nominally three percent is significant because in this study the technology development assumptions required were relatively modest, and completely commensurate with the component research that will be discussed below. Figure 2.1-1 illustrates the STARC-ABL architecture and summarizes many of the key technology assumptions.

In addition to evaluating aircraft designs with fixed technology assumptions, it is also instructive to parametrically compare performance improvements of specific aircraft concepts as the performance of the powertrain

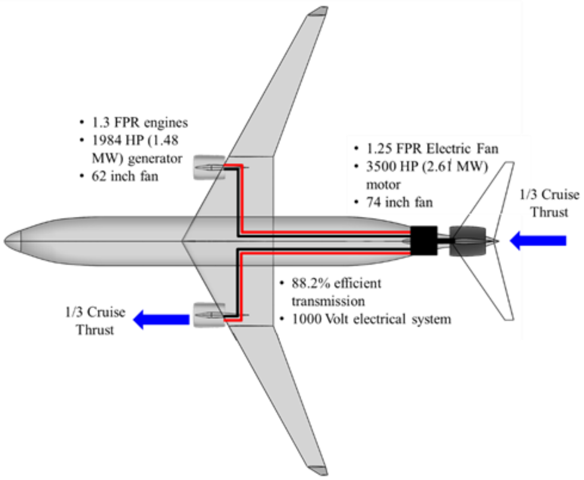


Figure 2.1-1: Single Aisle Vehicle Concept

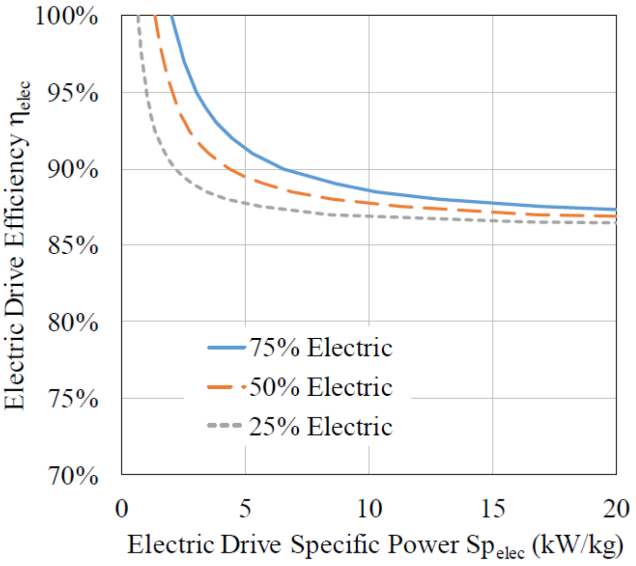


Figure 2.1-2: Breakeven Curves for turboelectric propulsion

components improves. NASA authors have used a series of breakeven based evaluations to trade between competing parameters such as specific power and efficiency, and to evaluate the relative value of improvements in one component class versus another (Jansen, 2015; Duffy, 2018). Figure 2.1-2 shows the breakeven curves as a function of electrical drive system specific power and efficiency for a STARC-ABL type configuration, when considering varying electrical contribution to the partial turboelectric propulsion. Here points of specific power and efficiency that lie on the curves represent power system architectures with equal fuel consumption to the conventional propulsion system, while points above the curves describe improvements beyond this breakeven point. Note that the relationship between efficiency and specific power is not flat, and that a positive benefit is achieved with less aggressive technology when a smaller fraction of the propulsion power is required.

The aircraft configuration studies and power architecture performance assessments show that aircraft fuel and energy savings potentially exist. Technology development at the subsystem, component, and material levels are required to make these designs viable. A few key efforts are summarized here. NASA has developed test beds specifically for EAP architectures (Jansen, 2017). NASA is investing in electric machine (motor/generator) development to achieve 13.2 kW/kg specific power and 96 percent efficiency (Anderson, 2018; Yoon, 2018; Jansen, 2018). NASA investment has demonstrated power inverters (machine controllers) with 19 kW/kg specific power and greater than 99 percent efficiency (Zhang, 2018, Niu, 2019). New soft magnetic materials have been demonstrated that operate with low electrical losses at frequencies up to 100 kHz and operating temperatures as high as 400°C (Leary, 2019). Furthermore, NASA is using unique modelling approaches to design motor slots as a composite system, and to tailor motor wire insulation for optimal thermal performance (Woodworth, 2018).

2.2 X-57 Maxwell

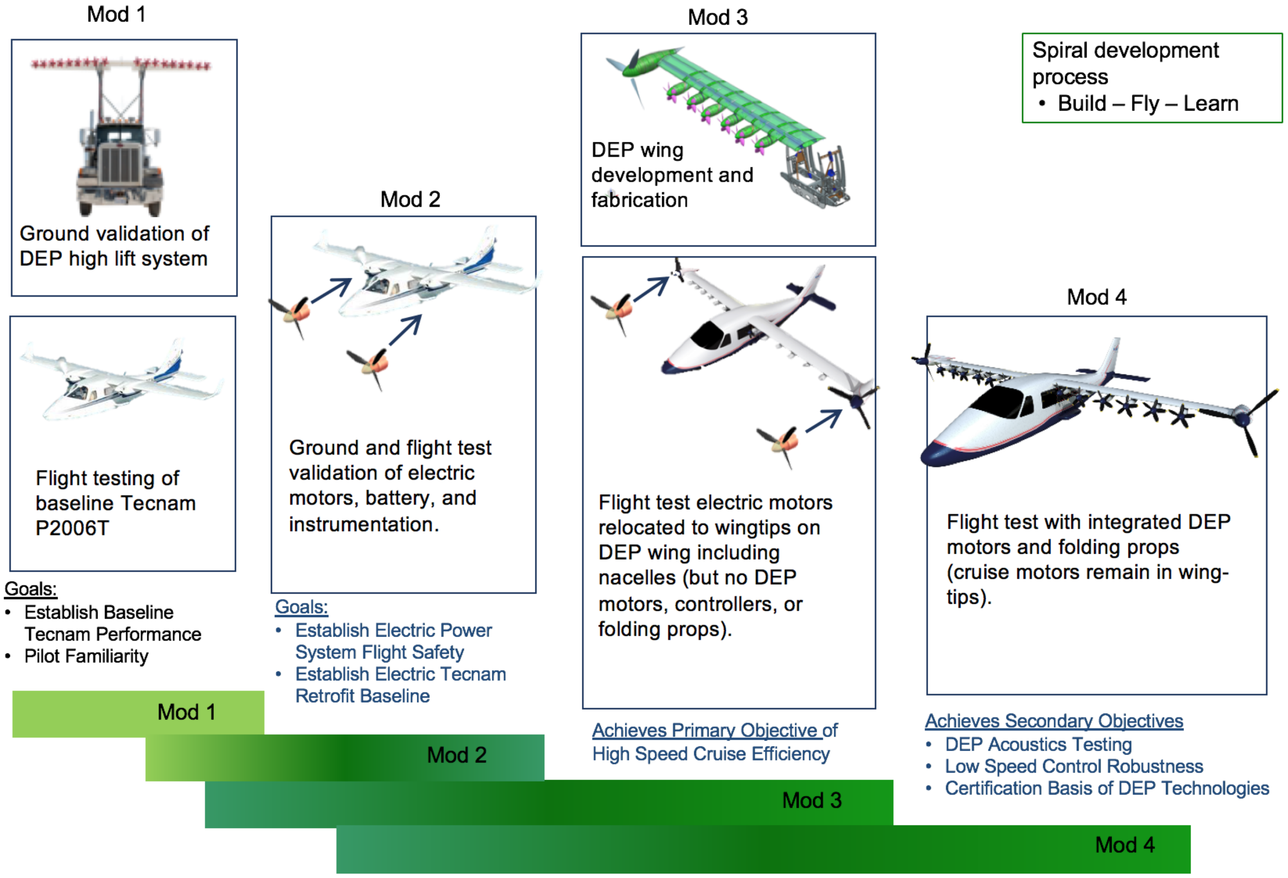
The X-57 “Maxwell” is a technology demonstrator aircraft supported by the NASA Flight Demonstrations and Capabilities Project. This experimental plane uses a crew-rated electric propulsion system designed to augment the aircraft performance in the high speed cruise condition (Borer, 2016)[2]. FAA certification standards do not currently exist for EAP propulsion technologies. The project will develop best-practices knowledge for passenger applications of electric propulsion technologies, and will demonstrate the principles to achieve an 80% reduction in energy required per passenger-mile in the 150-knot speed class. Development of new airworthiness standards in key regulator and industry forums is needed to accelerate safe adoption of EAP technologies on Urban Air Mobility and Thin Haul vehicles.

The X-57 vehicle test program is divided into three spiral-development configurations shown in Figure 2.2-1 (Clarke, 2015). Mod I established baseline flight performance with piston engines. Mod II is an electrified modification which will increase the maturity of the new electric power plant and propulsion system. Mod III integrates the new, optimized wing with the propulsion system mounted at the wingtips, but without the original low speed flight envelope. Mod IV recovers performance across the original flight envelope with the addition of distributed folding propellers driven by electric motors that provide high lift during low speed flight. The baseline performance characterization phase (Mod I) is complete. The electrified powertrain developed for Mod II is being integrated into the vehicle presently, with formal system-level tests planned for the end of 2019 followed by taxi tests and a series of flight tests in 2020. The high-performance Mod III/IV wing has been fabricated and will complete flight loads testing in 2019, followed by traction and instrumentation system integration before flights in 2021. The Mod IV systems are in the preliminary design phase with critical design review planned for late 2019 followed by flight inverter and motor development, qualification, and acceptance testing in 2020, and flights in 2021 and 2022 following the Mod II flight program.

Integrated design for effective interaction between the wing, the propellers, and the mission flight path is the core demonstration effort on the X-57 aircraft. Modern advancements in high-performance electric motors, power inverters, and battery technologies enable this new design paradigm. The X-57 is the first electrified X-plane and because the electric powertrain is central to the capability of this platform, the aircraft has been designated "Maxwell" in honor of James Clerk Maxwell's foundational work describing the nature of the electromagnetic forces that are harnessed in the electric motors, motor inverters, power buses, and batteries that comprise the X-57 traction system.

The high lift system design, coupled with the high aspect-ratio wing design and the mission flight path planning approach (Schnulo, 2018) require an innovative, multi-disciplinary development to achieve the planned advances. The high-performance wing has been optimized to maximally improve aerodynamic efficiency at cruise flight conditions of 150 knots, and incorporates an innovative vortex drag reduction capability through the location of the cruise propellers at the wingtip, enabled by lightweight, high-efficiency electric motors. The low-speed aerodynamic performance of the wing is ensured by incorporating 12 propellers distributed along the leading edge of the wing, each driven by a smaller electric motor and inverter system, which would be used only for low-speed maneuvers such as takeoff and landing. The X-57 project team has developed advanced propeller design and optimization workflows that enable uniform velocity boosting when activated, while also supporting folding and low-drag stowing of the propeller blades during high speed mission segments (Litherland, 2017).

The X-57 avionics power, traction power, and command systems are optimized for system reliability, given the constraints of a flight research program showcasing experimental hardware in critical systems (Clarke, 2016). The system architecture relies on redundancy to limit the scope of failures, component testing to limit the likelihood of failures, and failure analysis and training to limit the persistence of failures. The resulting architecture may serve as a case study for development of future experimental aircraft or commercial aircraft that rely on these technologies. Evaluation of each developmental component by way of component independent design review, endurance testing, and function validation in the integrated system are essential to ensuring reliability. The integrated X-57 system design will be evaluated for failure modes and will be integrated into an aircraft simulator with a flight-like cockpit that will be used for pilot training, ensuring rapid response to the



Mod 1

Ground validation of DEP high lift system

Flight testing of baseline Tecnam P2006T

Goals:
- Establish Baseline Tecnam Performance
- Pilot Familiarity

Mod 2

Ground and flight test validation of electric motors, battery, and instrumentation.

Goals:
- Establish Electric Power System Flight Safety
- Establish Electric Tecnam Retrofit Baseline

Mod 3

DEP wing development and fabrication

Flight test electric motors relocated to wingtips on DEP wing including nacelles (but no DEP motors, controllers, or folding props).

Achieves Primary Objective of High Speed Cruise Efficiency

Spiral development process
- Build – Fly – Learn

Mod 4

Flight test with integrated DEP motors and folding props (cruise motors remain in wing-tips).

Achieves Secondary Objectives
- DEP Acoustics Testing
- Low Speed Control Robustness
- Certification Basis of DEP Technologies

Figure 2.2-1: X-57 Spiral Development Approach

Figure 2.2-2: - X-57 Maxwell with Mod II systems integrated including electrified powertrain.

Figure 2.2-3: X-57 cockpit includes new instrument panel configured to manage the electric powertrain

most severe fault cases. Figure 2.2-2 and **Error! Reference source not found.** show the Mod II aircraft and cockpit.

The X-57 vehicle test program is designed to solve a number of technical challenges for electrified propulsion in crew-rated aircraft. Aircraft electric propulsion requires special consideration to accommodate weight, safety, and operating environment requirements, which complicates adaptation of commercially available solutions. While electric propulsors (motors and inverters) are more efficient than fuel-burning engines, they still produce heat during operation, requiring integrated vehicle-level thermal management designs. The common technique of solving such heat problems is to employ dedicated heat dissipation methods such as liquid cooling or large metal heat sinks, but these can cause dramatic increase in airplane weight, reducing the benefit of the electric conversion. In order to address these issues, research and development in the areas of material science, high efficiency motors and power electronics, additive manufacturing, and advanced controls is used by X-57 project.

2.3 Revolutionary Vertical Lift Technology (RVLT) Project

The overarching goal of the Revolutionary Vertical Lift Technology (RVLT) Project is to develop and validate tools, technologies, and concepts to overcome key barriers for vertical lift vehicles. The scope encompasses technologies that address noise, speed, mobility, payload, efficiency, environment, and safety concerns for both conventional and non-conventional vehicle configurations as well as new missions and markets. One of these new markets, Urban Air Mobility (UAM), is a concept for passenger-carrying air transportation around metropolitan areas. Vehicles for these missions use all-electric and hybrid-electric propulsion concepts capable of vertical take-off and landing, and are referred to as eVTOL. A critical challenge for UAM market growth is the public acceptance of eVTOL as being as safe as, or safer than, commercial air travel and automotive transportation.

Standards are developed by significant in-service experience and analysis supported by experimental evidence. FAA certification standards do not currently exist for these new propulsion technologies. The certifying authorities are adapting/adopting new modified rules to better match the new electric propulsion technologies and are working closely with Industry Standards Groups (Horan, 2018). Part of the RVLT Project focus is to perform research that informs standards for electric and hybrid-electric propulsion systems of eVTOL.

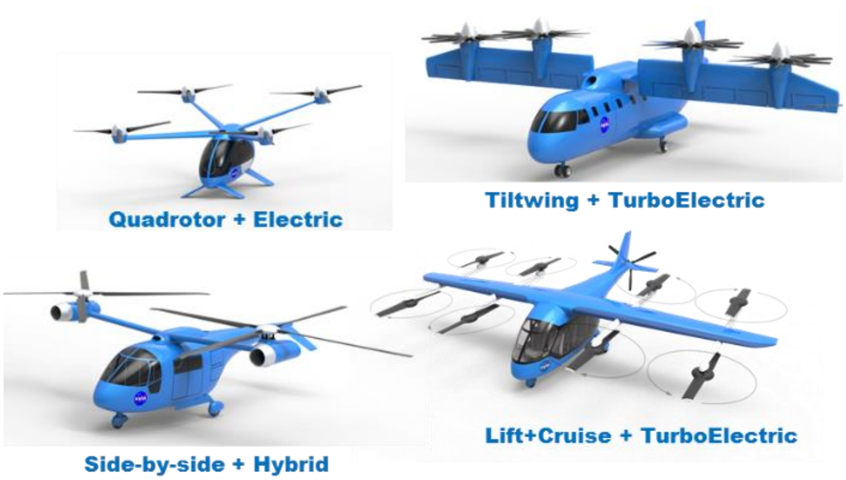


Figure 2.3-1: RVLT Concept Vehicles

To enable this research, NASA designed four UAM concept vehicles of varying payloads, range, type and propulsion systems to identify crucial technologies, define research requirements, and explore a range of propulsion systems (Johnson, 2018; Silva 2018). Figure 2.3-1 illustrates the concept vehicle configurations and their propulsion systems.

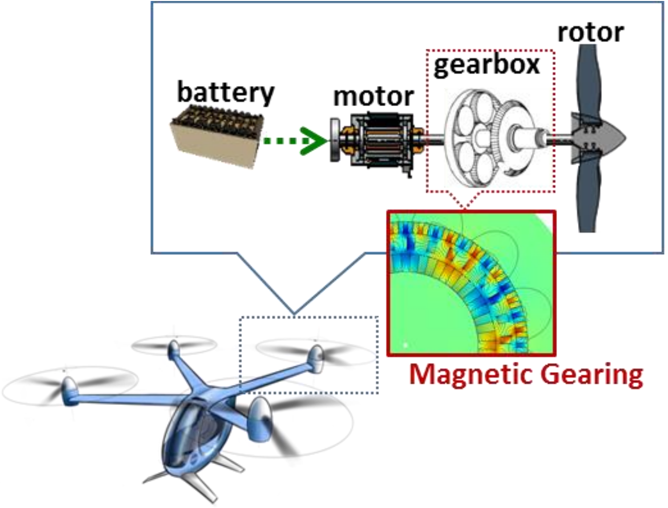


Figure 2.3-1: Magnetic Gearing

The propulsion system architectures are being used to establish system safety assessments and to identify knowledge gaps in safety, durability, means of compliance, and provide insights into critical component areas. Results can be used to inform standards for future certification needs and provide guidance to new eVTOL developers.

Under RVLT sponsorship, NASA is also developing electrical ports in Numerical Propulsion System Simulation (NPSS), a software tool used for conceptual design of propulsion systems, for future electric propulsion capabilities (Csank, 2018). The addition of an electric port will enable electrical power systems for eVTOL to be designed and analyzed within the NPSS framework. RVLT is also leading the development of magnetic gearing for use in the propulsion architectures of eVTOL. Magnetic gearing technology uses magnets to transfer torque through magnetic forces, eliminating the need for physical contact between gear teeth. Figure 2.3-1 illustrates an example of a concentric magnetic gear replacing conventional gearing in the RVLT quad rotor concept vehicle. NASA research has resulted in lightweight, reliable powertrain designs for aerospace applications and a new facility to test magnetic gearing powertrain designs (Scheidler, 2018).

Results of RVLT electric propulsion research will contribute to improving the safety, reliability, and efficiency of eVTOL for the UAM market.

2.4 Potential EAP Benefits for Commercial and Military Applications

In the commercial aviation world, hybrid/electric propulsion is considered to be a promising technology for fuel, emissions, and noise reduction in support of the challenging goals established by 2050 EU Flightpath/SRIA, NASA ARMD Strategic Implementation Plan, and the US Air Force ATTAM programs. Ongoing results indicate operational benefits are possible in those three technical areas.

Considering military applications, hybrid/electric propulsion may yield further significant improvements by enabling new, unorthodox mission capabilities. Potential benefits are expected in the areas of vehicle signature reduction (lower noise, lower exhaust signature), usage in enhanced flight environments, minimized human-in-the-loop workload by offering a platform compatible with future goals of autonomous operations facilitation, maintenance cost reductions, and performance burst/dash energy. Additional synergies are likely when used in conjunction with energy weapons.

Some potential areas of mutual interest could include, dusty operations capability, remote supply capability, extended surveillance, dispatch able power, fuel-flexible vehicles, and autonomous rescue equipment. In order to establish a technology roadmap toward relevant systems, we must identify both mission requirements as well as potential future technology gap estimates. Results show that the role of the battery in hybrid electric propulsion systems regional air vehicles with 350 NM range can be competitive to conventional propulsion systems. As shown in Figure 2.4-1 and Figure 2.4-2, most of the near-term small Unmanned Aerial Systems (SUAS) hybrid electric vehicles under development have a range of less than 1000 nm and are in Groups 1-3 (Hoelzen, 2018; Rottmayer, 2017).

In addition, hybrid electric aircraft architectures enable new ways of integrating components to achieve new mission capability. Specifically, the ability to integrate atypical energy sources and the ability to place propulsors more broadly across the airframe broadens the vehicle design space. Synergistic use of vehicle subsystems has the potential to enable quiet, long endurance, pulse-power for dash and directed energy weapons. While the technologies required are still immature, it is prudent to consider their military applications in advance to guide future research thrusts.

A future task is to identify key performance corner points in which hybrid/electric propulsion systems could improve tactical, logistics, and operations on the battlefield while leveraging existing commercial technology development. Many of the key technologies that have been demonstrated in ground operation must now be qualified for altitude conditions. We expect to have many flight qualified powertrain systems over the next decade for military planners to choose from for new future battlefield capability.

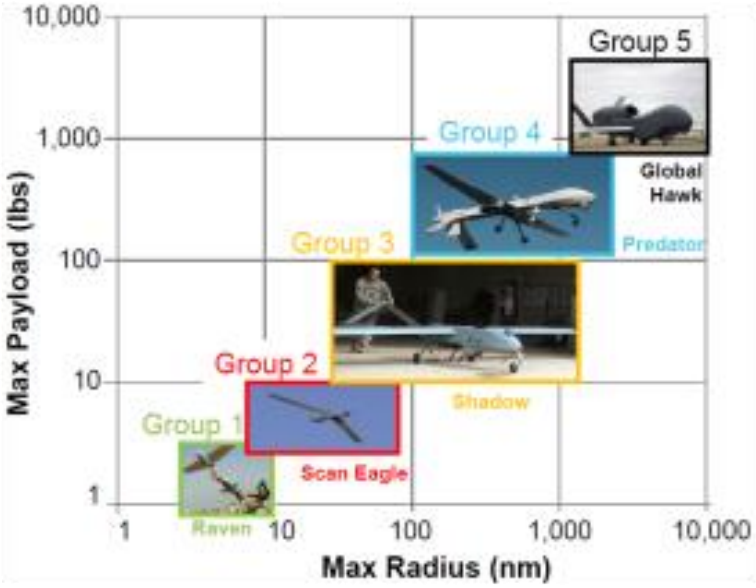


Figure 2.4-1: Unmanned Aerial System Sizes

Near Term <2021
- > 500 hrs MTBF
- Up to 2x Range/Endurance
- 10% Dash Capability
- 25% Payload Power Growth

Mid Term <2026
- > 2000 hrs MTBF
- Up to 4x Range/Endurance
- 50% Dash Capability
- 100% Payload Power Growth

Logistic Fueled STUAS
Hand-Launched SUAS
Air-Dropped TLEU

(Group 1 – Group 3 Propulsion)

Recoverable Air-Dropped UAS
Large Class UAS APU

(Group 1 – Group 3 Propulsion)
(Group 4 / Group 5 Secondary Power)

Figure 2.4-2: SUAS Power/Propulsion Goals

3.0 CONCLUSION

NASA is broadly investing in Electrified Aircraft Propulsion (EAP). NASA investments are guided by a combination of potential market impacts and technical key performance parameters. The impact of EAP varies by market and NASA is considering three markets: national/international, on-demand mobility, and short haul regional air transport. Technical advances in key areas have been made that indicate EAP is a viable technology. Flight research is underway to demonstrate integrated solutions and inform standards and certification processes. Significant progress has been made to reduce EAP adoption barriers and further work is needed to transition the technology to a commercial product and improve the technology so it is applicable to large transonic aircraft.

4.0 ACKNOWLEDGMENTS

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REFERENCES

1. Anderson, A.D. et al, (2018), “System Weight Comparison of Electric Machine Topologies for Electric Aircraft Propulsion”, in proceedings of AIAA/IEEE Electric Aircraft Technologies Symposium, AIAA Propulsion and Energy Forum, AIAA, Reston, VA, AIAA 2018-4983.
2. Borer, N.K., Patterson, M.D., Viken, J.K., Moore, M.D., Bevirt, J., Stoll, A.M., Gibson, A.R. (2016), "Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator", *16th AIAA Aviation Technology, Integration, and Operations Conference*, *AIAA AVIATION Forum*, (AIAA 2016-3920)
3. Bowman, C., et al. (2018), “Turbo- and Hybrid-Electrified Aircraft Propulsion Concepts for Commercial Transport,” in proceedings of AIAA/IEEE Electric Aircraft Technologies Symposium, AIAA Propulsion and Energy Forum, AIAA, Reston, VA, 2018-4984.
4. Bradley, M. K. and Droney, C. K. (2012), “Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development,” NASA/CR—2012-217556, NASA. Available at: https://ntrs.nasa.gov (accessed 2 May 2017)
5. Clarke S., Papathakis K., Samuel A., Lin Y., Ginn S. (2016), "NASA SCEPTOR electric concept aircraft power system: X-plane electric propulsion system design and qualification for crewed flight testing", *2016 IEEE Transportation Electrification Conference and Expo*, *ITEC 2016*, art. no. 7520287
6. Clarke, S. (2015), "Aircraft Electric Propulsion Systems Applied Research at NASA", [online] NASA. Available from https://ntrs.nasa.gov/search.jsp?R=20160005232
7. Csank, J. and Sadey, D. (2018), “Electrical Power System Sizing for Electric Aircraft Using NPSS,” 2018 NPSS Governing Board Technical Session, February 28 - March 2, 2018, San Antonio, Texas.
8. Duffy K .P. and Jansen R. (2018), “Partially Turboelectric and Hybrid Electric Aircraft Drive Key Performance Parameters”, in proceedings of 2018 AIAA/IEEE Electric Aircraft Technologies Symposium, AIAA Propulsion and Energy Forum, AIAA, Reston, VA, 2018-5023.
9. Felder, J. L., et al. (2011), “Turboelectric Distributed Propulsion in a Hybrid Wing Body Aircraft,” in proceedings of 20th International Society for Air Breathing Engines, Gothenburg, Sweden, ISABE-2011-1340.
10. Hoelzen, J., Yaolong, L., Bensmann, B., Winnefeld, C., Elham, A., Friedrichs, J., Hanke, R. “Conceptual Design of Operation Strategies for Hybrid Electric Aircraft”, Energies, 2018, 11, 217, pp 26.
11. Horan, G. (2018), “Panel on Flight Qualification/Certification of Advanced VTOL - Electric Propulsion,” AHS International 74th Annual Forum & Technology Display, May 14-18, 2018, Phoenix, Arizona.
12. Jansen, R. et al. (2015), “Turboelectric Aircraft Drive Key Performance Parameters and Functional Requirements”, in proceedings of 51st AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, AIAA, Reston, VA, 2015-3890.
13. Jansen, R. et al. (2017) “Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports”, in proceedings of 53rd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, AIAA, Reston, VA, 2017-4701.
14. Jansen, R. et al. (2018), “High Efficiency Megawatt Motor Conceptual Design”, in proceedings of 2018 Joint Propulsion Conference, AIAA Propulsion and Energy Forum, AIAA, Reston, VA, 2018-4699.

15. Johnson, W., Silva, C and Solis, E. (2018), “Concept Vehicles for Air Taxi Operations,” AHS Aeromechanics Design for Transformative Vertical Lift, January 16-19, 2018, San Francisco, California.
16. Leary, A. et al. (2019), “High Temperature Performance of Soft Magnetic Nanocomposites”, presented at TMS 2019, in San Antonio, TX, March 10-14.
17. Lents, C., et al. (2016), “Parallel Hybrid Gas-Electric Geared Turbofan Engine Conceptual Design and Benefits Analysis” in proceedings of 52nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA, Reston, VA, 2016-4610.
18. Litherland, B.L., Patterson M.D., Derlaga, J.M., Borer, N.K. (2017), "A Method for Designing Conforming Folding Propellers", *17th AIAA Aviation Technology, Integration, and Operations Conference, AIAA AVIATION Forum*, (AIAA 2017-3781)
19. Niu, J. et al. (2019), “Design of a single controller for multiple paralleled inverters”, in proceedings of Applied Power Electronics Conference, IEEE New York, NY.
20. O’Brien, M., et al, (2018), “Electrically Variable Engine (EVE): 2018 NRA Review” presented at NASA Research Award Review, 18 October, Brook Park, OH.
21. Perullo, C., et al. (2017), “Cycle Selection and Sizing of a Single-Aisle Transport with the Electrically Variable Engine (EVE) for Fleet Level Fuel Optimization,” in proceedings of 55th AIAA Aerospace Sciences Meeting, AIAA, Reston, VA, 2017-1923.
22. Rottmayer, M., “UAS Hybrid Electric Power & Propulsion”, AFRL/RQQE, Public Distribution Approved, 2017
23. Silva, C., Johnson, W., Antcliff, K.R, and Patterson, M.D. (2018), “VTOL Urban Air Mobility Concept Vehicles for Technology Development,” AIAA Aviation and Aeronautics Forum and Exposition, June 25–29, 2018, Atlanta, Georgia.