ANALYSIS OF HYBRID AND BATTERY POWERED VARIANTS OF THE TRANSCEND AIR Vy400 AIRCRAFT

EXECUTIVE SUMMARY

A detailed analysis of battery-driven and hybrid-electric variants of the Vy400 aircraft was conducted by VerdeGo Aero to explore the design space and assess feasibility. Mission profile, performance requirements, aircraft configuration, and powertrain design options were considered to assess both the current viability and likely future viability of different propulsion options. City to City (C2C) missions have significant differences in the demands they place on VTOL aircraft powertrains when compared to Urban Air Mobility (UAM) missions.

The current design specification for the Vy400 is best served with a conventional powertrain configuration consisting of a turbine and mechanical drivetrains linking to the propulsion rotors. This is driven by factors including: the high power to weight ratio of turbines, the high energy density of liquid fuels, and the Vy400 configuration with only 2 rotors which lends itself to mechanical powertrains.

Multiple hybrid-electric configurations were assessed in the Vy400 and a design study was performed to examine the design space for varying the sizing of major aircraft components (rotor diameter, wing area), aircraft weight, and mission (speed, range). There is an interesting design space for a hybrid-electric aircraft based on the Vy400, targeted at shorter range, lower speed flights that are still longer and faster than UAM missions but are shorter and slower than the current Vy400 mission. Potential advantages to this configuration include the use of a significantly smaller and lower priced turbine, and the capability for the aircraft to leverage multiple redundant onboard sources of energy in the event of a partial power failure, which may be particularly attractive for a VTOL design without autorotation capabilities.

Battery-electric variants of the Vy400 were assessed in an array of scenarios that modeled the aircraft capability with batteries ranging from current state of the art to hypothetical batteries that are decades from commercialization. Based on current battery industry trends, it is unlikely that battery-driven variants of the Vy400 will be viable for 20 years or more. A 6X+ energy density improvement is required to enable missions that are still shorter and slower than the current design specifications for the Vy400. It is recommended that Transcend Air not focus on battery-driven propulsion architectures for this aircraft and mission until there are viable battery technologies emerging that can deliver pack-level energy density of above 1,000Wh/kg (including cells, pack structure, cooling system, shielding, and safety systems).

BACKGROUND

The Urban Air Mobility (UAM) market for VTOL aircraft is driving the development of battery-electric and hybrid-electric power systems to enable Distributed Electric Propulsion (DEP) powertrains on these aircraft, which typically utilize 6 to 10 propulsion systems (electric motors) for providing both thrust and attitude control. The City-to-City market for VTOL aircraft involves longer cruise segments and significantly higher cruise speeds when compared to UAM missions. These factors create challenges when applying DEP powertrains and it is important to understand the relative merits of battery-electric, hybrid-electric, and turbine/piston direct drive propulsion configurations in the context of different mission requirements.

The City-to-City (C2C) mission for VTOL aircraft (relevant to the original Vy400 design) places a unique set of demands on an aircraft and its powertrain when compared with typical Urban Air Mobility (UAM) mission requirements. Propulsion systems and aircraft that are optimized for C2C missions may look radically different than those optimized for UAM. Transcend Air is interested in understanding the relevance of both hybrid-electric and battery-electric powertrain solutions for future variants of the Vy400 C2C aircraft, and they have approached VerdeGo Aero to apply VerdeGo's proprietary engineering design tools to assess the feasibility of utilizing these power options in Transcend's twin-rotor architecture for C2C missions with significantly longer range and higher cruise speeds than the typical UAM mission.

VerdeGo Aero is a leader in hybrid-electric and battery-electric propulsion solutions for VTOL aircraft. VerdeGo's Integrated Distributed Electric Propulsion (IDEP™) systems are designed for the rigors of commercial flight operations to enable new classes of VTOL aircraft. VerdeGo's founders have worked in the field of battery-driven aircraft and hybrid-electric aircraft for more than 10 years, and VerdeGo has developed proprietary engineering tools that are customized for the unique attributes of VTOL aircraft using next-generation electric propulsion technologies. VerdeGo's experience performing thousands of modeling scenarios on different aircraft, missions, and propulsion configurations was applied to the baseline Vy400 design to explore the design space for battery-electric and hybrid-electric configurations of a twin-rotor C2C aircraft.

ANALYSIS SCENARIOS

The exploration of this design space started with a baseline model of the current turbine-driven Vy400 to validate VerdeGo's modeling tools against the engineering work that has already been performed on the Vy400 by Transcend. Once the baseline model was validated, engineering simulations of both hybrid-electric and battery-electric variants were created and tested with a wide variety of potential missions to determine technical feasibility and predicted performance.

HYBRID SCENARIOS

The Vy400 baseline model was constructed using the mission profile included in Table 2, provided by Transcend to VerdeGo. The Vy400 baseline served not only as validation for VerdeGo's modeling tools but also served as a tool for choosing which variables would be considered constant through the various potential missions and propulsion configurations tested in this analysis. One such variable was the structural weight of the aircraft. Based on the initial phase of the analysis and the experience of the team, it was determined that in all subsequent scenarios, the investigation would consider the structural weight of the aircraft to be approximately half of the total gross weight. This is a conservative assumption for the hybrid scenarios due to the presence of additional heavy propulsion items such as the generator and battery pack, but it is a good initial approximation to map the design space. The early analysis also led to the determination that the wingspan and rotor diameter would be varied in each scenario to minimize cruise power and maintain a constant disk loading on the rotors.

The next step for the analysis was to review the mission profile outlined in Table 2 and assess the compatibility of a hybrid-electric powertrain with the original mission profile of the Vy400. The objective for the design team was to identify and adjust any necessary flight segments to enhance the feasibility of utilizing hybrid-electric propulsion while still maintaining C2C capabilities. The flight conditions impacting the feasibility of hybrid-electric solutions were identified as: duration of hover and cruise speed (which is linked to cruise power). This analysis also resulted in the implementation of an alternate structure for the flight segments involved in a diversion of the flight. It is necessary to consider the peak power requirements during a go-around at critical times in the flight mission, and these peaks in the power curve are typically drivers of the size of the battery pack in a hybrid or battery-electric aircraft. A more in-depth discussion regarding these changes will follow in the conclusion. The new mission profile has been outlined in Table 3.

With the new mission profile constructed, the analysis then progressed to assess four powertrain scenarios in aircraft that all are configured similarly to the Vy400, but with differing dimensions. These four scenarios include: the original Vy400, a new baseline scenario with conventional turbine propulsion that is optimized for the revised mission profile, a "peaks and valleys" hybrid, and a "minimal battery" hybrid. The parameters for these scenarios are seen in Table 1. A "peaks and valleys" hybrid powertrain refers to a powertrain wherein the components are sized such that the battery pack is utilized to boost power output during hover stages of flight where "peak" power demands are high, and wherein the hybrid generator recharges the battery in cruise during the "valleys" in total power demand. A "minimal battery" hybrid refers to a powertrain wherein the battery is sized to be an emergency backup source of power for the aircraft, but the hybrid generator supports the power demands of a normal mission directly.

Case Name	Propulsion Configuration	Mission Profile	Mission Classification	Vehicle Width (Rotors+Wings) ft	Payload lbs	Cruise Speed knots
Current Vy400 Baseline	Turbine Direct Drive	Original Vy400 Mission	C2C	40	1,200	310
New Baseline	Turbine Direct Drive	New Baseline	C2C	34.5	1,200	200
PV	"Peaks and Valleys" Hybrid	Baseline	C2C	46.5	1,200	200
MB	"Minimal Battery" Hybrid	Baseline	C2C	48.5	1,200	200

Table 1: Overview of 4 hybrid-electric scenarios

Flight Segment	Start Alt [ft]	End Alt [ft]	ROC [fpm]	Airspeed [kts]	Distance [nm]	Time [min]
Warmup	0	0	0	0	0	10
Taxi	0	0	0	0	0	5
Takeoff	0	1,000	1,000	0	0	2
Transition	1,000	1,000	0	100	0	2
Climb	1,000	15,000	4,500	Best L/D	0	~
Cruise	15,000	15,000	0	310	160	~
Diverted						
Cruise	15,000	15,000	0	Best L/D	80	~
Descent	15,000	1,000	-3,000	1.2 Vs	0	~
Loiter	1,000	1,000	0	Best L/D	0	30
Transition	1,000	1,000	0	100	0	2
Landing	200	0	-200	0	0	5
Taxi	0	0	0	0	0	5

Table 2: New York to Boston mission profile provided to VerdeGo Aero from Transcend

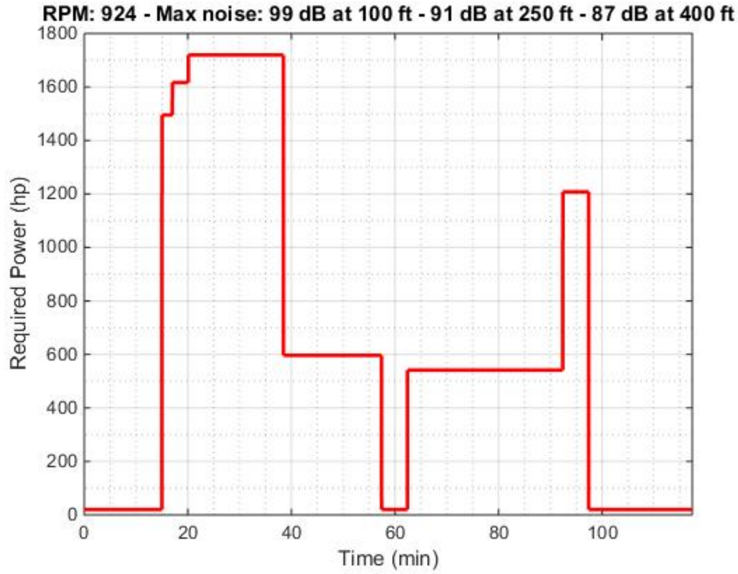

Figure 1: Power profile for Transcend's original New York to Boston mission for the Vy400 aircraft

Flight Segment	Start Alt [ft]	End Alt [ft]	ROC [fpm]	Airspeed [kts]	Distance [nm]	Time [min]
Warmup	0	0	0	0	0	10
Taxi	0	0	0	0	0	5
Takeoff	0	250	500	0	0	.5
Transition	250	250	0	100	0	2
Climb	1,000	15,000	2,500	Best L/D	0	~
Cruise	15,000	15,000	0	200	~	40
Descent	15,000	100	-3,000	1.2 Vs	0	~
Transition	100	100	0	100	0	2
Landing	100	0	-200	0	0	.25
Diversion						
Takeoff	0	250	500	0	0	.5
Transition	250	250	0	100	0	2
Climb	1,000	15,000	2,500	Best L/D	0	~
Cruise	15,000	15,000	0	200	160	~
Descent	15,000	100	-3,000	1.2 Vs	0	~
Transition	100	100	0	100	0	2
Landing	100	0	-200	0	0	.5
Taxi	0	0	0	0	0	5

Table 3: "New Baseline" mission profile created by VerdeGo Aero for use in Hybrid-Electric Scenarios

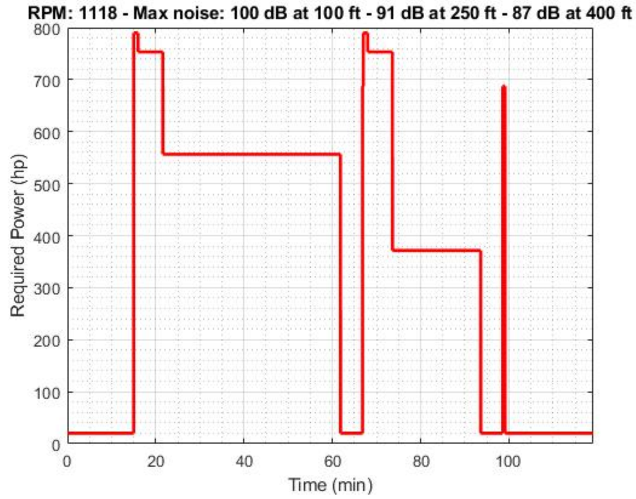

Figure 2: Power profile for new baseline mission for use in Hybrid-Electric Scenarios

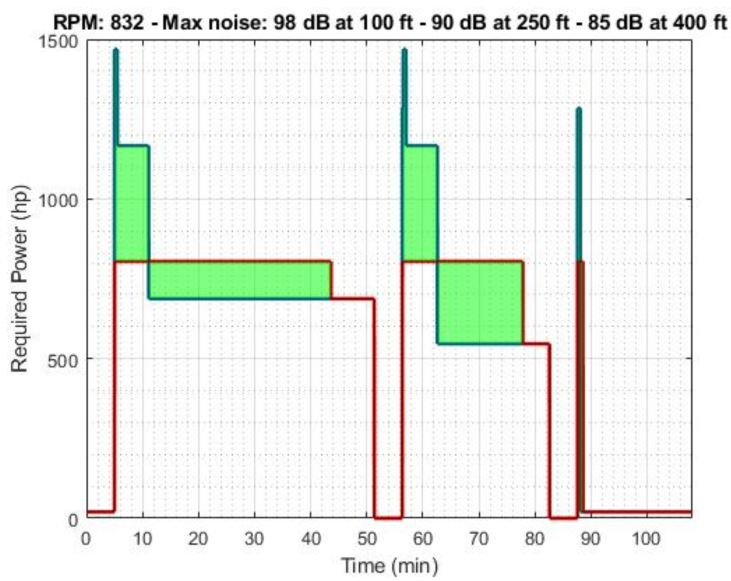

Figure 3: Peaks and Valleys Hybrid Power Profile based on new baseline mission

Green areas above the red power line indicate flight segments where the battery is providing power for propulsion. Green areas below the red power line indicate flight segments where the battery is being charged by the hybrid generator

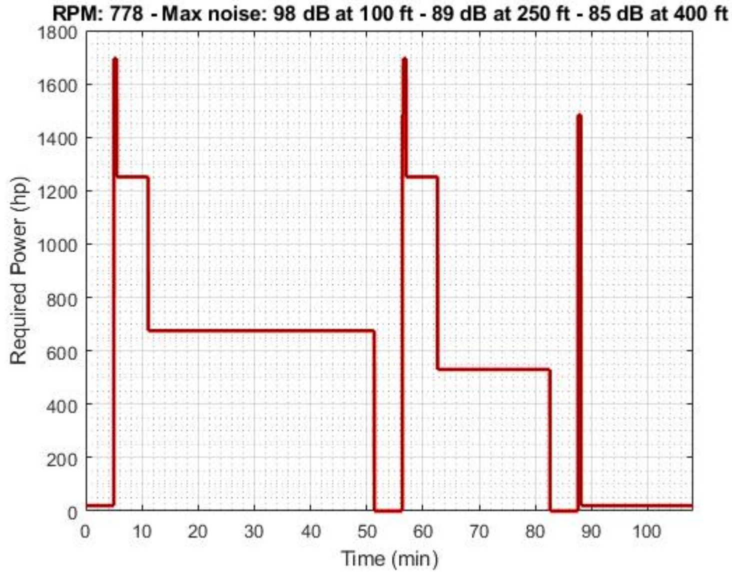

Figure 4: Minimal Battery Hybrid Power Profile based on new baseline mission

Scenario	Weight lbs	Fuel Burned lbs	Battery Wh/Kg	Battery kWh	Peak Power hp	Peak Turbine Power hp	Range (nm)	Cruise Speed (knots)	Rotor Diameter (ft)	Wing Span (ft)
Vy400 Current Mission	6,635	534	N/A	N/A	1,659	1,659	160	310	15	25
New Baseline Turbine	4,823	338	N/A	N/A	790	790	133	200	12.5	22
Hybrid PV	8,659	471	242	55	1,469	804	133	200	16.5	30
Hybrid MB	9,580	480	242	N/A	1,625	1,625	133	200	17.5	31

Table 4: Summary of results from analysis of the four hybrid-electric scenarios

HYBRID CONCLUSIONS

The initial evaluation of the current Vy400 mission indicates that a hybrid-electric powertrain configuration is not beneficial for this scenario. The high cruising speed and low cruise altitude of the current mission profile proposed by Transcend for the Vy400 results in the peak power requirement occurring during the entirety of the cruise segment of the flight. The typical motivators for hybrid electric power in a VTOL aircraft are either to reduce the mechanical complexity of the drivetrain in the case of

Distributed Electric Propulsion (DEP) aircraft, and/or to utilize a balance of batteries and generator output to manage the short-duration peak power demands at takeoff and landing along with the lower power requirements in cruising flight. The standard Vy400 aircraft and mission profile does not meet either criteria.

Altering the mission profile to reduce cruising speed from 310kt to 200kt and reducing the typical flight segment to 133nm from 160nm altered the relationship between takeoff power and cruise power such that cruising power is significantly lower than the takeoff and landing power. This change shifts the aircraft into a design space where hybrid-electric propulsion may be desirable. Advantages of a hybrid for this mission include the ability to specify a smaller/cheaper turbine that is optimized around the cruising flight segment's power requirements, and the ability to have multiple onboard sources of power. The latter point is of particular interest for VTOL aircraft that may lack the ability to autorotate in the event of a power failure. A hybrid powertrain utilizing a turbine and a battery pack sized for takeoff & landing power has multiple sources of energy to drive the propellers/rotors. In the event that there is a turbine or generator failure, the battery pack has sufficient energy for a short cruise segment and a powered normal landing. In the event of a failure of a cell or module inside the battery pack, there are many "stacks" of cells in a large-scale aerospace battery pack such that the remaining stacks of cells contain sufficient energy to continue to power the aircraft. A single-engine hybrid may offer similar redundancy benefits to those found in a twin-engine turbine helicopter powertrain configuration.

BATTERY SCENARIOS

In addition to the evaluation of hybrid-electric powertrains in the Vy400 platform, fully battery-electric powertrains were also evaluated for feasibility. Ahead of the analysis it was already known that battery energy density is a significant limiting factor in the feasibility of battery-electric Urban Air Mobility aircraft, and this issue is magnified in a C2C mission. For the feasibility analysis of battery-electric powertrains, three battery capabilities were considered and were labeled as follows; Near-Future (NF), UBER, and Distant Future (DF). In all three scenarios the aircraft were considered to be similar in geometry and weight to that of the current Vy400 design.

The battery capabilities for the NF investigation represent what VerdeGo currently believes will be available within the next 5 years, during the likely design timeline for the initial Vy400 aircraft. The battery analyzed in the “UBER” scenario represents capabilities that UBER has claimed would be possible by 2023. It is important to note that current battery industry trends do not align with the viewpoint that the “UBER” battery will be available in the mid 2020s. However, this theoretical battery capability is referenced frequently by aircraft manufacturers developing next-generation VTOL aircraft, and therefore it is important to understand what performance capabilities are possible if this battery comes to fruition. As a final scenario, VerdeGo analyzed the battery performance characteristics required to deliver a commercially useful C2C aircraft with a design similar to the Vy400 architecture. This battery represents a significant step-change in performance vs. currently available technologies and this scenario illustrates the challenges in delivering a battery-electric C2C aircraft with competitive performance.

Case Name	Propulsion Configuration	Battery Specific Energy kw/kg	Mission Classification	Vehicle Width (Rotors+Wings) ft	Payload lbs	Cruise Speed knots
Near Future Battery	Battery-Electric	242	Marginal	40	1,200	120
“UBER” Battery	Battery-Electric	300	Marginal	34.5	1,200	120
Distant Future Battery	Battery-Electric	1,345	C2C Capable	46.5	1,200	200

Table 5: Overview of three battery-driven cases run in this section of the analysis

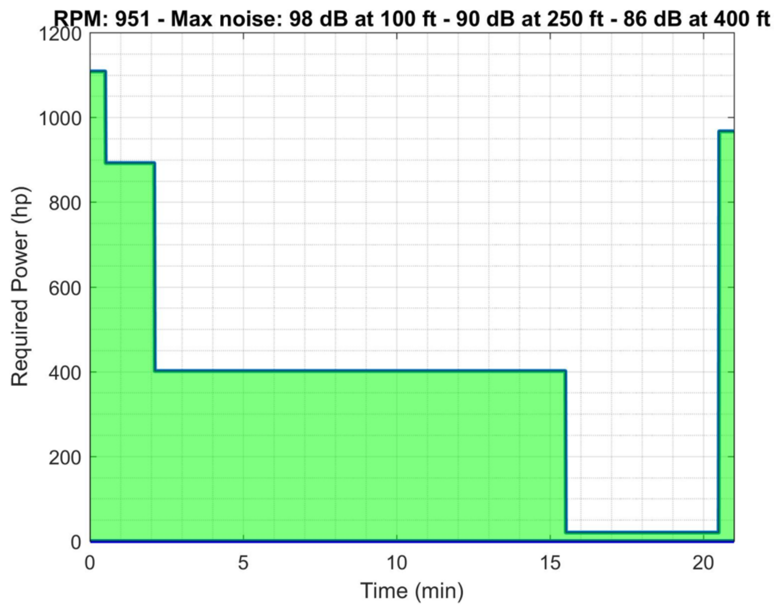

Figure 5: Power profile of a battery-electric aircraft using a Near Future battery
(note: this power profile does not contain any safety reserve for power and is not viable for a production aircraft)

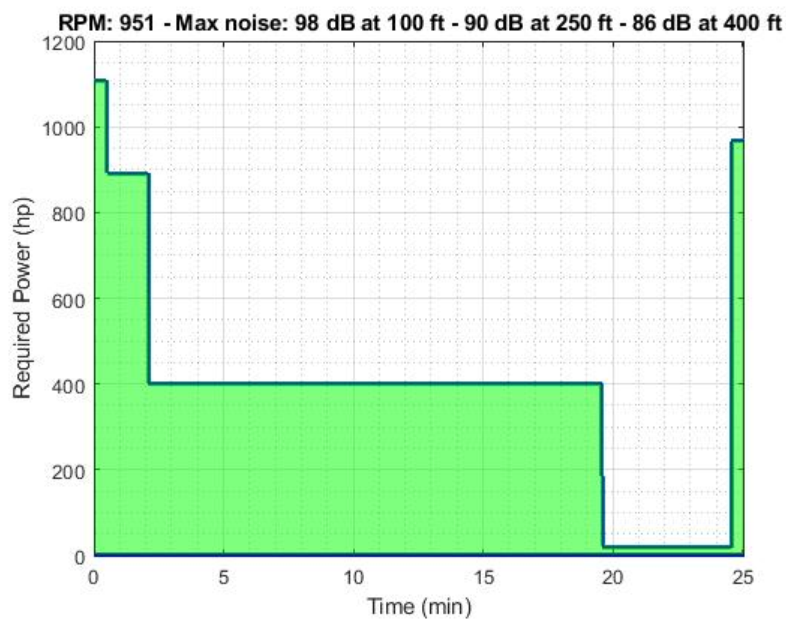

Figure 6: Power profile of a battery-electric aircraft using the "UBER" theoretical battery
(note: this power profile does not contain any safety reserve for power and is not viable for a production aircraft)

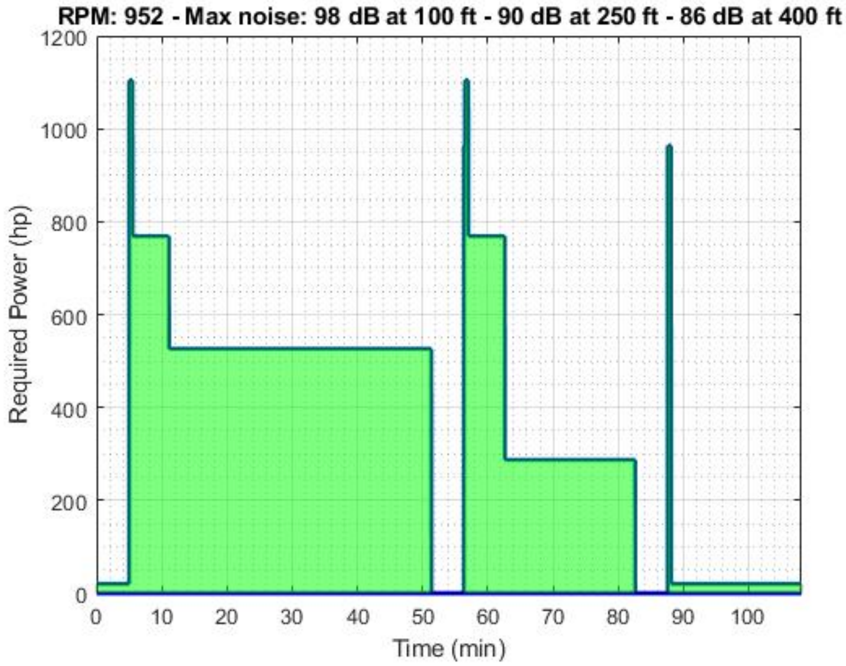

Figure 4: Power profile of a battery-electric aircraft using a Distant Future battery

Scenario	Weight lbs	Battery Weight lbs	Battery Wh/Kg	Battery kWh	Peak Power hp	Peak Turbine Power hp	Range (nm)	Cruise Speed (knots)	Rotor Diameter (ft)	Wing Span (ft)
Battery NF	6,651	1,154	242	110	1,105	N/A	29	120	15	25
Battery UBER	6,651	1,154	300	136	1,105	N/A	38	150	15	25
Battery DF	6,651	1,154	1,345	610	1,105	N/A	133	200	15	25

Table 4: Summary of results from Battery Scenarios

BATTERY CONCLUSIONS

To summarize, we first took the Vy400 conceptual model created early into the investigation and replaced the propulsion system with a battery-electric system. We then used this new battery-electric model as a test bed for the capabilities of different potential battery packs. Two of the previously mentioned battery packs were meant to represent both a conservative (NF) and ambitious (UBER) view for where battery technology should be in the next few years. The results of this section of the investigation highlight the reality that a battery-electric version of the Vy400 is severely compromised in its capabilities and does not meet regulatory safety requirements for reserve energy with battery cell technologies that are projected to be available in the near term. Even if the “UBER battery” becomes available, the aircraft does not have the ability to both have a useful mission capability and legal reserve energy onboard.

In the long-term it is expected that battery energy density will continue to improve. If future trends track with the past several decades, then improvement will continue to track at around 5% per year compounded. While it is likely that battery-electric aircraft will eventually be viable for C2C missions, the need for a 5X+ improvement in energy density means that it will be decades before appropriate battery cells are available to support an aircraft designed for a useful and legal C2C mission.

CONCLUSIONS

This analysis led to several important conclusions about the feasibility of hybrid-electric and battery-electric propulsion in an aircraft based on the Vy400's configuration. It is important to note that based on this analysis, if it is the intent of Transcend to focus on the mission profile that was originally provided to VerdeGo for a high-speed longer range C2C mission, then it is our recommendation that Transcend should focus on turbine-driven powertrains with mechanical drivetrains connecting the turbine to the props. The high-speed cruise segment of the flight negates the potential advantages of a turbine by placing the peak power demand into the long-duration cruise segment of flight and not in the short-duration takeoff and landing segments. A battery-electric aircraft is also unlikely to be feasible at any point in the next 15 to 20 years due to the large amount of energy required for the high-speed cruise. However, if Transcend is interested in making adjustments to their mission profile to add a potential new variant of the Vy400 platform that is within the design space enabled by hybrid-electric propulsion, then there may be attractive options available.

The first major conclusion from this analysis is that in order to enable hybrid-electric propulsion, there are some mission-related conditions which must be met for C2C flights. The first condition that must be met relates to the total power and length of time in vertical takeoff and landing configuration. Hovering/vertical flight requires high power levels and it is important to minimize the duration spent in these flight segments. In figure 2, 3, and 4 it can be observed that the duration of the peak power segments of the flight is dramatically shorter than in the original profile from Figure 1, which is one of the key enabling factors that enables the PV hybrid scenarios to be attractive for a modified mission. If it is determined that there is a market segment for aircraft with lower cruise speed than the Vy400 and with shorter range, then there is a valid design space for a hybrid electric powertrain configuration.

Our second major take away from this analysis is that if Transcend desires to pursue hybrid-capabilities then it is our recommendation to pursue a Peaks and Valleys (PV) architecture as opposed to the Minimal Battery (MB) configuration. It is important to note that with current battery technologies, both the PV and MB configurations result in significant increases to the weight of the aircraft due to the addition of the battery pack and generator onboard the aircraft. The PV hybrid powertrain enables the use of a smaller/lower priced turbine and it enables some level of multi-engine redundancy through the ability to supply power from multiple onboard energy sources. The added redundancy with multiple energy sources may have particular value for VTOL aircraft that lack autorotation capabilities.

The final conclusion from this analysis relates to battery-driven propulsion for an aircraft similar to the Vy400. The power and energy requirements of C2C missions, where high cruise speeds and longer range are desirable, are not compatible with the low energy density of batteries. It is not advised to invest resources pursuing a battery driven powertrain architecture for this aircraft configuration and mission. Even a reduction in speed and range still requires battery energy density of more than 6X the current state of the art levels. It is likely to be decades before there are batteries available that would make it relevant to explore propulsion scenarios involving only batteries. Given the potential for non-linear advances in battery capabilities, it is recommended that Transcend monitor the battery market and should advances occur that deliver the potential for battery pack energy densities above 1,000Wh/kg at the pack level (including structure, cooling, shielding, and safety hardware) then it would be advisable to initiate a more detailed study of battery-drive C2C aircraft at that point.