Personal Rotorcraft Design and Performance with Electric Hybridization

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ABSTRACT

Recent and projected improvements for more or all-electric aviation propulsion systems can enable greater personal mobility, while also reducing environmental impact (noise and emissions). However, all-electric energy storage capability is significantly less than present, hydrocarbon-fueled systems. A system study was performed exploring design and performance assuming hybrid propulsion ranging from traditional hydrocarbon-fueled cycles (gasoline Otto and diesel) to all-electric systems using electric motors / generators, with batteries for energy storage and load leveling. Study vehicles were a conventional, single-main rotor (SMR) helicopter and an advanced vertical takeoff and landing (VTOL) aircraft. Vehicle capability was limited to two or three people (including pilot or crew); the design range for the VTOL aircraft was set to 150 miles (about one hour total flight). Search and rescue (SAR), loiter, and cruise-dominated missions were chosen to illustrate each vehicle and degree of hybrid propulsion strengths and weaknesses. The traditional, SMR helicopter is a hover-optimized design; electric hybridization was performed assuming a parallel hybrid approach by varying degree of hybridization. Many of the helicopter hybrid propulsion combinations have some mission capabilities that might be effective for short range or on-demand mobility missions. However, even for 30 year technology electrical components, all hybrid propulsion systems studied result in less available fuel, lower maximum range, and reduced hover and loiter duration than the baseline vehicle. Results for the VTOL aircraft were more encouraging. Series hybrid combinations reflective of near-term systems could improve range and loiter duration by 30%. Advanced, higher performing series hybrid combinations could double or almost triple the VTOL aircraft's range and loiter duration. Additional details on the study assumptions and work performed are given, as well as suggestions for future study effort.

NOTATION

DGW = design gross weight
GTE = gas turbine engine
ISA = international standard atmosphere
MCP = maximum continuous power
NDARC = NASA Design and Analysis of Rotorcraft
OGE = out of ground effect
SAR = Search and Rescue
SMR = single-main rotor (helicopter)
SOA = state of the art
V_{be} = best endurance velocity
V_{br} = best range velocity
VTOL = vertical takeoff and landing
η = efficiency

INTRODUCTION

New generations of electric motors / generators are achieving high power-to-weight, efficiency, reliability and operational flexibility that offer the potential for new, aviation vehicle and mission opportunities, while mitigating noise and emissions impacts. Concepts that employ vertical takeoff and landing (VTOL) operations have an additional, unique potential to enhance personal mobility; but VTOL operations require significant power. Electrical energy storage has not achieved parity with energy-dense hydrocarbon fuels, but may be adequate for shorter range missions envisioned for on-demand mobility. The optimum combination of electric motors and batteries for short-duration, high power operations, while leveraging hydrocarbon-fueled engines for additional range capability needs to be explored and better understood.

To help explore these potential propulsion and energy combinations, a system study was performed using two, representative vertical lift concepts. One is the more traditional and understood, single-main rotor (SMR) helicopter; the other, an all-electric VTOL aircraft. As opposed to trying to directly compare such distinct concepts against each other, propulsion system options were explored for each vehicle concept. From such efforts, it is hoped to recognize general results that extend to both concepts, while understanding which combinations might have the most benefits or penalties, based on each concept's particular design and operation. Traditional and advanced hydrocarbon-fueled engines were modeled as either the main propulsion system or a secondary system to enhance range capability, depending on the vehicle. Electric motors and generators with battery energy storage that represent state of the art (SOA) systems or be flight ready in 15 and 30 years

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were also explored. These electric systems could also be the main vehicle propulsion or short duration, high-power assist to improve vehicle capability. The combination of various propulsion and hybrid systems will be discussed in a subsequent section.

Vehicle concepts will be covered first, highlighting similarities and differences among the chosen vehicles and their respective design philosophy. Next, present and future motive propulsion and energy systems will be examined, including performance levels expected in the near and farther term. Then, the analysis methodology section will explain the various study assumptions, the specific tools and vehicle models. Finally, results will be presented, potential future efforts will be proposed, and some final conclusions given.

VEHICLE CONCEPT

A SMR helicopter and two, all-electric VTOL aircraft enabled by distributed propulsion were modeled to estimate their performance with a combination of propulsion and power systems. Notional vehicle representations are shown in Figure 1 and baseline concept vehicles specifications are given in Table 1.

The vehicle payload mission capability was selected as one to two passengers (450 lb., 205 kg maximum total payload) with a 200 pound (91 kg) pilot. The design range capability varied between these two concepts. The SMR helicopter model is representative of present, operational vehicles in that size class. This particular vehicle class has almost 200 nautical mile range and significant loiter capability, although at typical helicopter speeds (generally best range velocity, V_{br}, is around 100 knots, with maximum endurance velocity, V_{be}, closer to 60 knots). Approximately one hour flight duration seemed reasonable for the VTOL aircraft. The notional design had a V_{br} approximately equal to 170 knots. This combination of design choices led to the design mission range being set to 150 nautical miles. A few, additional design considerations are mentioned for each concept in the next section; a more thorough discussion for each concept can be found in many textbooks and is unnecessary here.

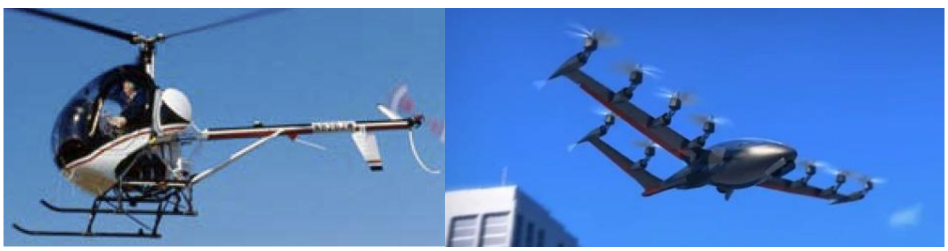

Figure 1. Notional vehicle representations: left) Single Main Rotor (SMR) Helicopter, right) All-Electric VTOL Aircraft.

Table 1. Baseline Concept Vehicles Specifications.

Vehicle → Parameter ↓	Single Main Rotor (SMR) Helicopter	All-Electric VTOL Aircraft, 15 year technology	All-Electric VTOL Aircraft, 30 year technology
Design gross weight (DGW), lb. (kg)	2,050 (930)	2,840 (1,291)	2,172 (987)
Empty weight, lb. (kg)	1,100 (500)	2,185 (993)	1,517 (689)
Disk loading / wing loading, lb./ft^2	3.6 / N.A.	15 / 50	15 / 50
Nominal fuel weight, lb. (kg), % DGW *	160 (73), 8%	588 (267), 21% (552 MJ battery)	250 (113), 11% (421 MJ battery)
Sea level maximum rated power, hp (kW)	190 (142)	465 (347)	336 (251)
Engine type	Reciprocating (Otto cycle)	All-electric, 15 year technology	All-electric, 30 year technology
Engine weight, lb. (kg), % DGW	270 (123), 13%	136 (62), 5%	69 (31), 3%
Engine power / weight, hp/lb. (kW/kg)	0.71 (1.2)	3.4 (5.6)	4.9 (8.0)
Sea level power specific fuel consumption, lb./hp-h (kg/kw-h)	0.500 (0.305)	N.A.	N.A.
Power / DGW, hp/lb. (kW/kg)	0.09 (0.15)	0.16 (0.27)	0.15 (0.25)
Cruise velocity (V_{br}), knots (km/h) *	100 (185)	170 (315)	170 (315)
Range, nautical mile (km) *	195 (360)	150 (280) †	150 (280) †

* from mission analysis † Design value

All-Electric VTOL Aircraft

The all-electric, VTOL aircraft is a hybrid helicopter / airplane design, enabled by advances in electric propulsion technologies. Advanced electric motors, with their high efficiency and power-to-weight, also have the potential to scale with reduced or no performance penalties. Instead of one or only a few, vertical lift rotors; many, distributed, smaller electric motor / rotor combinations can be used to enhance performance, propulsion redundancy and safety. Using distributed propulsion adds the potential for additional design freedom to optimize for one or multiple missions (including bias toward various cruise, hover or other desired requirements). Many of the vehicle and multiple-rotor propulsion design interactions are still being explored as the requisite technologies develop. A recent work by Young (Reference 1) noted both positive and negative interactions from multi-rotor designs, but that level of detail was not included in this study. This particular vehicle's design and performance is also highly sensitive to electrical energy storage density, especially for 15 year battery technology, where it comprises over 20% of vehicle design gross weight. The matrix of propulsion and energy storage concepts used for this effort is discussed in the next section.

MOTIVE PROPULSION AND ENERGY STORAGE CONCEPTS

This study included a range of hydrocarbon-fueled engines, including performance estimates that are expected to be achieved with some technology investment. As noted in Table 1, total vehicle power levels can approach 500 hp (375 kW), but individual engines and motors are under 200 hp (150 kW) and are generally closer to 100 hp (75 kW) or less. Table 2 gives a quick comparison for this study's matrix of motive propulsion system power-to-weight and efficiencies with their respective fuel of choice energy density. Values for the electric motor / generators and their energy storage (batteries) are from Reference 2. The combination of gross fuel energy density with motive propulsion efficiency illustrates the net energy density realizable by vehicles over their missions. Although the high efficiency of electric systems imparts less penalties to the net energy density for batteries, electric energy storage is still significantly less net, energy dense than hydrocarbon fuels. Since most of the traditional, hydrocarbon-fueled propulsion systems are fairly well understood, their particular discussions will be brief. Electric motors and their assumed, battery electric energy storage are also discussed, but in a bit more detail to help orient the reader. The discussion concerning the various combinations of the electric and hydrocarbon systems will be covered later during the analysis methodology.

Reciprocating Gasoline (Otto) Cycle

Hydrocarbon-fueled systems have been the aviation standard for over a century. The high energy density of hydrocarbon fuels have enabled a substantial variety of vehicle and mission capabilities. For smaller power levels (< 250 hp / 186 kW), the spark-ignited, Otto cycle is dominant. Such legacy engines best operate using leaded, aviation gasoline, but the adverse effects from the lead additives have resulted in legislation to eliminate the leaded versions of this fuel and the engines that use it. Fuel and engine research have developed non-leaded fuel alternatives and it appears these engines will remain in operation for the foreseeable future. Overall efficiency is rather poor (≈ 27%) and power-to-weight also tends to be low, partially a result of conservative design margins to achieve safety. Since there seems to be insufficient interest for significant investment for improvements, only one technology level was assumed for this cycle.

Table 2. Motive engine and energy storage characteristics (100 hp / 75 kW class).

Engine type	Power / weight, hp/lb. (kW/kg)	η, %	Fuel energy density, MJ/kg	Net energy density, MJ/kg
Reciprocating gasoline (Otto) cycle	0.71 (1.2)	27	Gasoline, 43.5	11.7
all-electric, SOA*	1.9 (3.1)	85	0.70	0.60
15 year	3.4 (5.6)	93	1.75	1.63
30 year	4.9 (8.0)	97	3.15	3.06
Diesel cycle, SOA	0.53 (0.9)			
15 year	1.06 (1.8)	37	Diesel, 43.0	15.9
30 year	1.59 (2.7)			
Gas turbine, SOA	2.0 (3.3)	14	Jet-A	5.9
Advanced	3.0 (4.9)	15	42.8	6.6

* "Fuel" is lithium battery, cell only average of lithium ion and sulfur technologies, from Reference 2.

Diesel Cycle

Diesel engines use compression ignition to achieve significantly higher efficiency compared to gasoline cycles, but that higher compression ratio presently results in larger and heavier engines. Many advanced concepts can be found that suggest substantially improved power-to-weight; different technology levels were included to estimate the potential benefit. Diesel fuel is also much more available than aviation leaded gasoline and without the premium price for aviation versions. Diesel cycles have the potential to reduce carbon dioxide emissions because of their higher efficiency versus the Otto cycle or gas turbine; if improved power-to-weight diesel engines can be developed and certified for aviation (Reference 3). Current, certified aviation diesel engines have lower power-to-weight than existing helicopter engines, adversely impacting engine and overall vehicle weight, and diminishing (or negating) fuel burn benefits.

Gas Turbine (Brayton) Cycle

At higher power levels (> 1,000 HP, 750 kW), the gas turbine engine is easily the dominant cycle because it is robust, smooth and dependable. At large sizes, it can also achieve fairly high efficiency (≈50%) and high power-to-weight (6-

8 hp/lb. or 10-13 kW/kg). However, for small engines, size-induced losses reduce power-to-weight to about 2 hp/lb. (3.3 kW/kg) and overall efficiency to 15% or less. With such low efficiency and therefore high fuel use, the gas turbine is not the typical engine for this vehicle and power class. Efforts to improve efficiency often increase engine size, weight, and complexity for modest efficiency improvements; which for flight systems can result in a worse overall system. Still the gas turbine is included to understand its potential for these particular vehicles and missions.

Electric Motors

There is substantial interest in all-electric systems for a new generation of aviation propulsion systems. Impressive levels of electric motor / generator power-to-weight, efficiency and reliability are being demonstrated in hybrid cars. There are concurrent efforts developing and testing various architectures for aircraft. Additional potential advantages of high efficiency and power-to-weight are maintained at various scales, while efficiency is maintained during part-power operation. These attributes enable innovative designs and operations to further improve redundancy, safety, and overall vehicle capability and flexibility. As mentioned previously, Reference 2 discusses recent efforts to quantify various technology approaches to realize significant weight and efficiency improvements for non-cryogenic electric propulsion components. As shown in Table 3, projected material and design improvements reduce losses by a factor of five from SOA electric motors, while reducing weight by over a factor of 2.5.

Table 3. Electric motor parameters (from Reference 2).

Technology year	Power/weight hp/lb. (kW/kg)	η, %	Controller η, %	Net η, %	Total loss, %
SOA	1.9 (3.1)	90	94	85	15
15 year	3.4 (5.6)	95	98	93	7
30 year	4.9 (8.0)	98	99	97	3

Power-to-weight includes electric motor + controller

Fuel and Net Energy Density

Hydrocarbon-fuels are very energy dense and as fuel weight is reduced during use, their weight penalty on the vehicle diminishes. Even with high efficiency, all-electric propulsion systems are presently limited by the low energy density of present battery, capacitors, or other electrical energy storage systems, which maintain constant weight or can even increase their weight during use (an example of the latter is some metal-air battery systems). As previously shown in Table 2, hydrocarbon-fueled systems are substantially less efficient than the electrical systems. However, it is reemphasized here that the high energy density of hydrocarbon fuels enables these fueled systems to have significantly better net energy density than even 30 year projections for batteries. The next section discusses how these various motive propulsion and energy storage concepts were analyzed for the various concepts.

ANALYSIS METHODOLOGY

This section discusses the analysis tools, baseline vehicle models, mission profiles and vehicle / propulsion system sizing and analyses. Different sizing methodologies are used for each vehicle and are discussed below. Similar mission profiles are used for both vehicles; however, slightly different cruise and loiter speeds result from the varying aerodynamics for each vehicle. Also, because of the differences in each vehicle's propulsion architecture, slightly different hybrid combinations were explored and are discussed below.

Analysis Tools and Baseline Models

The design code, NASA Design and Analysis of Rotorcraft (NDARC, References 4-7) is used to model the various vehicle and propulsion systems, performing vehicle sizing and performance analysis. As described in Reference 7, NDARC's propulsion models were expanded to include additional propulsion and power system concepts, including those necessary for electric propulsion components and hybrid systems. The vehicle and mission models were developed from the SMR helicopter and tilt rotor examples distributed with NDARC v1.10. The actual sizing models for the SMR helicopter and VTOL aircraft were already available from previous efforts (References 8 and 9). The VTOL vehicle design was updated to slightly reduce its design disk loading and hover power requirement. Its vehicle sizing mission range was maintained at 150 nautical miles (resulting in roughly an hour mission time), although the actual vehicle sizing mission profile was updated from Reference 9. The two mission profiles used for this effort are discussed in the next section.

Mission Profiles

The simple mission profile shown in Figure 2 was used to determine the maximum range for both vehicles for all propulsion combinations and size the VTOL aircraft. Cruise altitude was set to 2,000 ft., ISA for both vehicles. Previous studies results suggested that 5,000 ft., ISA was a more efficient cruising altitude for the faster VTOL aircraft. However, because the descent was not explicitly modeled, the benefit from the higher cruise altitude was not realized and it was found that the 2,000 ft., ISA cruise altitude resulted in a slightly improved mission range.

Since vertical-lift vehicles are often used for search and rescue (SAR) operations, range versus hover and loiter duration was also calculated using the mission profile in Figure 3. Based on some of the on-demand mobility mission work, takeoff and landing hover requirements for both vehicles was reduced from the previously used study value of five to two minutes each at takeoff and landing. Mission energy reserves were maintained at roughly 5% each (as applicable) of fuel by weight and battery charge capacity or energy.

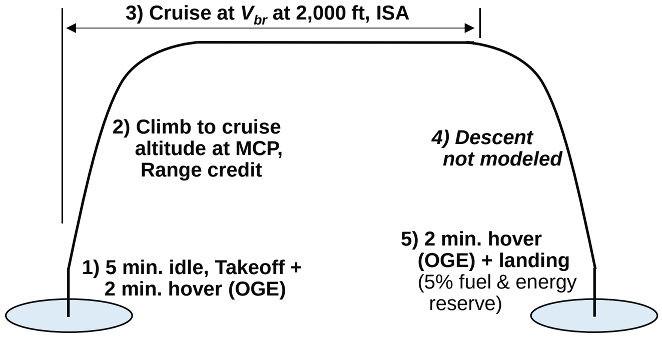

Figure 2. Vehicle maximum range and VTOL sizing mission profile.

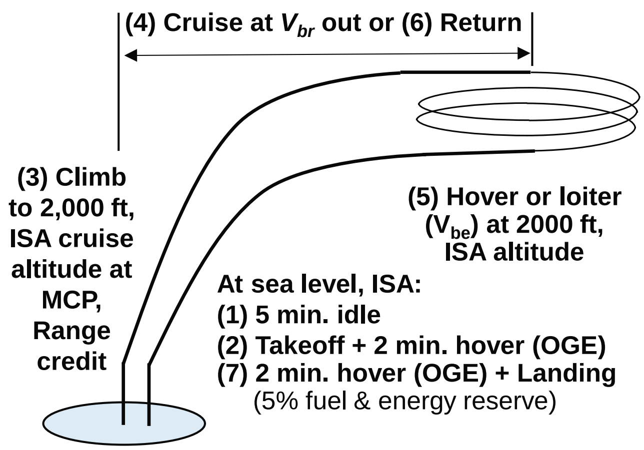

Figure 3. Vehicle hover / loiter mission profile.

Propulsion Modeling

For this effort, relatively simple (constant power or energy to weight and efficiency) models were developed for the electric system components to understand gross sizing effects and develop understanding for the most critical performance parameters and component operating range over defined missions. Performance values for electric motors, motor controllers and batteries came from Reference 2 and were listed and discussed in the previous section. The battery management system weight is assumed to be 20% of battery active weight to account for cell containment and thermal management. Another 20% of battery active weight is added to account for power management and distribution, with its losses assumed to be included within the electric motor and controller losses. Batteries are also limited by discharge rate, noted as C rating. This study generally used a 3C discharge level to help minimize battery size, but should still allow a significant number of charge / discharge cycles. For the hybrid helicopter, assuming SOA electric systems, a 5C discharge level was assumed for the sizing exercises to allow for some gasoline fuel weight and still meet the study's vehicle empty plus fuel weight limit. For those cases, the resulting fuel allowance was still too low for any viable mission capability. Further description of the sizing methodology can be found in the next section.

Vehicle / Propulsion System Sizing and Analysis

For both vehicles, any change in the vehicle empty plus fuel weight would directly affect payload and mission performance. Therefore, for each type and combination of propulsion system architecture, vehicle empty plus fuel weight was held constant. Propulsion systems with higher power-to-weight would result in additional fuel to maintain the constant weight assumption and could have improved range and hover / loiter duration.

The SMR helicopter contains a single engine and main rotor. To minimize duplicative components and meet its stringent weight levels, a parallel hybrid propulsion architecture is assumed (shown in Figure 4). An electric motor would assist the hydrocarbon-fueled engine for motive propulsion, and act as generator to recharge the battery if sufficient excess power was available during the mission. The zero and totally electric combinations are fairly easy choices. To select other values for the degree of hybridization, the approach similar to that discussed by Pokhel (Reference 10) is used. The total power required is driven by hover, but reducing the engine size and meeting hover requirements with some electric motor power assist might free up some weight to use for the electric motor / generator, its battery pack and still maintain or increase weight for fuel.

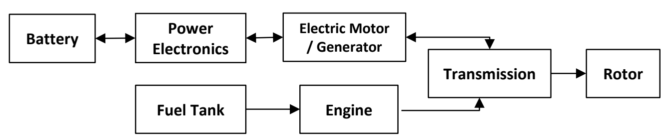

Figure 4. Parallel hybrid propulsion architecture block diagram.

The power required versus velocity for the SMR helicopter is shown in Figure 5. The heavy, hydrocarbon-fueled engine could be sized for the minimum power / maximum endurance velocity (V_{be}), the power required for best range speed (V_{br}), and some value in-between, the latter two cases could give some power margin that could be used to recharge the battery during flight. The electric motor / generator would be sized to provide the remainder of required hover motive power, and its battery pack sized by the power or energy levels to meet hover or other mission requirements (whichever is greater). Any weight saved from the reduction in the size from the hydrocarbon-fueled engine after addition of the electric motor / generator and its battery pack would be used for additional fuel mass and therefore satisfy the study assumption to maintain constant vehicle empty plus fuel weight.

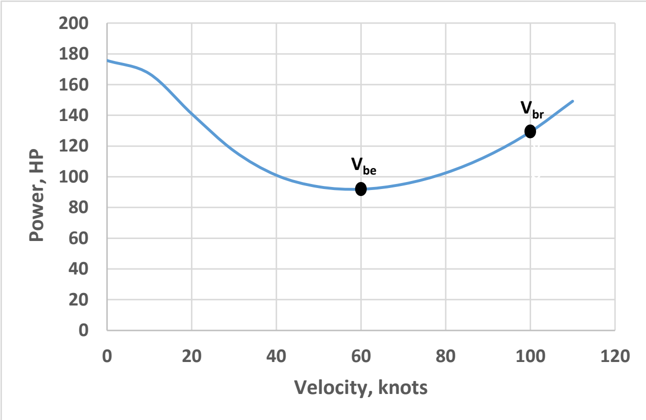

Figure 5. SMR Helicopter propulsion power versus velocity.

The all-electric VTOL aircraft uses multiple electric motors / rotors and a redundant battery pack. For this vehicle, a series hybrid propulsion architecture is assumed (shown in Figure 6). Although there are duplicative motors and generators, direct coupling to reduce or eliminate such duplication does not seem practical. The power required versus velocity for the VTOL is shown in Figure 7 and the V_{be} and V_{br} points noted. Since there was not a large variation in the power at these two flight points, hydrocarbon-fueled engine sizes of 100, 150, and 200 hp (75, 112, and 150 kW) were chosen. The first point is a little below best endurance power, but offered the potential to match fueled and electrical energy usage over range or loiter missions as well as minimize engine and generator size. The latter two engine power points allow operation at either V_{be} or V_{br}, with varying capability to recharge the battery. The battery pack for the electric motors could be sized for the nominal power required only for hover requirements (which would allow takeoff and landing in electric-mode only) or the battery nominal power could be reduced by including the power produced by the hydrocarbon system. The latter option would reduce battery size, enabling more mass for the hydrocarbon system and additional fuel to increase range potential; but would also require the hydrocarbon system to be operating during hover or the required power extraction from the battery pack would exceed the study assumed 3C discharge limit, risking damage and shortening its life. The battery pack was again sized for the minimum size to maximize potential weight available for the hydrocarbon system and fuel and satisfy the study constraint of constant vehicle empty plus fuel weight.

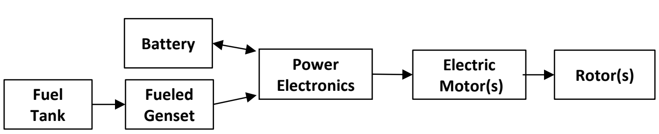

Figure 6. Series hybrid propulsion architecture block diagram.

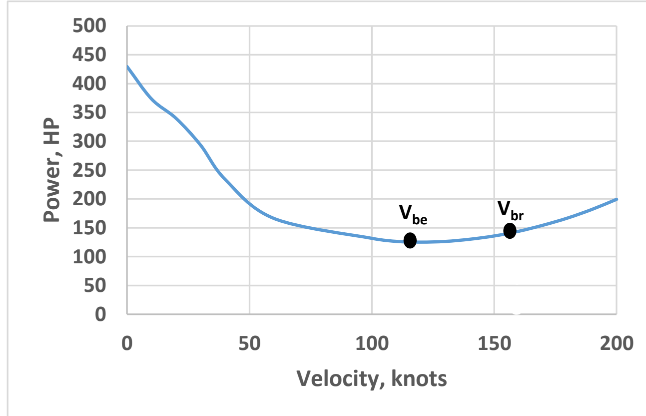

Figure 7. VTOL aircraft propulsion power versus velocity.

RESULTS AND DISCUSSION

For clarity, the results for the hover-optimized SMR helicopter and cruise-optimized VTOL aircraft are discussed separately, although some results are common to both vehicle concepts. The baseline SMR helicopter and VTOL aircraft are optimized based on their initial propulsion architectures. There is some weight impact for adding systems for hybridization, which has significant impacts on aerospace vehicle performance; that is especially true for vertical lift vehicles. Hybridization of the SMR helicopter resulted in some weight reduction for the main engine as its power requirement was reduced, but replacing that power with an electric motor / generator and its necessary battery pack resulted in reduced main fuel weight allowance to maintain vehicle empty plus fuel weight. An example weight breakdown for one helicopter hybridization case is shown in Table 4. By nature of the VTOL aircraft design, hybridization adds a fueled engine, and its generator and fuel. The only offsetting weight can be achieved by removing part of the VTOL vehicle's battery pack. The results for these types of trades to meet various requirements quickly become obvious in the performance results discussed next.

Table 4. Example weight breakdown for SMR helicopter hybridization.

Component	Baseline version weight, lb. (kg)	Hybrid version weight *, lb. (kg)
Main engine	300 (136)	261 (119)
Fuel	160 (73)	120 (55)
Electric motor + ancillary systems	0	34 (15)
Battery	0	44 (20)
TOTAL	460 (209)	459 (209)

* Electric motor / generator sized for 40 hp (30kW), 15 year technology

SMR Helicopter Hybridization Results

The matrix of hybridization cases for the SMR helicopter are listed in Table 5, and were performed assuming SOA, 15 and 30 year electrical component technologies. Mission radius versus hover and loiter duration for the SMR helicopter is shown on Figure 8 and Figure 9, respectively. Maximum range would be twice the no hover or loiter duration mission radius. Many combinations have some mission capabilities, but results indicate that all cases have less, maximum hover, range and loiter capability than the baseline vehicle. For hybrid cases, hover duration does not match the approximately ½ of loiter duration previously reported in Reference 9, but that is a result of study sizing assumption. Maximum electric motor power is required for hover; the electric motor's battery pack was sized for minimum weight for takeoff and landing power levels to maximize cruise fuel levels. The battery, sized for 3C discharge, would result in a maximum, continuous 20 minutes hover duration with no reserves. The maximum hover duration reported includes the decrement required for takeoff, landing and reserves. The hybrid cases sized with enough fueled engine capacity to recharge the battery after takeoff gain a few additional minutes of hover duration for some cases, but are still severely limited by hover's high power requirement, limited battery capacity, and requirements for landing and reserves. The all electric versions do not exhibit the same, substantially reduced hover characteristic as the hybrid versions, but still fall short of the baseline capability, even at assumed 30 year technology levels. Replacing the fueled engine with a higher power-to-weight engine or decreasing payload capability to increase weight available for fuel could improve the loiter results, but that is outside the scope of this effort.

Table 5. SMR helicopter hybridization analysis matrix.

% Hybrid-ization	Fueled engine sizing point	Electric motor, hp (kW)	Recharge battery?
0	Hover	0	N.A.
20	V_{br}	40 (30)	Yes
29	V_{be} +	58 (43)	Yes
38	V_{be}	75 (56)	No
100	0	200 (149)	N.A.

VTOL Aircraft Hybridization Results

It is important to reemphasize the study assumption of constant vehicle empty plus fueled weight, therefore the VTOL aircraft battery pack was resized to only meet hover power requirements (to free up weight allocation for hybridization). This results in approximately 11 minutes maximum hover duration for most of the VTOL concepts (and all the hybrid concepts). Exceptions include the baseline vehicle (almost 18 minutes hover duration) and the baseline with its battery pack updated to 30 year battery technology (all other systems constant). Updating from 15 to 30 year battery technology almost doubles battery energy and slightly more than doubles maximum hover duration to almost 40 minutes; although that result did not include any potential impact pertaining to the volume from the enhanced battery, which might mitigate some of the improvement. There is some battery recharge capability available at higher fueled-engine power levels. In-flight recharging can add a few minutes of hover duration, but requires the vehicle to fly a little slower (closer to V_{be} as opposed to V_{br}). Flying at V_{be} is about 7% less efficient in distance per energy expended than V_{br} and therefore would sacrifice some range for slightly improved hover duration.

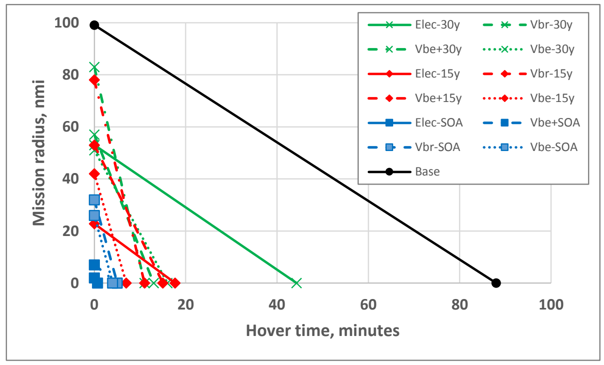

Figure 8. SMR helicopter mission radius versus hover time.

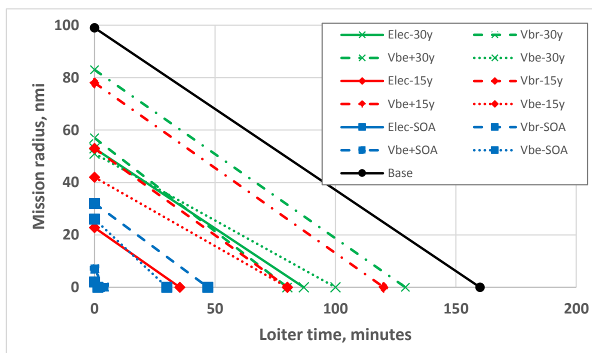

Figure 9. SMR helicopter mission radius versus loiter time.

To better understand the loiter performance results with hybridization for the VTOL aircraft, results are separately reported among those fueled engines with engine power-to-weight less than 1 hp/lb. (1.6 kW/kg), shown in Figure 10, and those above that threshold, shown in Figure 11. The lower power-to-weight cases represent present, fueled engines using SOA or near-term electrical component technology assumptions. For the lower power-to-weight plot, IC represents a reciprocating, gasoline (Otto) cycle engine and Diesel assumes SOA diesel technology. The numbers (100, 150, and 200) are the fueled engine horsepower. All electrical system components shown assume 15 year technology values. Data was calculated assuming other electrical system component technology levels, but the fueled-engine weight dominates the hybridization weight and the selected results exemplify all the relevant trends. The VTOL also has a very stringent weight requirement. Increasing fueled-engine power increases its weight (which reduces fuel allowance) while its output power reduces the hover electrical power draw and the VTOL battery size (which helps the fuel allowance). At 200 hp (150 kW) size, fuel allowance is severely compromised (less than 20 lb. / 9 kg). At lower fueled-engine power levels (100 and 150 hp), the resulting larger battery pack can be used to augment flight power (fly closer to V_{br} speeds) to extend range. Based on each engine's power-to-weight and efficiency, almost 30% more range and loiter capability can be achieved by trading engine power (and weight) for fuel.

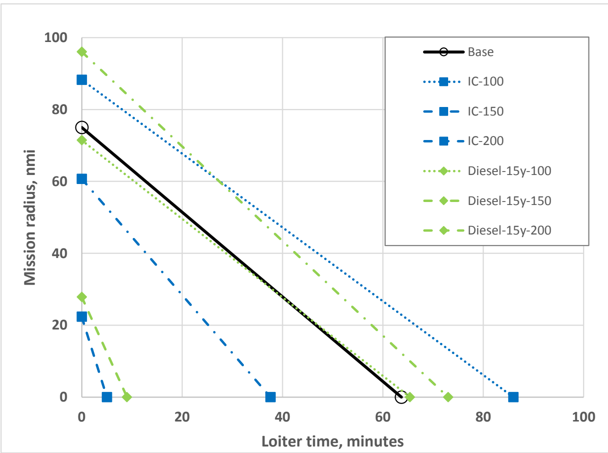

Figure 10. VTOL mission radius versus loiter time for engine power-to-weight less than 1 hp/lb.

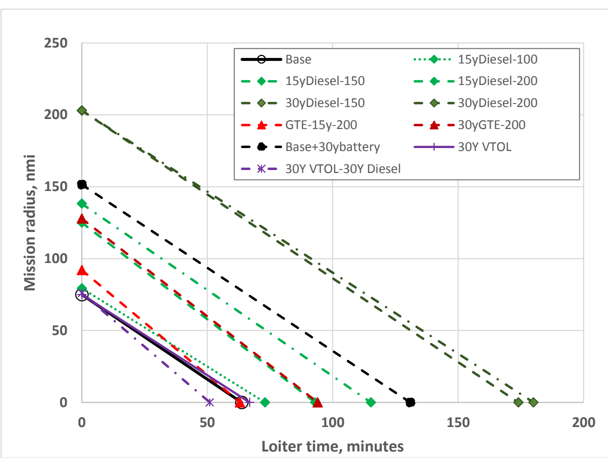

Figure 11. VTOL mission radius versus loiter time for engine power-to-weight greater than 1 hp/lb.

A reduced number of higher engine power-to-weight hybridization cases are shown in Figure 11. More permutations were run, but the results clearly overlapped; the cases shown represent the important trends. To help orient the user, discussion will first cover the notation used in the legend to define the various propulsion and power combinations shown and then discuss the results. Similar technology levels were assumed for the engine and electrical components. The numbers (100, 150, and 200) are the fueled engine horsepower. For the gas turbine engine (GTE), "GTE-15y" is the base with 15 year electrical technology; "30yGTE" is the advanced gas turbine and 30 year electrical technology. "30Y VTOL" is an advanced design for the VTOL aircraft assuming 30 year electrical technology (vehicle specifications previously shown in Table 1). "30Y VTOL-30Y Diesel" is a hybridization of the 30 year technology VTOL design, assuming the best (30 year) diesel and electrical component technology levels.

Results shown in Figure 11, which assumed higher engine power-to-weight and advanced electrical component technologies, were even more encouraging, increasing range and loiter capability by 100 to 200% over the baseline. At higher engine power-to-weight, there is significant weight allowance for fuel, but engine efficiency is still required. Gas turbine engines have some of the better engine power-to-weight characteristics, but lose efficiency rapidly at these small engine sizes (< 200 hp or 150 kW). Their light weight enable a larger fuel load, but loiter and range isn't significantly better than the baseline 15 year technology VTOL until 30 year gas turbine technology is assumed. The advanced (15 and 30 year) diesel, with decent power-to-weight and relatively high efficiency clearly enhances VTOL loiter and range capability. Loiter capability increases with increasing diesel technology (resulting in lower hardware weight) which increases fuel weight allowance. Range and loiter generally increase with smaller diesel power until the 100 hp (75 kW) case. After losses, power output for that case is below endurance requirements and the vehicle is limited by battery capacity, not fuel load. An interesting future study could trade advanced diesel size and fuel versus vehicle battery size to see the effect on hover, loiter and range performance. Almost as effective for increasing capability is updating the baseline VTOL's 15 year technology battery pack with 30 year technology, which roughly doubles its performance on range, loiter and hover. Assuming 30 year electrical technology and resizing the VTOL (although retaining the 150 nautical mile design range) results in similar performance trends with the baseline vehicle, just at a smaller and lighter size. Hybridization of the 30 year electrical technology VTOL design with the best (30 year) technology diesel did not improve range or loiter range; and with resized battery pack showed the same loss of hover duration as other VTOL hybridization designs. As technology improves, there is less room for adding systems and their overhead to improve performance such as range, hover, etc. However, the addition of such systems have the potential for improving other characteristics such as safety or redundancy.

CONCLUSIONS

New generations of electric motors / generators are achieving high power-to-weight, efficiency, reliability and operational flexibility that offer the potential for new, aviation vehicle and mission opportunities, while mitigating noise and emissions impacts. A system study was performed to better understand the performance effects for electrical hybridization of two, vertical lift vehicle types; a single main rotor (SMR) helicopter and vertical takeoff and landing (VTOL) aircraft. Missions included a baseline cruise mission and mission radius incorporating varying amounts of hover or loiter duration. Based on study assumptions to maintain the stringent, constant vehicle empty plus fuel weight as the baseline vehicles, battery weight was minimized to meet takeoff and landing power requirements (with reserves) to maximize fuel load. This results in all designs having a short hover capability in hopes of improving loiter and range capabilities.

The traditional, SMR helicopter is a hover-optimized design; electric hybridization was performed assuming a parallel hybrid approach by varying degree of hybridization. For all cases, even with 30 year technology electrical components, the weight of additional systems resulted in less available fuel allowance than the baseline. Many combinations have some mission capabilities, but results indicate that all cases have less, maximum hover, range and loiter capability than the baseline vehicle.

The advanced, all-electric VTOL is a cruise-optimized design, with vertical lift capabilities to enhance personal mobility options. A series hybrid approach was used to estimate the effect of hybridization with energy-dense hydrocarbon fueled engines to try to enhance its range and loiter capabilities. For fueled-engines with power-to-weights less than 1 hp/lb. (1.6 kW/kg), representing present fueled engines using SOA or near-term electrical component technology, a few combinations of engine type and size resulted in sufficient fuel allowance to improve maximum range and loiter approximately 30%. For fueled-engines with power-to-weights greater than 1 hp/lb. (1.6 kW/kg), representative of 15 or 30 year technology advancement, there is the potential to double or triple range and loiter duration versus the baseline values. Gas turbine engines have some of the best power-to-weight for fueled-engines in this class, but their efficiency at this small size (< 200 hp, 150 kW) is very poor (high fuel usage). Advanced diesel combinations (assuming 15 and 30 year technologies) equaled or better the gas turbine results, with 100 to 200% improvement in range and loiter capability, because of their greater fuel efficiency combined with "good enough" engine power-to-weight. Results indicate that updating the battery pack in the VTOL vehicle from 15 to 30 year technology would improve range, loiter and hover by 100%. Hybridization of the 30 year electrical technology VTOL design with the best (30 year) technology diesel did not improve range or loiter range; and with resized battery pack showed the same loss of hover duration as other VTOL hybridization designs. As technology improves, there is less room for adding systems and their overhead to improve performance such as range, hover, etc. However, the addition of such systems have the potential for improving other characteristics such as safety or redundancy.

Future areas of interest should include new fuel-engines in the SMR helicopter, as well as hybridization, to understand what potential technology paths should be explored to understand and maximize potential. For the VTOL design, mission requirements are still fluid. Although cruise-optimized, there are many design trades that can be explored that will modify its hover, cruise and loiter characteristics. There are also propulsion and power trades (such as fueled-engine power, fuel load and battery capacity) to gain insight for the optimum combination, based on various requirements.

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