

Misconceptions of Electric Propulsion Aircraft and their Emergent Aviation Markets

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Over the past several years there have been aircraft conceptual design and system studies that have reached conflicting conclusions relating to the feasibility of full and hybrid electric aircraft. Some studies and propulsion discipline experts have claimed that battery technologies will need to improve by 10 to 20 times before electric aircraft can effectively compete with reciprocating or turbine engines. However, such studies have approached comparative assessments without understanding the compelling differences that electric propulsion offers, how these technologies will fundamentally alter the way propulsion integration is approached, or how these new technologies can not only compete but far exceed existing propulsion solutions in many ways at battery specific energy densities of only 400 watt hours per kilogram. Electric propulsion characteristics offer the opportunity to achieve 4 to 8 time improvements in energy costs with dramatically lower total operating costs, while dramatically improving efficiency, community noise, propulsion system reliability and safety through redundancy, as well as life cycle Green House Gas emissions. Integration of electric propulsion will involve far greater degrees of distribution than existing propulsion solutions due to their compact and scale-free nature to achieve multi-disciplinary coupling and synergistic integration with the aerodynamics, highlift system, acoustics, vehicle control, balance, and aeroelasticity. Appropriate metrics of comparison and differences in analysis/design tools are discussed while comparing electric propulsion to other disruptive technologies. For several initial applications, battery energy density is already sufficient for competitive products, and for many additional markets energy densities will likely be adequate within the next 7 years for vibrant introduction. Market evolution and early adopter markets are discussed, along with the investment areas that will fill technology gaps and create opportunities for the effective, near-term electric aircraft products. Without understanding both the context of how electric propulsion will integrate into the vehicle system, and evolve into the market place it is likely that electric propulsion will continue to be misunderstood.

Nomenclature

<i>APU</i>	= <i>Auxiliary Power Unit</i>
<i>CFD</i>	= <i>Computational Fluid Dynamics</i>
<i>DEP</i>	= <i>Distributed Electric Propulsion</i>
<i>ECM</i>	= <i>Electronic Control Module</i>
<i>FAR</i>	= <i>Federal Aviation Regulations</i>
<i>GA</i>	= <i>General Aviation</i>
<i>GPU</i>	= <i>Graphic Processing Unit</i>
<i>IC</i>	= <i>Internal Combustion</i>
<i>LEAPTech</i>	= <i>Leading Edge Asynchronous Propellers Technology</i>
<i>NM</i>	= <i>Nautical Mile</i>
<i>SOA</i>	= <i>State Of the Art</i>
<i>UAS</i>	= <i>Unmanned Aerial Systems</i>
<i>Whr/kg</i>	= <i>Watt Hours per Kilogram</i>

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I. Introduction

The objective in writing this paper is to help those who aren't necessarily experts in conceptual design or propulsion technologies better understand the significant differences and potential that exists for electric propulsion for aircraft. The approach this paper takes is to answer fundamental misconceptions that exist which the author has confronted repeatedly over the past few years with those who are less familiar with the design of electric aircraft. Prior publications by the author and other recent publications from authors such as Rob McDonald¹, Brian German and Michael Patterson^{2,3}, Amir Gohardani⁴, Jack Langelaan⁵, Martin Hepperle⁶, Moore⁷, Fredericks⁸, etc. provide a good basis for understanding the technical characteristics and an abundance of references to other papers. However, this position paper is more of a guide for managers and decision makers to be in a better position to ask the right questions when it comes to applying electric propulsion to their aircraft platform and mission needs.

Clearly there are many misconceptions that exist with regard to electric propulsion, which the authors have repeatedly encountered over the prior years as they have published research. Four key motivating events took place over the past several years that compelled the authors to write this paper. Before sharing these events, it should be pointed out that each of the researchers involved are highly intelligent and have an excellent understanding of the propulsion discipline domain, and it is not the intent of the author to critique their expertise. However, in many cases, individuals are sharing strong opinions in important venues, without having published any prior studies in this area; and especially without publishing system studies that place the technology in the context of a vehicle integration for a specific mission.

The first event took place at a NASA review at the National Academies where a specific breakout session was established to discuss the feasibility of electric propulsion for aircraft. The chair of that session made a memorable, lengthy opening statement that started like this "Electric propulsion for aircraft is an incredible technology; by this I mean the literal definition in that the technology is not credible." His core position was that a direct comparison of either a turbine or reciprocating engine along with their associated energy needs (as an isolated propulsion technology) far exceeded the performance characteristics of any electric propulsion system in the near-term. The main point was that with electrical energy storage being 2-4% of the energy density of hydrocarbon fuels, it was rather ludicrous for NASA to be even considering investment in this research area. This perspective only considered the propulsion plus fuel comparison, without understanding how electric propulsion integrates differently, or understanding how strongly important metrics are modified. With many important decision makers in the room, the authors found this meeting to be strongly biased towards the entrenched propulsion technologies and industry, with a poor understanding that integration fundamentally alters the comparison, and the future of electric propulsion is not merely a function of battery or fuel cell specific energy density. Many aviation markets, and emerging aviation markets, don't require extended range capability and are able to integrate so effectively and efficiently into the airframe that a very large portion of the energy storage deficit of batteries is made up in other ways.

The second event was internal to NASA where a single electric propulsion approach of developing an electric gearbox (similar to a locomotive) was considered reasonable for funding support, while parallel or series hybrids and full electric propulsion systems were automatically excluded from research investigations. Electric drivetrains are great methods of routing power via electrons (instead of mechanical shafts and gearboxes). However this type of integration approach invalidates most of the main benefits that electric propulsion has to offer, since substantial conversion losses are present with all the power/energy being provided from an on-board source. The propulsion researchers were appropriately absorbed in the complex details of this new powertrain (which converted turbine power to electricity at the multi megawatt scale to a distributed highly integrated set of fans). However, the total aircraft system impact was never even determined, because of the complexity embraced in this integration approach. In conceptual aircraft design, it is a frustration of the authors to have discipline experts optimizing their specific discipline metrics to local minima while being quite removed from the total aircraft system metrics and global minima. A quote that aircraft system analysts like to share is that "the optimum aircraft is always a compromise of non-optimum discipline components" and that "discipline experts will often give up almost infinite amounts of goodness in other discipline areas to achieve a limited goodness in their own discipline". While the 'electric gearbox' propulsion integration being explored was technically interesting, it lacked an aircraft system bias for ensuring that the most appropriate propulsion system architecture was being

investigated to achieve the stated metrics, within the context of a specific mission. One issue limiting the usefulness of this research was that an integration approach wasn't selected that permitted high confidence for the total aircraft comparability, because very high complexity was embraced as a first study into electric propulsion. Therefore comparisons of the total emissions, energy use, operating costs, and community noise (which are the key tracking metrics that NASA has in place for determining technology value) were never evaluated, and it was never realized that alternate hybrid electric integration strategies could have been demonstrated to be far more effective at accomplishing greater benefits.

The third event was during the design of a future technology prize challenge that would follow on from the accomplishments of the NASA Centennial Challenge Green Flight (GFC) Challenge in 2011. The GFC laid a foundation for electric propulsion technologies in terms of showcasing the efficiency that could be achieved, with greater than 100 miles per gallon per passenger achieved for a 200 mile mission (2 to 6 times current General Aviation products). Recently a researcher proposed that in the subsequent competition the gross and payload weights as well as the power should be forced to be equivalent to permit direct comparison of electric propulsion systems. Such a prize would make sense for a mature technology area where clear incremental benefits are desired to be shown; much like many racing competitions attempting to normalize cars to emphasize small key differentials. But such a competition is inappropriate for a new propulsion technology that wants to distribute around the airframe to achieve synergistic integration and coupling with control, aerodynamics, acoustics, and structural components. Attempting to normalize in this fashion eliminates the incentive to achieve such integration benefits which can enable reductions in power, and sizing benefits that are derived through intelligent coupling. It would be far more desirable instead to merely provide a compelling mission, and let a wide diversity of different integration approaches be attempted that result in different power required and gross weight vehicles. Such a competition would mimic the Genetic Algorithm in terms of attempting many new combinations to rapidly converge upon new aircraft species that are adapted to the new technology paradigm, instead of attempting to force existing integration architectures upon a fundamentally new (and liberating) technology.

The fourth event involved a fellow NASA researcher presenting a comparative study he performed of a reciprocating engine to an electric propulsion system. This study compared only the propulsion system for identical power/energy requirements applied to a General Aviation (GA) aircraft, and showed a 10 fold penalty for the electric system, with a favored energy storage solution of fuel cells. The study assumed the same 500 nm range was required, and didn't consider hybrid-electric methods to accommodate such ranges; i.e. the use of a small reciprocating or micro-turbine Auxiliary Power Unit (APU) to effectively increase specific energy storage density. This study came to the conclusion that batteries required a specific energy of ~1500 Watt hours per kilogram (Whr/kg) before electric aircraft could match the capabilities of reciprocating engines for GA aircraft missions. Subsequent discussions between this researcher and the author are in fact the basis of this paper, as he continues to believe that his study yielded meaningful results. While his results were accurate, they didn't provide value because the questions his study was asking weren't indicative of a fair and complete system comparison of the capabilities required or offered by each integrated propulsion solution. In fact, worse than lacking value, these results tended to fundamentally mis-educate decision makers as to how electric propulsion technologies will begin to evolve into the marketplace. In particular, if sensitivities had been investigated, strategies would have quickly been realized to most effectively use electric propulsion to achieve different benefits across key metrics. A lack of understanding of these sensitivities will clearly cause some institutions to miss out on the opportunities that will be quickly developing for this new propulsion technology frontier. The primary reason for all four of these misconceptions is that isolated analysis likely isn't capable of making assessments of this new technology without the context of the complete integration. An analogy comparing electric propulsion to another disruptive technology that has already evolved into markets will likely better explain the authors concern with the misconceptions that are currently in place relating to this new technology.

Consider an analogy of flash memory compared to magnetic hard drive technologies evolving over the past decade for data storage. Let's say there is the desire to show a comparison between magnetic and flash memory for data storage to understand whether to invest in the newly evolving flash memory technology. It's decided to do a side by side comparison of only the key parameters that are used for comparing current hard drives to one another as the basis for your evaluation. So after collecting the facts, the conclusion is that flash memory requires 10x the cost for the same Gigabyte storage capacity, and therefore product parity. Such a statement, while

accurate, is fallacious and misleading in terms of representing the potential impact that flash memory could provide to the data storage market. Any person acting on such a recommendation of that study would be poorly served because the wrong questions were being asked in the comparison, because the technologies and resulting products are fundamentally different and integrate into systems in different ways, and provide different utility to match consumer needs. Even though today flash memory storage continues to be far more expensive than magnetic storage, it has quickly developed a huge market in its own right; with completely new products that never existed previously (i.e. memory sticks, storage data cards, etc.). These markets have increased flash memory production so dramatically, that significant cost reductions and performance improvements were achieved which a decade ago weren't thought possible. Yet during this decade of advancement, flash memory has never been competitive to magnetic storage on a simple cost per gigabyte comparison. This is still true today, yet many current laptops have replaced the use of magnetic drives with flash memory hard drives, because they offer sufficient storage for user needs while offering other desirable qualities (shock resistance, improved access speed, start-up time, compactness, etc.). So even though flash memory storage still cannot compete on a storage capacity or cost/storage metric, their market shares are very impressive, and continue to accelerate in terms of capturing market share for data storage products. It is likely that at some point in the future, flash drives will nearly completely replace magnetic storage for consumer products. Therefore the comparative study that was fictitiously performed attempting to compare flash and magnetic storage would have poorly served a technology portfolio investment decision maker, as it came to erroneous conclusions because the study evaluated the different technology solutions without looking at all the comparative metrics, or evaluating these metrics with an integrated solution benefits context. The right questions that such a study should have asked are "How can flash memory effectively compete with magnetic storage in the future even though it is more expensive, what new products do the different characteristics of flash memory enable, what evaluation metrics should be used to compare these fundamentally different technologies, and how will flash memory evolve to eventually replace magnetic storage?" These questions would have effectively predicted the incredible market rise of flash memory over the past decade; while the simple (disciplinary) study question failed to predict or guide the future evolution of the flash memory market.

The argument is made that the flash to magnetic data storage comparison is analogous to comparing battery-electric and hybrid-electric aircraft to conventional propulsion aircraft. The right question to ask is not "What will it take for battery electric to match the same power and energy storage per weight of a conventional propulsion aircraft?" Instead the right questions to ask of electric aircraft are "How can battery electric effectively compete with conventional propulsion aircraft even though they are energy constrained, what new aircraft types and architectures do the different characteristics enable, what evaluation metrics should be used in their comparisons, and how could electric aircraft evolve to eventually replace reciprocating and even turbine aircraft?" These are the questions that were asked in the NASA Zip Aviation studies that investigated the enabling characteristics of autonomy and distributed electric propulsion technologies towards the On-Demand Aviation emergent market needs. The results of that study indicated that even at a mere 400 Whr/kg advanced electric GA aircraft are not only competitive to reciprocating aircraft, but that they achieve 2 to 8 time factor improvements across metrics of comparison including cost, safety, community noise, propulsion component reliability, and efficiency. The Zip study indicates that research investment can yield far better products than State Of the Art (SOA) GA aircraft in less than 10 years across key future societal metrics of interest, and predicts the rapid implementation of electric propulsion to the GA market (as well as newly enabled markets).

<p><u>Electric Propulsion Benefits</u> <i>6x the motor power to weight</i> <i>3-4x efficiency of SOA Engines</i> <i>Scale-free efficiency and power to weight</i> <i>High efficiency from 30 to 100% power</i> <i>Extremely compact</i> <i>High Reliability</i> <i>Safety through Redundancy</i> <i>Low Cooling Drag</i> <i>+100% Power for 30-120 Seconds</i> <i>Continuously Variable Transmission</i> <i>Extremely Quiet</i> <i>No power lapse with altitude or hot day</i> <i>10x lower energy costs</i> <i>Reduction of engine-out sizing penalty</i> <i>Zero vehicle emissions</i></p>
<p><u>Electric Propulsion Penalties</u> <i>Energy Storage Weight</i> <i>Energy Storage Cost</i> <i>Certification/Safety?</i></p>

Figure 1: Comparative characteristics of electric propulsion to reciprocating or turbine engines for use in initial Unmanned Aerial System (UAS) or GA market small aircraft mission applications.

If the criteria of achieving equivalent comparable propulsion system weight to performance is used for electric propulsion, and batteries continue to improve their energy density at ~8% per year, it'll take 30 years before they achieve a 10x improvement and parity for this metric. Electric propulsion versus reciprocating or turbine propulsion systems shouldn't be compared merely through legacy metrics that don't include other important characteristics of future interest, which could provide important latent value. Latent value in terms of electric propulsion system includes dramatic reductions in the total energy used because of the high conversion efficiency from electricity to shaft power, which translates to dramatic reductions in emissions, as well as many other fundamentally new and improved characteristics. A comparison across all the potential metrics of interest is shown in Figure 1. Only the specific energy and cost of the energy storage are penalties compared to existing propulsion characteristics for the initial markets involving small aircraft, with many of the characteristics superior to even large commercial aircraft propulsion systems (which have benefited from 50+ years of dedicated aerospace investments of hundreds of billions of dollars to achieve this highly optimized state). Detailed explanation of how these characteristics translate to aircraft system improvements is discussed in the subsequent portions of this paper.

The remainder of this paper attempts to dispel many of the misconceptions that currently exist among even the brightest propulsion and discipline specific aerospace researchers, and asks them to 'open their apertures' to the possibilities that this new technology frontier offers them. Because these four events have repeated so frequently, there is the desire to create a common foundation of understanding. Clearly in the past propulsion technologies have been responsible for the most spectacular aviation advances, because propulsion technology sensitivities are so high in comparison to other disciplines. Likewise, electric propulsion sensitivities demonstrate opportunity for incredible advances, far more than in any other discipline. Because of this potential to achieve such breakthrough changes, and because (like flash drives compared to magnetic drives) electric propulsion offers new latent benefits while relatively poor legacy metric characteristics, electric propulsion is considered to be a classic disruptive technology that has the potential to quickly displace conventional propulsion technologies; but in ways that will likely be perceived as unexpected (but with comparison to other disruptive technologies, are actually quite predictable).

II. Misconception 1: The Design of Electric Aircraft is No Different than Existing Aircraft

Because electric propulsion is a relatively scale independent technology, the ability to distribute the propulsion system across the airframe to achieve integration advantages is penalty-free, or in many instances, offers substantial benefits. Scale independence is considered to mean that whether electric motors and controllers are distributed to motors of 1 hp, 10 hp, or 100 hp; their power to weight and efficiency are essentially the same. As electric propulsion is pushed into larger and larger aircraft applications, this trend may extend to far larger motor sizes as well. The desire to distribute the propulsion is also encouraged by the compactness of electric motors. Scale independence is not a characteristic of reciprocating or turbine engines which suffer significant penalties as they are scaled down in size, with the power to weight, efficiency, and reliability suffering dramatically. These are not merely a matter of engine development focusing research dollars on large engines, but fundamental physics including volume to surface area ratios, Reynolds numbers, and tolerances required and achievable in manufacturing. This scale independence results in electric integration approaches favoring high levels of distribution, with very tight coupling of the propulsion system to other disciplines. This inherently increases the analysis complexity and challenge for the design process to be far more multi-disciplinary. Instead of designing aircraft with podded engines with the least amount of coupling to the aerodynamics, there is now an incentive to 'put the thrust where the drag is' and seek nearly optimum integrated aerodynamics characteristics. Instead of being satisfied with aerodynamic-structural control surfaces that are sensitive to operating speed and wind gust conditions, there is now an incentive to achieve propulsion control across the pitch, roll, and yaw axes with far stronger control forces achievable at the lower critical speeds. Instead of limiting acoustics to a few degrees of freedom to lower community noise, there now become a myriad of new possibilities to achieve shielding benefits and constructive/destructive interference. Of all the statements made in this paper, this is the most important one; this new ability to distribute electric propulsion scale-free results in enormous new degrees of design freedom which simply have not been available to aircraft designers until now. While this is highly enabling, it also comes

with the new challenge of far greater difficulty in performing the analysis of these highly coupled disciplines, with new physics-based tools required to be able capture this complex interactions.

Several of the new and existing tool capabilities that are being applied to Distributed Electric Propulsion (DEP) aero-propulsive coupling investigations currently being investigated by NASA Langley and our industry/academia partners are shown in Figures 2, 3, and 4. While computational aerodynamics would indicate that engineers have had a capability to analyze such coupling for many years, this is only true with extensive modeling efforts, with each analysis case requiring a week of execution time on a cluster with hundreds of processors. Performing conceptual design and optimization of these DEP configurations requires more rapid analyses that can still capture the interactions with similar trends across the key parameters of interest. This need has led to the recent extension of the NASA CBAERO tool to include actuator discs, while also providing a direct import of geometry (including wakes) from the OpenVSP parametric geometry modeler. CBAERO is a panel method with integral boundary layer analysis, reducing analysis time by orders of magnitudes as compared to higher-order CFD tools such as STARCCM, or NASA Langley tools such as USM3D that are used for single point analysis. This rapid analysis permits many more integration strategies to be analyzed and regressed full aerodynamic drag polars (at different power levels) to be incorporated into aircraft sizing tools. However, in the case of CBAERO, the actuator discs are averaged quantities that don't provide a feedback of a closely coupled wing or tail to provide a feedback into the open rotor (propeller) performance. For this reason, a new multiple lifting line wing-tail-propeller analysis tool has been developed to very rapidly capture the wing and propeller aerodynamics, with feedback between each these lifting/propulsive surfaces. This tool development has focused on achieving extremely rapid analysis tools that still capture the arbitrary configuration physics (with multiple open rotors integrated in any fashion with the wing/tail). CUDA acceleration of this Matlab-based tool has already demonstrated a 10 times increase in execution time using a single Graphic Processing Unit (GPU) card instead of a single CPU. Therefore it's important to realize the fundamental difference in designing DEP configurations, which can't use existing regression-based sizing analyses; but must move to physics-based methods across the coupled disciplines. DEP configuration development will require sophisticated new design tools, that currently only exist in limited ways, and not within integrated conceptual design suites.

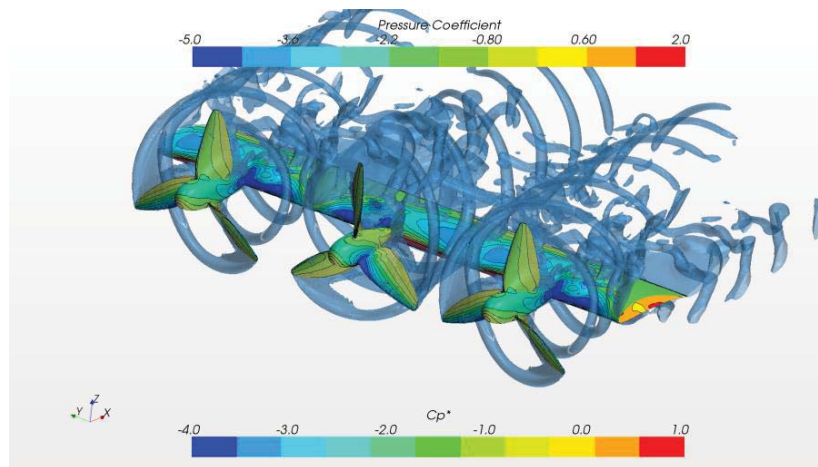


Figure 2: STARCCM time stop unsteady analysis of an infinite aero-propulsive wing (Joby Aviation, Alex Stoll)

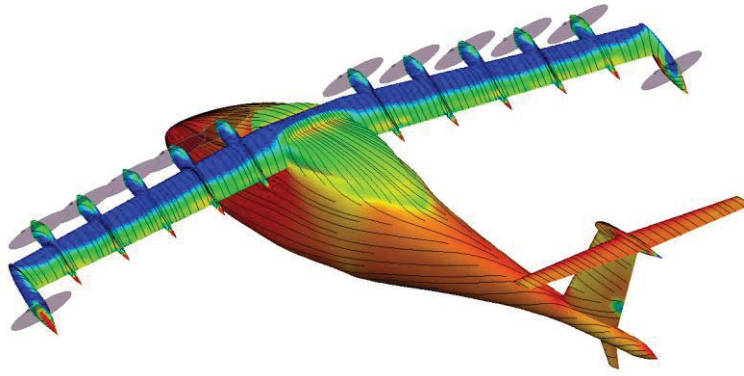


Figure 3: CBAERO panel method with integral boundary layer and actuator discs analysis of the NASA Leading Edge Asynchronous Propellers technology (LEAPTech) DEP advanced concept (NASA Ames, Dave Kinney).

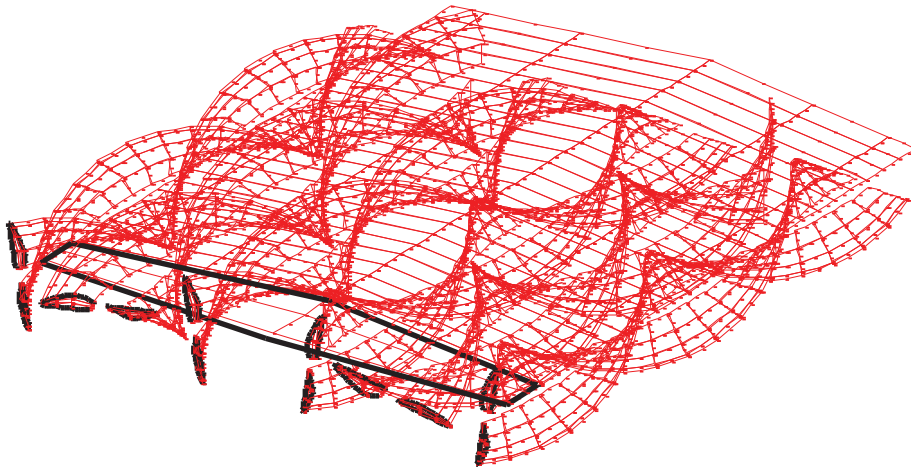


Figure 4: Multiple lifting line methodology for combinatory wing and open-rotor analysis provides a rapid physics-based design tool that captures aero-propulsive integration effects, with feedback between the propulsors and wing/tail (Georgia Tech, Patterson and German).

It is interesting to note that many of the current electric propulsion design and demonstrator aircraft efforts are performing retrofit installations where an electric motor is dropped-in as a replacement for the existing conventional propulsion system, or with minimally modified aircraft. Without going to more complex multi-disciplinary analyses, electric propulsion designs are relegated to relatively poor installations such as these retrofit integration approaches, or poorly understood integrations because the required level of design wasn't performed to achieve optimal conditions. Retrofit efforts can be viewed as an incremental step towards understanding electric propulsion; however, without taking advantage of the new degrees of freedom that electric propulsion provides, the energy storage penalties are certain to result in non-competitive solutions, except for missions with minimal range or endurance. Retrofits essentially are advocating that an effective way to understand the differences between electric and conventional propulsion is to perform isolated propulsion system comparisons (within the same integration context), which is another important misconception.

III. Misconception 2: Electric and Conventional Propulsion Should be Compared on an Isolated Propulsion System Basis to Achieve Fair Comparisons

Incremental propulsion technologies appropriately use specific comparison of isolated propulsion systems to clearly articulate the changes that are occurring. However, when fundamentally different propulsion technologies potentially integrate very differently with the overall aircraft system such a strategy cannot provide meaningful comparisons. This subject relates to the idea of achieving synergistic integration benefits by applying integration strategies that accomplish multi-functional benefits (e.g.: instead of 1 + 1 equaling 2, 1 + 1 can equal 3). This is a

critical factor in comparing electric aircraft because the synergistic coupling potential across the disciplines is so significant. Ideally a Pareto analysis that identifies the potential synergy sensitivities across all the discipline areas to determine a priority ranking of research investigations would be conducted; however, doing this requires substantial input across a number of discipline experts and considerable effort to map out potential interactions. Many examples could be provided, such as using portions of the airframe structure as batteries (i.e. multi-functional carbon nanotube structural batteries to effectively increase the energy storage densities). Prior year efforts at NASA Langley have focused on understanding aerodynamic-propulsive-control synergies. A subjective polling across Langley experts has resulted in a qualitative assessment ranking that prioritizes the synergistic potential of electric propulsion as follows in terms of magnitude of resulting impact across each disciplinary metric; aerodynamics, acoustics, operations, control, and structures. But the key point relating to this misconception is that it isn't fair to compare a new technology in an isolated way, when its characteristics beg for highly integrated coupling with other disciplines.

There are many potential architectures and integration approaches relating to DEP. Architectures include electric power routing through a drivetrain without any energy storage, hybrid-electric in parallel (with power going straight from an engine to propulsion) or series (with power going to a power management system and then routed to propulsion) with the use of some degree of energy storage, or pure electric architectures that utilize only energy storage (such as batteries or fuel cells). Architecture selection depends on the specific application intent and mission, with on-board power conversion from turbine or reciprocating engines providing reduced efficiency and emission benefits. Hybrid-electric solutions in particular offer the ability to provide power matching between highly dissimilar requirements between peak and cruise conditions. Pure electrics, while offering the highest efficiencies and lowest operating costs, are severely energy constrained with limited range. Potential aircraft integration approaches are numerous, with likely many new novel approaches to be invented as electric propulsion design space is fully explored.

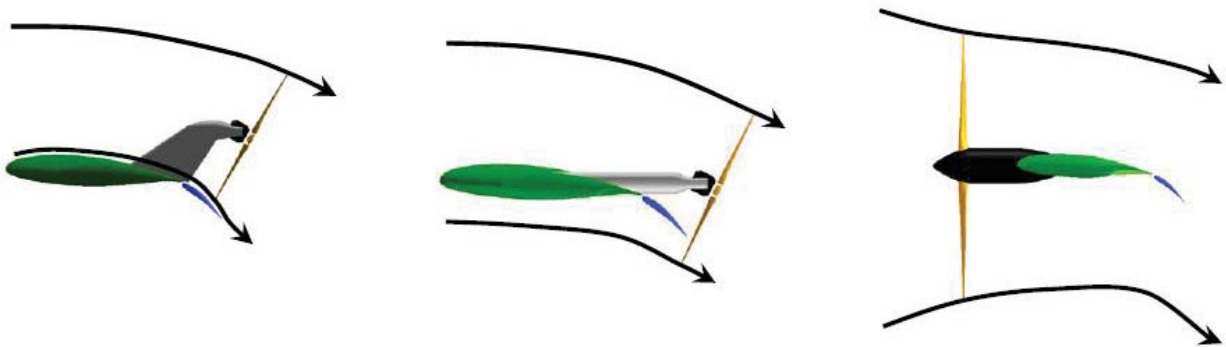


Figure 5: Several DEP wing integration strategies that demonstrate various trade-offs between maximizing flow circulation impact versus structural integration complexity.

A few open rotor (propeller) integrations investigated by NASA Langley specifically target tight coupling with the wing to provide enhanced dynamic pressure and circulation to reduce the wing area required to meet takeoff and landing constraints (Figure 5). These examples show the type of tradeoffs considered when pursuing synergistic integration. The leftmost integration of Figure 5 applies vectored thrust with an aft integration that maximizes the circulation impact, however requires structural attachment (where there is minimal wing structure for attachment) in the trailing airfoil adverse pressure gradient and seriously risks inducing separated flow while also embracing articulation complexity of the flap and motor. The center integration strategy also attempts to maximize circulation but with less structural complexity while causing the additional problem of worsened inflow characteristics (with not only an attachment arm wake but also flap wake ingestion) which will result in increased propeller noise. The rightmost approach of Figure 5 offers the least structural attachment complexity with loads able to be transferred directly to the main wing spar, the cleanest inflow conditions for the lowest propeller noise, the maximum dynamic pressure impact on the wing surface, and the least uncertainty in terms of lift and drag analysis. However, the rightmost integration is not nearly as effective at inducing circulation (leading edge devices are less effective than trailing edge devices, and the propeller effectively acts like a powered slat to turn the incoming flow when at an angle of attack). For all of these reasons, the rightmost integration was selected,

not because the authors consider it to be the optimal integration, but because minimizing uncertainty was highly valued at this initial stage of electric propulsion integration exploration. There is an important misconception relating to this rightmost integration strategy. Several years ago a glider strapped many small propellers across the wing leading edge, however because no method was provided to turn this flow, it was found to be quite ineffective at achieving a synergistic benefit from the enhanced dynamic pressure along the wing. This integration strategy will only achieve benefits if a mechanism is provided to turn the enhanced flow field (through either large chord or multi-elements flaps or a method of varying the complete wing angle of attack, i.e. incidence). Initially this integration approach focused on the use of a Fowler flap, however, as analysis progressed it became clear that the enhanced dynamic pressure resulted in a ~50% increase in velocity from the induced propeller velocities. With lift varying with the square of the induced velocity increase, lift enhancement by ~2 times results in an effective C_{Lmax} of ~5.0. Because of this, the wing loading increases by the same ~2 times to maintain equal lift as an unpowered wing; and with the same span, the chord is decreased by this same ~2 times. With such short chords resulting, a variable wing incidence approach became the favored approach as the least structural complex. This approach is called Leading Edge Asynchronous Leading Edge Propellers Technology (LEAPTech), and is demonstrative that electric propulsion can only be fairly compared to other propulsion solutions through integrated system comparisons. To achieve a detailed understanding of these integration benefits, the LEAPTech integration is described below in detail.

As explained, the LEAPTech concept takes an aggressive approach of laterally distributing the thrust across the wing to achieve a high lift system capable of an effective C_{Lmax} of 5.0, while avoiding the structural wing complexity of multi-element systems that are capable of a lesser C_{Lmax} value. This advanced concept has the goal of increasing the wing loading of GA aircraft by a factor of ~2.5 times to ~60 lbs/ft² (similar as regional jets), while still maintaining a stall speed of less than 61 knots (the FAA requirement for single engine aircraft) and balanced field lengths of less than 2000 feet. High wing loading provides high aerodynamic efficiency at higher cruise speeds, as well as improved ride quality with less gust sensitivity. The key to achieving this capability is to reduce the wing area through an incredibly effective high lift system that permit permits a wider speed bracket (the ratio of cruise speed to the takeoff speed). Using many small diameter propellers (instead of a few large diameter propellers) provides the highest propeller induced velocities over the entire wing surface (and the greatest lift augmentation). Fewer propellers using the same total power would result in lower induced velocities and a larger effective streamtube. This approach of using 12 small diameter propellers also permits direct drive electric motors to achieve the lowest electric motor specific weight and complexity (i.e. a gearbox is avoided). The resulting impact of achieving the higher wing loading is the ability to cruise at high speed at a lift coefficient near the optimum L/D_{max} (for a high aspect ratio LEAPTech wing at a CL of ~1.0, versus existing GA aircraft which must operate at CL 's of ~.25 which operate far below their L/D_{max} potential). This matching of the wing area to that desired for optimal high-speed cruise flight results in greater than a 60% improvement in aerodynamic efficiency.

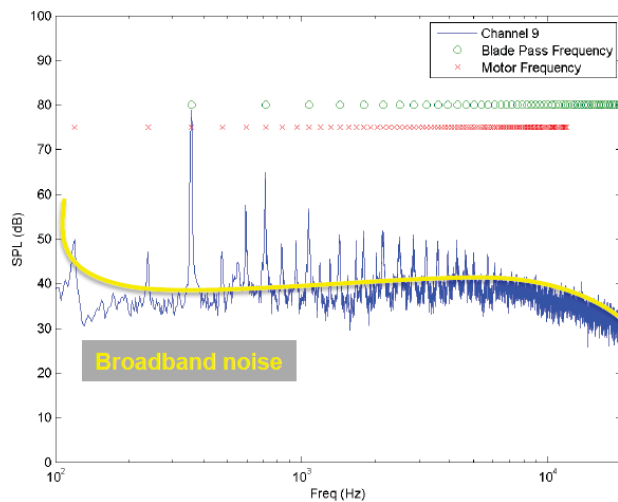


Figure 6: Acoustic signature of a conventional 3 bladed propeller, including strong harmonics at the blade passage frequency.

Initially, experiments were conducted with exact motor digital control synchronization, which permitted intermeshing the propellers to promote the best velocity distribution across the wing surface, since radial velocity distributions are present across each propeller. Typically performing such intermeshing would dramatically increase the noise, while decreasing the efficiency of the propellers. However, as part of the associated electric propulsion research being performed by the authors, detailed OVERFLOW and WOPWOP analyses have indicated that favorable noise and efficiency benefits could be derived, if precise synchronization of the propellers was achieved. Unique phase coupling experiments were conducted across multiple propellers to achieve a master-slave operation of the electric motor's Electronic Control Module (ECM) capable of precise syncing of the propeller blades. This permitted each propeller blade to remain out of phase with the adjacent propeller blade to maintain a 90 degree azimuth separation. However, this approach was discontinued as the robustness of the resulting acoustics and efficiency remained unproven experimentally. An alternate approach was then adopted which offered the potential for more compelling acoustic improvements. Since electric motors offer a broad operating rpm at constant power and efficiency, electric propulsion offers the ability to run each of the 12 motors at slightly different rpm. By using asynchronous rpm across each motor, with appropriate frequency distribution to prevent acoustic beating phenomena, there is the potential to dramatically decrease the strong harmonics of a single propeller blade passage frequency, as shown in Figure 6 for a conventional single 3 bladed propeller. By instead having the same amount of power going through 12 propellers, each at slightly different rpm, it's possible to dramatically decrease each blade passage harmonic (by a factor of 12) and shift the blade passage harmonic down into the broadband noise. This electric acoustic integration strategy has the potential to greatly reduce overall community noise, a detailed analysis effort is currently under way by Langley acousticians to quantify this benefit as well as develop auralizations of this considerably different noise signature due to its higher frequency content to insure human perception issues are captured comparative to a single propeller signature.



Figure 7: NASA Langley LEAPTech Distributed Electric Propulsion concept, that coupled highly integrated propulsion and control with a variable wing incidence highlift system (images on right are at the takeoff 19 degree and landing 34 degree conditions), high aspect ratio wing, and fuselage boundary layer ingestion propulsion.

This LEAPTech integration of distributed propulsion (with concept rendering shown in Figure 7) would never be undertaken with reciprocating or turbine engines, through a mechanical system of shafts and gearboxes because of the extreme complexity, weight, efficiency losses, and resulting poor reliability. But with distributed electric motors, none of those penalties are present. The motor sizing criteria for this concept is based on the required induced propeller velocities at the 61 knots stall speed to achieve a specific effective C_{Lmax} . While technically the Federal Aviation Regulations (FARs) permit multi-engine aircraft to exceed the 61 knots stall speed limitation, this constraint is still relevant for this concept to maximize takeoff/landing safety (which is based upon lower runway speeds), while still being able to meet the 2000 feet field length (which equates well with small airport accessibility). Higher stall speeds were not embraced, even though a multi-engine rating would have permitted this relaxing of constraints. It has yet to be proven how many motors or propellers can fail while maintaining the same field length capability, through varying the thrust across the propellers and going into short-term emergency

ratings. Electric motors also have a favorable characteristic of being able to run at short-term peak conditions that are greater than their maximum continuous rating. This results in heat saturating the motor for anywhere from 30 to 120 seconds, until thermal runaway; as the electric motors heat up, the efficiency of the motor decreases, which results in additional heating which is called thermal runaway. However, the lighter advanced electric motors become, the less capable they become at over temping because there is simply less motor mass to provide heat saturation capability.

The ability of DEP to reduce wing sizing to achieve greater aerodynamic efficiency has been described, however, electric also offers propulsion sizing benefits. This is most easily understood by comparing the LEAPTech concept to a conventional reciprocating GA aircraft. The Cirrus SR-22 represents a good State-of-the-Art (SOA) baseline comparative system concept, being a high performance 4 passenger, single engine piston designed for a similar 200 knot cruise and a 2000 foot field length. The Cirrus SR-22 is a similar gross weight as a series hybrid electric version of the LEAPTech concept designed for a 200 nm range on battery only energy storage (assuming 400 Whr/kg 5C batteries), but capable of a 400 nm range while using the 40 hp APU as a range extender. as a thrust and motor sizing condition. The LEAPTech concept is slightly less range capable than the SR-22 which can accomplish a 500 nm range with both aircraft operated at a 800 lb payload. Range parity was shown in the prior Zip study paper to not impact a significant fraction of desired or actual trips taken. Now that the comparative baseline has been introduced, the difference in engine power sizing can be clearly identified. The engine sizing condition for the SR-22 is a high/hot takeoff field length and climb rate. These conditions approximate Denver in the summer with a 95 degree temperature and 6000 foot altitude, and results in a power reduction of ~20% from the SR-22 IO-550 engine, decreasing power available from 310 to ~240 hp. Since electric motors aren't air breathing, they don't experience a power reduction at these conditions. This means that electric propulsion achieves a power sizing benefit of ~20% comparative to reciprocating or turbine solutions, and that the total power required to meet the same takeoff and climb conditions is only 240 hp. The specific LEAPTech distributed integration provides another power sizing benefit, with ~59 square feet of propeller area (12 propellers at 2.5 feet diameter), compared to only 33 square feet for the single 6.5 foot diameter 3 bladed SR-22 propeller. This lower disc loading of the DEP provides greater low speed thrust and superior rates of climb than the baseline. Therefore not only significant wing sizing benefits are achieved through DEP, but also power sizing benefits are present.

The LEAPTech concept uses additional synergistic drag reduction approaches due to the ability of electric propulsion to distribute. Reduction in the parasite drag is possible through remote thrust locations. With the propeller flow only over the wing, no wasted scrubbing drag exists, since the additional velocity of the propellers is accomplishing increased lift (instead of simply increased the parasite drag on the fuselage such as single engine piston aircraft experience). However, at the cruise condition, the induced velocities are only barely greater than the freestream velocities, so the scrubbing effect is not substantial at cruise (this is not true at the lower takeoff/landing velocities where large differentials exist between the propeller and freestream velocities). A newly developed version of Boundary layer Ingesting (BLI) propulsor has been developed for the aft fuselage. This ~1.5 foot diameter BLI propulsors on the aft most portion of the fuselage re-accelerates the slow fuselage boundary layer air to fill in the wake deficit. For this portion of the thrust provided, the effective propeller efficiency increases ~35%, compared to thrust being developed at the freestream velocity. However, this efficiency increase only relates to the portion of thrust being provided by this small wake propulsors, which accounts for less than 25% of the total cruise thrust. However, as the wing drag is reduced by achieving higher wing loadings, it becomes increasingly important to also reduce the fuselage drag (as that portion becomes increasingly large).

The other DEP drag reduction approach relates to induced drag. Remotely locating thrust to include a propeller that can act within the wingtip vortex offers the potential to recapture a portion of this lift-based drag. This can be bookkept as either an induced drag reduction (if the propeller is ahead of the wing and provides an axial thrust as the mechanism for interacting with the wake vortex to effectively increase span), or as an increase in propeller efficiency (if the propeller is behind the wing and rotates counter to the wake vortex to achieve an effective increase in the velocity through the swirl). The portion of wingtip vortex energy that can be recaptured depends on how much vortex drag exists (i.e. at high CL's there is more drag that can be recovered), the diameter of the propeller, and the induced velocities injected into the vortex core. The ideal case would apply all thrust into this

vortex core, with a small diameter propeller. Because of this, the thrust distribution is modified for the LEAPTech concept in cruise versus at takeoff and climb, to increase the effective propeller efficiency. This strategy aligns well with the use of low tip speed propellers at takeoff, while using the tip propeller at higher tip speeds at cruise. This type of optimal operation is only possible due to the broad operating rpm range of electric motors at their maximum power; reciprocating and turbine installations couldn't achieve this unless they incurred the penalty of a two-speed gearbox. Initial studies have also shown that propeller pitch is well matched between the takeoff pitch at 450 ft/sec tip speeds, and cruise pitch at 700 ft/sec. This equivalent propeller pitch requirement showcases another unique electric propulsion capability, that is, the ability to use fixed pitch propellers near optimum efficiency through the ability to vary the advance ratio and avoid variable pitch propeller complexity. The impact of the wingtip propeller depends on the exact operating conditions, but is likely to provide an additional ~15% of efficiency increase.

The wing aspect ratio is pushed to as high as reasonable, due to the small required wing area coupled with the desire to maintain as much span as possible for aerodynamic efficiency. An aspect ratio of 20 was selected based on aeroelastic concerns, and is an active constraint on this design. This concept utilizes a tail that carries lift when flaps are retracted to prevent a large trim moment during their deployment. The result of this is reduced longitudinal stability, requiring a control system to provide artificial longitudinal stability. Since the tail carries lift in cruise, a high aspect ratio tail is utilized; however, the aspect ratio of the tail is less than the wing, which keeps the $C_{L\alpha}$ of the tail less than the wing to ensure the wing stalls before the tail. As indicated previously, a variable incidence system is used to achieve the required change in wing angle of attack from 4 degrees at cruise, to 19 degrees at takeoff, to 34 degrees at landing. The variable incidence approach has the added benefit of providing vectored thrust to enhance the takeoff/landing C_{Lmax} , and not just an enhanced dynamic pressure. The variable incidence also provides improved drag generation capability during landing approach, which is important since power needs to be applied to achieve the C_{Lmax} during landing. Being able to achieve this high aspect ratio wing, with distributed motor masses is a critical enabling feature for DEP aircraft to accommodate constrained energy storage. An aeroelastic analysis has been initiated to determine whether the span loading effect of the motor is beneficial, or induces aeroelastic excitation; this analysis will also determine whether a modular battery approach is utilized with their co-location in each nacelle to minimize wiring weight.

A specific integration concept was explained to provide context on just how important it is to consider the entire integrated aircraft solution when comparing DEP to conventional, isolated propulsion solutions. A fair basis of comparison to understand the true potential of electric propulsion can only be achieved at the aircraft system level. Such systems comparisons are more complex than isolated propulsion comparisons, and therefore it's critical to reduce the uncertainty of these system comparisons so that the results are highly credible. NASA Langley is making an extensive effort to decrease this uncertainty through detailed multi-disciplinary research that can capture the tight coupling effects.

IV. Misconception 3: Just Like Electric Cars, Electric Aircraft Won't Make Financial Sense

Anyone who has considered buying an electric car has gone through the economic trade and determined that they currently don't provide a compelling economic justification for making the purchase. The additional cost of the more expensive electric vehicle is not effectively amortized by a typical driver; primarily because of high battery costs (~\$30,000 for a Tesla Model S¹ which has a similarly sized battery capacity as the LEAPTech concept). But the reason battery electric autos don't make sense is because people only use their autos ~300 hours per year (<1 hour per day on average) and it is not possible to amortize the high cost of batteries over such low utilization rates. If autos were used 1500 hours per year (>4 hours per day), everyone would buy electric autos (assuming batteries charging availability and distribution of trips for charge time feasibility). It currently requires >7 years to wear out Tesla batteries (~2000 hours of useful life); so there is a huge opportunity cost for the cost of those batteries to merely sit idle in the auto all those years. This is why the Zip Aviation study¹ highlighted the importance of adopting a shared use business model that accomplishes higher utilizations. High utilization is an essential feasibility ingredient for battery electric aircraft, and a key reason why research investments pertaining to On-Demand Mobility markets for DEP aircraft should also include autonomy research. Autonomy technologies offer a similar breakthrough potential as DEP, but specifically to accomplish a broad user base through ease of use capabilities.

The reason high utilization equates well with electric vehicles is due to the significant reduction in energy cost that translates to lower operating costs. Currently ~50% of GA aircraft total operating costs are energy costs, due to a combination of poor aerodynamic and propulsive efficiency of existing aircraft, as well as the high cost of low lead aviation fuel (currently ~\$6.00 per gallon, or a ~1.75 times additional cost of auto fuel). Electricity cost has a similar multiply of ~1.5 times less expensive than aviation fuel (for the equivalent amount of energy). This decreased energy cost, along with 8 times less energy use for the LEAPTech concept compared to the SR-22 baseline, provides a 12 time reduction in energy cost. The 8 times increase in efficiency is a combination of 3.3 times improvement in motor efficiency along with a total aerodynamic and propulsive efficiency improvement of 2.4 times better. However the 12 times reduction in energy cost needs to account for limited battery life and amortization of expensive batteries across their total life cycle, which reduces the true difference in energy cost to a 4 times improvement. This comparison does not take into account potential cheaper electricity rates that could be achieved from industrial or off-peak rates, which would provide a further 2 times reduction. Therefore, it is clear that there is potential for dramatic energy cost decreases, which are best accomplished with high utilization rates of the aircraft.

The other portion of economic feasibility relates to the higher acquisition cost of an electric car compared to a conventional Internal Combustion (IC) engine auto. Since automotive IC engines are manufactured at such high rates, it is difficult for electric propulsion components to compete economically (when the electric propulsion components are made at significantly lower production volumes). However for small aircraft, their IC or turbine engines are manufactured at very low production volumes, so there is no economy of scale advantage for these conventional technology engines. An example is the SR-22 310 hp IO-550 engine which costs ~\$60,000, when a similar power auto engine can be purchased crate complete for less than \$6000. This differential in aircraft propulsion component costs permits electric propulsion to compete more effectively with regard to acquisition costs.

V. Misconception 4: Electric Storage Energy Density is THE Issue, and Insufficient for Meaningful Range

The most common misconception relating to electric propulsion is that battery energy density is a fundamental limiting constraint on feasibility within the next 10 years. This issue has been somewhat discussed in the prior portions of this paper, with the projection that a 400 Whr/kg battery specific energy density is sufficient to enable meaningful electric and hybrid-electric aircraft. The key to understanding the importance of achieving this level of energy density is shown in Figure 8, where the sensitivity to battery energy density is shown for a retrofit electric SR-22 concept comparative to a conventional SR-22. This sensitivity is shown for a battery electric range of 200 miles along with the predicting distribution of trip distances that would be required for a on-demand aircraft product. The prior Zip study showcased that 77% of the On-Demand Aviation trip demand relates to trips less than 200 nm, and that 400 nm range captured 94% of the trips, this trip distribution is shown in Figure 8. Typically the range provided for GA aircraft exceeds the user needs because the sensitivity to increased range is quite low (i.e. there is no compelling reason for GA products to offer less range when the impact to the vehicle sizing is not a strong sensitivity). Electric aircraft have a much greater gross weight sensitivity to range, and therefore it is far more important to determine an accurate required range, instead of merely extrapolating what prior aircraft have offered. A reasonable projection for achieving this battery energy density is by 2020, which suggests research is justified now to understand this highly different propulsion technology appropriately.

Two other characteristics are important for achieving feasible electric aircraft; the specific power of the batteries (or rate at which the batteries can be discharged), and the charging time required. For application to Short Takeoff or Landing (STOL) or Vertical Takeoff or Landing (VTOL) aircraft, the power density is a far more important issue than energy density. Application of electric propulsion to STOL or VTOL aircraft is primarily to accommodate large differences in the power required at the takeoff/landing versus cruise flight. Hybrid-electric provide a means to size the core engine to the reduced cruise power required, while the batteries only provide a short-term supplemental energy source. For such aircraft, the time required to supplement takeoff power may be quite short if the mission doesn't require a sustained hover requirement, and the resulting total energy required I only on the order of 5 minutes at full power. Batteries for these applications require the ability to extract the energy very quickly (this is typically called high C rates, where C is multiplier of how quickly a battery can

expend its energy in relation to its charging time). The recharge rate is another factor determining the feasibility of being able to achieve high utilization rates, and requires low internal battery resistance for rapid charging. Significant progress is being achieved in both these areas, with 25 and 60 C batteries available at reasonable (although lower) energy densities. Tesla is already able to achieve an 50% charge within 30 minutes of charging through use of their high voltage rapid chargers⁹, with a near-term goal of achieving 80% charge within an hour. These two characteristics rapid charging time and rapid power extraction are equally important for electric aircraft to achieve feasible operational capabilities.

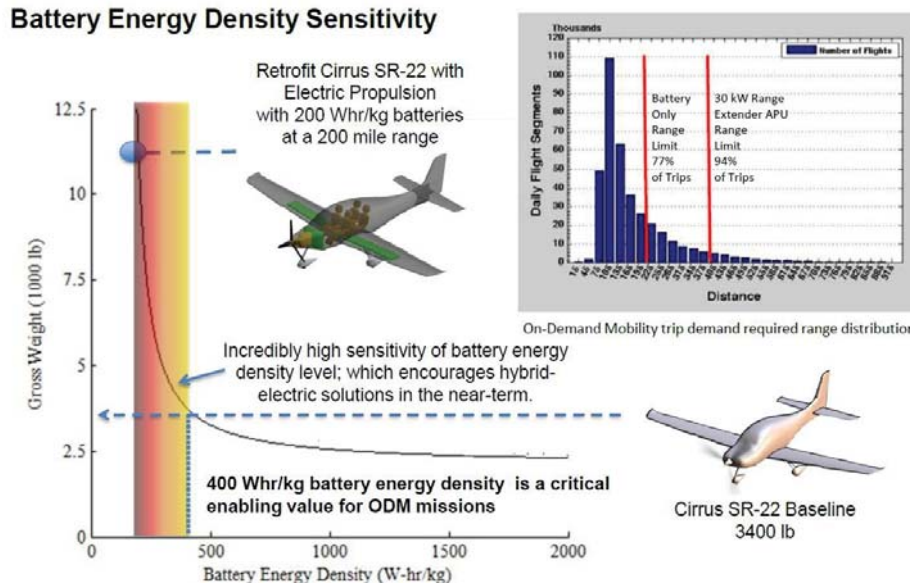


Figure 8: Battery energy density sensitivity for a 200 mile range Cirrus SR-22 electric retrofit concept compared to the existing conventional baseline, along with the predicted trip range distribution required for the On-Demand Aviation market.

VI. Misconception 5: Electric Aircraft Research Should Focus on Large Commercial Transports with a Market Introduction 20 Years from Now

The question of how a new disruptive technology such as DEP will progress is a critical one, if research institutions desire to be relevant to early adopter markets that will enable significant technology accelerations. Other disruptive technology case studies have showcased how critical it is to have both a highly adaptable/agile research and market plan. As a disruptive technology develops, the method in which it evolves into the market place significantly impacts further technology development. Investment in DEP cannot be effectively done without understanding the business case and opportunities that will present themselves along this ‘incrementally revolutionary’ development path. While the bulk of aerospace R&D relates to commercial transports (because this is where the majority of revenue passenger miles and profits currently exist), there is a poor fit at near-term technology levels for DEP application and this primary market. Just as with other disruptive technologies, DEP will progress through early adopter markets that involve less capable products, and smaller market shares. For DEP this market evolution will clearly involve first UAS and GA markets, and later increase in scale while progressing in capability.

Electric propulsion has already started in the motor glider market, with glider assist. Electric GA products are currently in development for trainers, motorgliders, Light Sport Aircraft, and even as component retrofit technologies (i.e. rotorcraft tail rotor drives). The current research and product momentum is centered in European investments, because the EU is essentially living in an energy constrained future with higher cost fuel and carbon taxing. A significant impetus for GA to evolve and adapt to electric and hybrid-electric flight relates to its current dependence on low leaded fuel (100LL), which is responsible for more lead emissions into the environment than any other source. Clearly electric aircraft are not 20 years away, due to the significant benefit potential that exists, with likely introduction into the civil UAS and GA markets within next 5 years, and

Commuter and Regional Jet aircraft market introduction within a 10 year timeframe. Part of the opportunity for electric propulsion to more quickly insert itself into the GA marketplace is the relatively poor performance that these products currently achieve. This is shown in Figure 9 across the metrics of aerodynamic efficiency (Lift to Drag ratio), ride quality (wing loading), and emission (overall mile per gallon efficiency per passenger). It can be seen that the GA market achieves far lower performance capabilities, which makes it easier for the new DEP concepts to transcend these capabilities with dramatically improved products. Figure 10 shows the authors projection for what should be possible to demonstrate within the next decade, based on the studies that have been conducted. These projections showcase the ability of achieving approximately 2 times the aerodynamic efficiency of current SOA GA products, with 2-3 times the wing loading (and with additional mechanical complexity), while achieving 8 times less overall energy and equating to 5 times less lifecycle emissions. These dramatic improvements are possible at the same, or improved, speeds, while at ranges of value to many aviation markets.

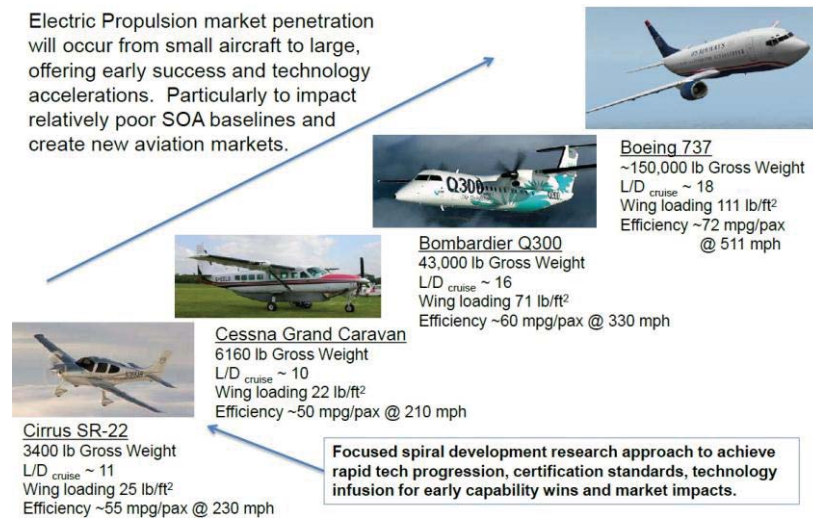


Figure 9: Electric propulsion market infusion pathway, from small aircraft to large, as technology and certification maturation develops over time.

Realizing how this market will evolve, a research investment strategy that focuses only on a long-term commercial transport future market will likely be misguided, with development of technology pieces that are out of alignment with the evolving markets. As an example, working on a multi-Megawatt lightweight electric motor depends on power electronics that currently are only lightweight and cost effective at smaller scales (voltages, amperage). Out of market sequence investment maximizes the research hurdles and development costs, while minimizing their potential near-term market impacts. For this reason, it is the opinion of the authors that research investment should be highly correlated to the evolving markets, and focus first on smaller scale aircraft that can permit rapid spiral development of DEP technologies, at far lower cost than attempting to work on DEP technologies for a future commercial transport market (that will likely evolve quite differently than we currently imagine due to the significant change in vehicle architectures that are encouraged by this new technology frontier).

When a fundamentally new technology such as DEP starts to become available, and reach an initial level of capability of interest to markets, there is undoubtedly a need to explore this new technology frontier fundamentally different than existing technologies. Gradient design approaches using established legacy configurations can't possibly explore this newly enabled design space. The equivalent of Genetic Algorithm design exploration is required, where many new integration approaches and configurations are attempted, with many failing but providing valuable DNA for cross-pollination to other off-spring. Rapidly exploring the many new degrees of freedom is essential to successfully capture the benefits that electric propulsion has to offer. Any research project that embraces electric propulsion will be most successful if there is built into that project the ability to fail early and often, while being able to re-vector the integration approach paths and configuration

choices rapidly. Success in this new technology frontier will require rapid adaptation, based on clear guiding metric goals that align well with the emergent capability set.

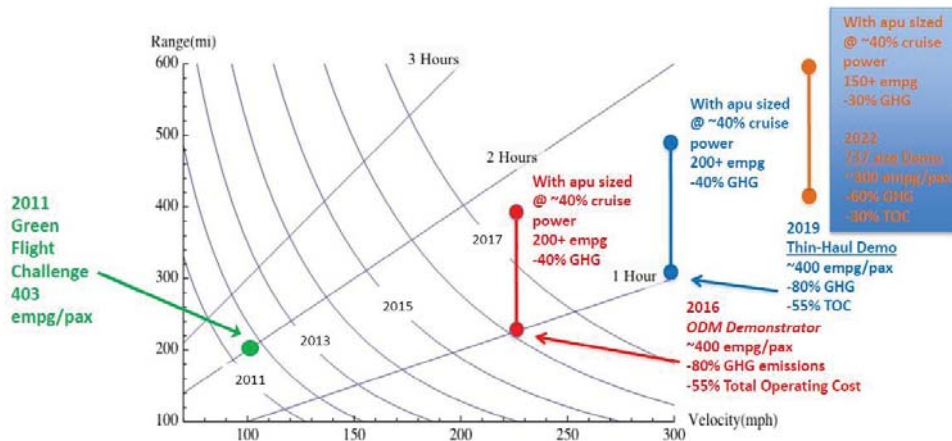


Figure 10: Projected capability demonstration timeline over the next decade for Distributed Electric Propulsion.

VII. Conclusion

Several prevalent misconceptions relating to electric propulsion for aircraft have been discussed. The authors believe that these misconceptions are currently inhibiting appropriate research investment to accomplish the maximum potential benefits. A specific DEP integration concept was described in detail to provide a foundational understanding of why future electric aircraft configurations will be very different from existing SOA aircraft. This context also provided evidence that it is inappropriate to compare isolated propulsion systems when trying to understand the differences that electric propulsion offers. While the authors are encouraged by the tremendous benefit potential of the LEAPTech concept, this is by no means the optimum solution, or the only electric propulsion integration approach that should be investigated. Due to the significant pace of discovery with this new technology frontier, it is likely that many alternative integration paths will be developed that are equally or more compelling.

Vibrant exploration of many DEP concept solutions is encouraged, with new design tools providing a critical new capability to accomplish rapid, highly-coupled, physics-based analysis. These explorations should be guided by the specific benefit metrics that are being pursued across the potential breakthrough improvements in efficiency, emissions, community noise, control robustness, operating costs, operational capabilities, and aircraft sizing. Battery specific energy is not nearly the limiting factor for achieving feasible electric aircraft that many propulsion discipline experts consider to be accurate. If batteries continue to develop at the same 30 year historical pace, then within 7 years sufficient energy density will be achieved for reasonable GA solutions, as hybrid-electric implementations that still achieve most of the benefits of a full battery electric. The potential for achieving dramatic reductions in operating cost will be a likely motivator for early electric propulsion adoption, particularly in higher utilization aviation business models. Research investment in electric propulsion should focus on complete integrated solutions to develop the most relevant cross disciplinary technology advances, and for the evolving markets that will provide accelerating advances for focused products.

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