Exploring propulsion system requirements for more and all-electric helicopters

Christopher A. Snyder
NASA Glenn Research Center
Cleveland, Ohio, 44135
USA
Christopher.A.Snyder@nasa.gov

Abstract

Helicopters offer unique capabilities that are important for certain missions. More and all-electric propulsion systems for helicopters offer the potential for improved efficiency, reliability, vehicle and mission capabilities as well as reduced harmful emissions. To achieve these propulsion system-based benefits, the relevant requirements must be understood and developed for the various component, sub-component and ancillary systems of the overall propulsion system. Three representative helicopters were used to explore propulsion and overall vehicle and mission requirements. These vehicles varied from light utility (one to three occupants) to highly capable (three crew members plus ten passengers and cargo). Assuming 15 and 30 year technology availability, analytical models for electric system components were developed to understand component and ancillary requirements. Overall propulsion system characteristics were developed and used for vehicle sizing and mission analyses to understand the tradeoffs of component performance and weight, with increase in vehicle size and mission capability. Study results indicate that only the light utility vehicle retained significant payload for an arbitrary 100 nautical mile range assuming 15 year technology. Thirty year technology assumptions for battery energy storage are sufficient to enable some range and payload capabilities, but further improvements in energy density are required to maintain or exceed payload and range capabilities versus present systems. Hydrocarbon-fueled range extenders can be prudently used to recover range and payload deficiencies resulting from battery energy density limitations. Thermal loads for electric systems are low heat quality, but seem manageable. To realize the benefits from more and all-electric systems, technology goals must be achieved, as well as vehicles, missions and systems identified that are best suited to take advantage of their unique characteristics.

Nomenclature

DGW =	design gross weight
EW =	empty weight
ISA =	international standard atmosphere
MCP =	maximum continuous power
NDARC =	NASA Design and Analysis of Rotorcraft
OGE =	out of ground effect
PMAD =	power management and distribution
PSFC =	power specific fuel consumption, lb./hp-h (kg/kw-h)
TOGW =	take-off gross weight
V_{be} =	best endurance velocity
V_{br} =	best range velocity
Vmax =	velocity at maximum effort

Introduction

Under NASA's Aeronautics Research Mission Directorate (ARMD), research and development over a broad range of technology efforts proceed "to meet future needs of the aviation community, the Nation, and the world for safe, efficient, flexible, and environmentally sustainable air transportation."[1] Within ARMD, the Advanced Air Vehicle Program (AAVP) / Revolutionary Vertical Lift Technology (RVLT) Project supports the development and validation of tools and models to help define and refine research themes for vertical lift vehicles and missions. Improvements in electric motor, generator and battery weights, along with their high system efficiency and scalability, make them an appealing technology for vertical lift vehicles. For new technologies, systems, vehicles or missions, complementary efforts will be required to enhance the various methods and tools to accurately assess their potential, as well as derive requirements as they evolve.

Social pressures to reduce aviation's environmental impact are increasing. For air quality considerations, the goal is reducing or eliminating aviation carbon dioxide and oxides of nitrogen emissions; which result from using hydrocarbon fuels. An additional goal for reciprocating (Otto cycle) engines using 100LL (low lead) or other, leaded aviation gasoline, is the elimination of leaded gasoline blends. The lead additives are toxic and the resulting emissions can have adverse human neurological consequences. Engine noise is another consideration, which is even more pertinent to helicopters; which tend to fly lower and operate closer to the general population. Environmental considerations, combined with the potential benefits for advanced electrical system have re-invigorated vertical lift design exploration. One recent effort by Datta[2] looked at technology requirements to match combustion engine performance for a manned, ultra-light utility class vehicle. For that effort, the optimum solution was a battery-fuel cell hybrid. The battery was used to meet high-power needs, such as take-off, while the hydrogen fuel cell was used to increase range potential. Sinsay[3] looked at various energy storage / propulsion alternatives for a vertical take-off and landing Metro-Regional public transport system, employing vehicles called "Hoppers". The work included all-electric vehicle design sensitivity to passenger load, battery energy density, range, and rotor disk loading. Results for three, all-electric vehicle concepts were also compared to a turboshaft-powered design. Nagaraj[4] performed "a comprehensive survey of power source choices for helicopter use", evaluated using a two-seat 600 kg and a 1,200 kg class helicopter. Power source choices included current, operating engines and those considered near-term. Advanced diesel was an optimum choice, by nature of its reasonable power to weight and relatively high efficiency. Other options tended to weigh too much, which would mitigate their efficiency benefits for vehicles as weight-sensitive as helicopters.

This paper describes assumptions, methodology and results exploring the effects of replacing the traditional hydrocarbon-fueled propulsion systems with electric motors powered by battery systems assuming improvements that could be flight-ready in 15 and 30 years for three classes of helicopters. The applicability of using a range extender will also be examined to mitigate deficiencies in energy storage technology. Although vehicle and mission performance will be calculated, propulsion system design and potential propulsion-focused results are emphasized. The vehicles and respective missions will be covered first, highlighting similarities and differences among study choices. Future propulsion and energy systems are then examined; including performance levels expected in the near and far term. Analysis methodology then follows; discussing the various study assumptions, the specific tools and vehicle models. After all this background information, results are presented and discussed. Finally, conclusions will be offered.

Vehicle concepts

Although there is a wide variety of vertical-lift vehicles and missions that are being explored, this preliminary effort is limited to more traditional vehicles and missions. This is done to gain further insight modeling these new propulsion and energy systems, while making the analysis more manageable. A single-main rotor (SMR) helicopter design was chosen, for a range of vehicle sizes and capabilities within general interest and validated models for the analysis tools being used. As vehicle size and capability increase, engine type or size, and fuel load also change; this is highlighted by normalizing to relevant factors, such as design gross weight (DGW). Three vehicles were chosen for this effort, ranging from a capable but Spartan light utility to a faster, more luxurious, medium utility class. The example vehicle classes chosen for this analysis are given in Table 1; with a similar vehicle listed for each class and shown in Figure 1 to help orient the reader. It must be emphasized that although the baseline study vehicle models may be similar to the examples listed, study effort was focused on the propulsion and fuel system modeling, not rigorously matching the examples cited. For the vehicle classes explored, DGW varies by a factor of four, empty weight (EW) varies by almost an order of magnitude, and range varies almost by a factor of two. Specific discussion about each class is found in the subsequent sections.

Light utility: The light utility vehicle is a versatile, cost-effective workhorse, generally used as a trainer or in an agricultural environment. Its Spartan design results in an empty weight just over half of its DGW. With the empty weight and pilot set, remaining weight allocations can be adjusted to meet mission requirements by balancing payload / passenger weight and fuel load. As an example, reduced payload to enable hover at altitude and /or hot day, or using an auxiliary tank with reduced payload to increase fuel load and range. The ratio of engine power to DGW is relatively low, requiring a large main rotor with a low disk loading for efficient hover capability. However, such a large rotor and the relatively low engine power to weight results in a more modest cruise velocity under 100 knots. The reciprocating (Otto cycle) engine has rather low engine power to weight, it is significantly larger and heavier than an equivalent-power gas turbine. However reciprocating engines have a fuel efficiency advantage over gas turbines that increases as engine size decreases.

Multi-mission: The multi-mission vehicle is roughly double the DGW of the light utility, but engine power is increased by a factor of four. Increased power results in additional speed capability, as well as maintaining additional payload and operability for high altitude or hot day (high / hot). Since it only requires one crew member (pilot), this class can carry up to five passengers. One important version of this vehicle class is the air ambulance: achieved by adding critical medical gear while reducing maximum passenger load. Other versions are effectively used to ferry important personnel to/from offshore platforms, or other important missions where speed or access are best served by this competent vehicle. Propulsion power increase is enabled by a change from reciprocating piston to gas turbine engine, which results in engine weight equal to only 5.6% of DGW. But the gas turbine's fuel efficiency is much worse, requiring 16% of vehicle DGW to be fuel (twice the percentage of the light utility, with similar range).

Medium utility: The medium utility vehicle is substantially larger than the multi-mission, with some of that increase used to augment number of passengers and their comfort, cargo capacity, speed, range, and improved high / hot capabilities. With increased vehicle size, number of passenger, and amenities, crew size grows from one to two or three (one or two pilots + assistant). Additional systems are also included for passenger safety and comfort, as well as operation in less than optimum flight conditions (instrument-only flying capability, cockpit automation, anti-icing, etc.). Twin gas turbine engines are used meet power needs and provide some propulsion redundancy, as opposed to a single, larger engine that should have improved fuel efficiency and weight. These latter capabilities and design choices can be critical when this vehicle is used for search and rescue (SAR) or humanitarian missions which often are most needed during less than optimum flying conditions. Such improved operational capabilities are part of a complex design trade with payload, speed and range.

Table 1. Vehicle Concept Specifications.

Vehicle class (approximate example) → Parameter ↓	Light utility (Sikorsky S-300C)	Multi-mission (Bell 206L4)	Medium utility (Airbus Helicopters EC175)
Design gross weight (DGW), lb. (kg)	2,050 (932)	4,550 (2,068)	16,000 (7,273)
Empty weight, lb. (kg)	1,100 (500)	2,447 (1,112)	10,100 (4,591)
Nominal fuel weight, lb. (kg), % DGW *	160 (73), 8%	737 (335), 16%	2,143 (974), 13%
Sea level maximum power, hp (kW)	190 (142)	750 (560)	2 x 1,600 (2 x 1,193)
Engine type	Reciprocating (Otto cycle)	Gas turbine	Gas turbine
Engine weight (each), lb. (kg), % DGW	267 (121), 13%	255 (116), 5.6%	430 (195), 5.4%
Engine power / weight, hp/lb. (kW/kg)	0.71 (1.2)	2.94 (4.8)	3.72 (6.1)
Engine volume (each), ft^3, (l)	14.1 (401)	13.0 (369)	14.2 (402)
Sea level PSFC, lb./hp-h (kg/kw-h)	0.500 (0.305)	0.689 (0.420)	0.454 (0.277)
Power / DGW, hp/lb. (kW/kg)	0.09 (0.15)	0.165 (0.27)	0.20 (0.33)
Cruise velocity, knots (km/h) *	95 (176)	120 (222)	130 (241)
Range, nmi (km) *	200 (370)	220 (407)	340 (630)
# crew (C) + passengers (P)	1 C + 1 or 2 P	1 C + 5 P	3C + 10P + 1000 lb. (450 kg)

* *from mission analyses*

Figure 1. Representative Vehicle Examples: (clockwise from top left) Sikorsky S-300C, Bell Model 206L4, Airbus Helicopters EC175

Future Propulsion concepts

Electric Motors: There is substantial interest in more and all-electric systems for a new generation of aviation propulsion systems. Impressive levels of electric motor and generator power-to-weight, efficiency and reliability are being demonstrated in hybrid cars, with concurrent efforts developing and testing various architectures for aircraft. Additional advantages are that high efficiency and power-to-weight are maintained with scale, with high efficiency maintained at part power operation. These attributes enable innovative designs to further improve redundancy, safety, and overall vehicle capability and flexibility. Reference 5 discusses recent efforts trying to quantify various technology approaches to realize significant weight and efficiency improvements for non-cryogenic hybrid electric propulsion components. As shown in Table 2, material and design improvements reduce losses by a factor of five. Thermal management is an important design factor, as this is low-grade heat. Present electrical systems include insulating materials limited to about 220°F (105°C). Future materials could raise this limit to 465°F (240°C), roughly tripling the temperature difference between these devices and ambient conditions. However, electrical resistance also increases with operating temperatures for present systems and materials, increasing losses and heat generation. An overall design optimization would be required to trade operating temperatures, size, weight and effectiveness for the electric motor and controller versus its thermal management system.

Table 2. Electric motor parameters (from Reference 5)

Technology year	Power/weight, hp/lb. (kW/kg)	EM eff.	Controller eff.	Net eff.
State of the art	1.9 (3.1)	90%	94%	85%
15 year	3.4 (5.6)	95%	98%	93%
30 year	4.9 (9.7)	98%	99%	97%

Power-to-weight includes electric motor + controller
EM = electric motor
eff. = efficiency

Engine / Energy Storage: Even with high efficiency, such systems are presently limited by the low energy to weight for present battery, capacitors, or other energy storage systems. This can be illustrated by comparison with present systems in Table 3. Hydrocarbon-fueled systems are substantially less efficient than electrical systems, but the high energy density of hydrocarbon fuels enables fueled systems to have significantly better net energy density than 30 year projections for batteries. As noted in reference 4, 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. Present, certified aviation diesel engines have lower power-to-weight than existing helicopter engines, adversely impacting engine and overall vehicle weight, and diminishing fuel burn benefits.

Range Extender: A possible design option with an all-electric propulsion system is using a range extender; a fueled device to produce electrical power for electrical systems, which can mitigate deficiencies in other energy storage technologies. It is generally optimized for maximum efficiency at a fixed operating point to extend vehicle range and endurance. Adding a range extender to an all-electric vehicle (without removing other energy storage devices) removes some payload capability and produces emissions during its operation, but can extend mission range and duration. Thus using a range extender enables some capability to perform a niche mission, without compromising vehicle / mission capability for the majority of its operating missions. Range extenders are generally most effective for long range / duration missions requiring significantly less than 50% available power. Low cruise power is important because the range extender should not have to be sized at power levels similar to the main propulsion system, as one is effectively doubling propulsion weight and size. For range extender performance and weight, performance buildup methodology is similar to reference 4 combining engine, motor, and controller characteristics into an overall power-to-weight and efficiency for each particular range extender system. Table 4 illustrates diesel and gas turbine-powered system and fuel weights for a system generating 100 hp (74.6 kW) electrical power output for 1 hour, with equivalent lithium ion batteries values assuming active mass only. As can be seen, significant weight reductions can be realized using a range extender versus 15 year lithium battery. Thirty year lithium battery values are comparable to advanced diesel, where hardware weight is higher because of the relatively low power to weight for the diesel engine. The gas turbine range extenders are the best performers, supported by high power-to-weight and tolerable efficiency. Such gas turbine performance is probably reasonable for larger systems (> 500 hp / 373 kW), but may be too optimistic for smaller systems, such as the light utility vehicle or smaller systems. For these small, gas turbine systems, power-to-weight and fuel efficiency would be comparable or worse than diesel and will not be considered.

Table 3. Example engine / energy storage characteristics

Engine type	Power / weight, hp/lb. (kW/kg)	Eff., %	Fuel, energy density, MJ/kg	Net energy density, MJ/kg
Reciprocating Otto Cycle	0.71 (1.2)	27	Gasoline, 43.5	11.7
gas turbine (750hp)	2.94 (4.8)	20	Jet-A, 42.8	8.6
gas turbine (1,600hp)	3.72 (6.1)	30	Jet-A, 42.8	12.8
battery 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 (9.7)	97	3.15	3.06
Diesel cycle, SOA Advanced	0.53 (0.9) 1.06 (1.8)	37	Diesel, 43.0	15.9

Lithium battery are average of lithium ion and sulfur, cell only
Eff. = efficiency
SOA – state of the art

Table 4. Example Range Extender performance

Engine type	Hardware weight, lb. (kg)	Fuel weight, lb. (kg)	Total weight, lb. (kg)
Advanced diesel 15 year	127 (58)	41 (18)	167 (76)
30 year	114 (52)	39 (18)	153 (70)
gas turbine 15 year	51 (23)	49 (22)	99 (45)
30 year	41 (19)	47 (21)	88 (40)
Lithium 15 year	-	337 (153)	337 (153)
30 year		188 (85)	188 (85)
100 hp (74.6 kW) output electrical power for 1 hour Diesel 1.1 hp/lb. (1.8 kW/kg), 0.377 lb./hp-h (0.23 kg/kw-h) Gas Turbine 5.0 hp/lb. (8.2 kW/kg), 0.454 lb./hp-h (0.277 kg/kw-h)			

Analysis Methodology

There were three goals for this analysis: 1) Develop electric propulsion system models and compare the payload and range for relevant vehicles and missions using electric propulsion systems versus their baseline capability. 2) Quantify thermal management requirements for electric motor and controller heat production and required cooling airflow levels over the mission profile. 3) Compare range extender fixed and fuel weights versus battery for 100 nautical mile range. After developing and analyzing the baseline vehicles and missions, effort turned to modeling electric systems. Modeling the vehicles with electrical systems might be considered a retrofit, replacing the engine, fuel and their related systems with the electrical system equivalents. No redesign for the remainder of vehicle components, including rotor, gearbox or drivetrain was performed. Vehicle battery energy capacity was sized by weight, such that the all-electric vehicle's empty weight (which included battery and ancillary battery weight, such as the battery management system) was equal to the sum of the baseline's empty weight plus its nominal fuel load. That all-electric configuration was analyzed with the same payload as the nominal baseline case to determine its mission range. If the all-electric configuration could not achieve 100 nautical mile range, add battery capacity (and weight) while reducing payload as necessary to not exceed DGW until the vehicle achieves 100 nautical mile range or determine vehicle range at DGW and no payload. The choice of 100 nautical mile range is arbitrary, but felt to be a reasonable value for an actual vehicle with no tailpipe emissions. Representative mission results were chosen to estimate thermal loads and equivalent airflow rates for cooling. Finally, the feasibility for using a range extender was explored.

Analysis Tools and Baseline Models: For such preliminary propulsion analyses, simpler methods could have been used to estimate sizing efforts among the various propulsion and energy storage choices. However, since the eventual goal is to develop comprehensive propulsion and power system models to capture component performance interaction, the design code NASA Design and Analysis of Rotorcraft (NDARC)[6-9] was used to study the sizing and performance effects among the various future electric propulsion technology levels. As described in reference 9, NDARC's propulsion models were expanded to include additional propulsion and power system concepts, including those necessary for electric propulsion components. The vehicle and mission models were developed from the single-main rotor helicopter examples distributed with NDARC v1.9, modifying various component performance models based on openly available brochures and technical specifications for the chosen vehicles and their actual engine systems to better approximate their performance. Vehicle design and performance values listed here are from the revised NDARC models and should approximate the actual vehicle performance.

Mission Profile: A typical, simple helicopter mission profile shown in Figure 2 was used to determine nominal fuel load and range for each vehicle. Cruise altitude was set to 6,000 ft ISA for multi-mission and medium utility vehicles' nominal mission calculations because of their greater speed and capability. For all cases, no wind was assumed.

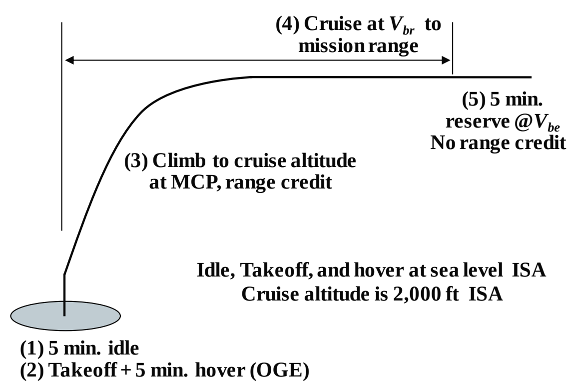

Figure 2. Simple helicopter mission profile

For the range versus payload analyses, the simple helicopter mission profile was used for the light utility class. A more stringent mission profile was selected for the multi-mission and medium utility vehicles that would be more representative of their required capability and is shown in Figure 3. Hover out of ground effect (OGE) requirements are at 4,000 ft, 95°F, with an initial climb and a high-speed dash at maximum obtainable speed for the first 25 nautical miles of mission range. The rest of mission range is determined at best range speed. Best range speed is about 15% slower than maximum obtainable speed, but specific range is about 20% better. Both mission profiles include a five minute reserve segment at best endurance speed, although no credit is given to mission range.

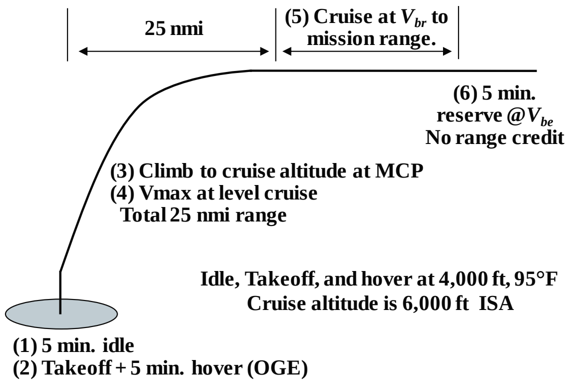

Figure 3. Range / payload mission profile for multi-mission and medium utility vehicles

Propulsion Modeling: For this preliminary effort, fairly 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 5 and are listed in Tables 2 and 3. Since electric motor power does not lapse with hot day or increased altitude, the all-electric vehicle electric motor may be sized to a different maximum power level than the baseline vehicle to meet mission requirements. Details concerning electric motor sizing will be discussed with results for each particular vehicle in the Results and Discussion 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 PMAD, with losses assumed included within the electric motor and controller losses. To assess viability of range extenders, values from Table 4 are used. Range extender hardware weight scales directly with cruise power; fuel weight scales directly with cruise power and inversely with cruise velocity (because fuel weight was determined for a given time).

Thermal Load: Electric propulsion thermal load was estimated by multiplying total propulsion power for each mission segment from the NDARC output by electric motor and controller losses, as given in Table 2. As mentioned previously, PMAD losses and thermal load are assumed to be captured within electric motor and controller losses for this analysis. Any battery losses and thermal load were not estimated. Instead, a penalty for the battery management system equal to 20% of battery weight was assumed. To estimate cooling airflow rates required, cooling airflow exhaust temperature was assumed to be 80% of the temperature difference between ambient conditions and motor / controller maximum temperature capability; assuming 220°F (105°C) and also 465°F (240°C) for 30 year technology.

Results and Discussion

The overall payload and range results are shown in Figure 4. For each vehicle, the nominal performance (for the simple helicopter mission) for each baseline vehicle is shown as a single point, with the 15 year electric version as a dashed line, and 30 year as a solid line. The baseline multi-mission vehicle suffered significant high / hot payload and range capability losses when flown over its payload / range mission and that performance is therefore shown as well (dotted line). The medium utility does not suffer this capability reduction for high / hot operations because of high engine power to design gross weight (DGW). As vehicle size and capability increase, so does the reduction in payload and range from baseline to 30 year to 15 year technology, as well as the rate of decline in payload versus range trend line. Thirty year results were encouraging; all vehicles were able to achieve the 100 nautical mile range with significant fractions of their baseline payloads, especially the light utility class. Fifteen year battery energy density resulted in significantly reduced vehicle performance, only the light utility retained a reasonable payload while achieving the 100 nautical mile range. Additional results and discussion are included for each vehicle.

Light utility: For the light utility vehicle, electric motor power was maintained equal to the original reciprocating, gasoline engine, to meet the sea level hover OGE capability. The electric motor and controller are significantly lighter than the original reciprocating engine, freeing up weight for battery energy storage. Engine weight gains and modest power requirements enable this vehicle to have the best payload / range performance with all-electric propulsion. Thermal load calculations were performed for 15 and 30 year technology at maximum take-off gross weight (TOGW) over the simple helicopter mission; results are shown in Table 5. Cooling airflow is roughly an order of magnitude less than the engine airflow from the original baseline, with hover OGE setting the maximum requirement for cooling. Thirty year electric motor and power electronics technology gains reduce losses and heat by just over half from 15 year technologies. Cooling airflow rate can be reduced another 60% if higher temperature motors and electronics can be achieved to improve waste heat quality (assuming no accompanying increase in losses). As previously mentioned, gas turbine range extender performance would not be applicable at this scale; just diesel range extenders are considered; range extender results are in Table 6. The initial weight of the diesel engine is significant, but its fuel efficiency and high fuel energy density can enable important capability and flexibility. Adding the range extender would utilize a significant portion of the vehicle's payload capability for the extended range mission, without removal of some nominal battery weight. The diesel's gain is reduced for 30 year technology; however, an additional 100 nautical mile of range would require an additional 269 pounds (122 kg) of batteries, while the range extender would only need an additional 56 pounds (25 kg) of fuel.

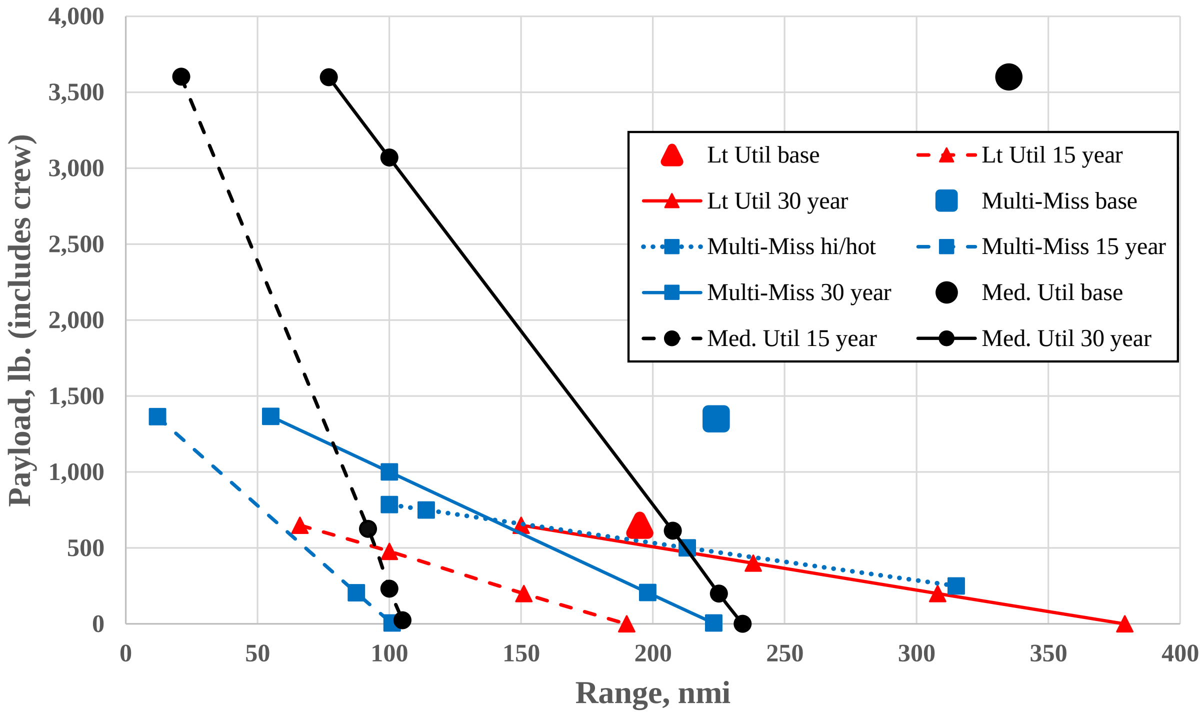

Figure 4. Range / payload mission results

Table 5. Light Utility thermal load

Mission segment → Vehicle, parameter ↓	1 idle	2 hover OGE	3 climb	4 cruise	5 endurance
Electric: 15 year technology					
Power, hp (kW)	61.1 (45.6)	196.5 (146.5)	172 (128.3)	136.2 (101.6)	101.3 (75.5)
Thermal load, hp (kW)	4.3 (3.2)	13.8 (10.3)	12.0 (9.0)	9.5 (7.1)	7.1 (5.3)
Cooling airflow, ft^3/min. (l/s)	76.1 (35.9)	245 (116)	210 (99)	172 (81)	126 (60)
Electric: 30 year technology					
Power, hp (kW)	61.1 (45.6)	196.5 (146.5)	172 (128.3)	136.4 (101.7)	101.3 (75.5)
Thermal load, hp (kW)	1.8 (1.4)	5.9 (4.4)	5.2 (3.8)	4.1 (3.1)	3.0 (2.3)
Cooling airflow (lo T), ft^3/min. (l/s)	32.6 (15.4)	105 (50)	89.9 (42.4)	74.0 (34.9)	54.1 (25.5)
Cooling airflow (hi T), ft^3/min. (l/s)	13.0 (6.1)	41.7 (19.7)	36.2 (17.1)	30.2 (14.2)	21.5 (10.1)

Table 6. Light Utility range extender (100 nmi)

Technology level ↓	Hardware weight, lb. (kg)	Fuel, lb. (kg)	Total, weight, lb. (kg)
15 year diesel	173 (79)	58 (26)	231 (105)
battery	-	483 (220)	483 (220)
30 year diesel	155 (71)	56 (25)	211 (96)
battery	-	269 (122)	269 (122)

Multi-mission: As opposed to the light utility, the multi-mission vehicle uses a gas turbine for main propulsion, with substantially better engine power to weight than reciprocating engines. Replacing the gas turbine engine with an electric motor realizes little or no engine weight reduction that can be used for additional battery weight. The baseline vehicle's nominal fuel load is only 16% of its DGW, enabled by the high fuel energy density. Therefore its payload and range are negatively impacted by the significantly lower battery energy density, as was shown in Figure 4. The baseline vehicle has significant range and payload capability for the simple, nominal mission (Figure 2). Over its range / payload mission (Figure 3) the take-off gross weight is limited by the 4,000 ft, 95°F (high / hot) hover OGE requirement, but it still has some payload and range capability to be traded between payload and fuel. The same sea level power (750 hp / 560 kW) is assumed for the all-electric versions, giving them superior capability for high / hot hover OGE at DGW. With 30 year technology, the all-electric vehicle can deliver 1,001 pounds (455 kg) of pilot and payload, 100 nautical miles, which is actually more than the baseline for the high / hot mission. Vehicle power and thermal load calculations are given in Table 7 for the 100 nautical mile range vehicles at DGW. Hover OGE sets the maximum cooling requirements, although climb cooling requirements are similar. This suggests that high / hot operations are not limited by cooling. Cooling airflow is roughly 5 times less than the engine airflow from the original baseline. Other trends are similar to those for the light utility for the effects of 15 and 30 year technologies. Using vehicle cruise power levels from Table 7, a gas turbine range extender should be a viable option. Range extender results for the multi-mission vehicle are in Table 8. The gas turbine range extender is substantially lighter than the diesel or battery options for both 15 and 30 year technology levels, stemming from the gas turbine's high power to weight. The gas generator does use 20% more fuel than the diesel engine, but it would require about 1,000 nautical miles for total of hardware and fuel to be equal between gas turbine and diesel. The gas turbine range extender would significantly improve payload and range for the 15 year technology case and be effective to increase range without exhausting all payload capability for the 30 year technology case.

Table 7. Multi-Mission thermal load

Mission segment → Vehicle, parameter ↓	1 idle	2 hover OGE	3 climb	4 Vmax cruise	5 Best range cruise	6 endurance
Electric: 15 year technology						
Power, hp (kW)	132.5 (98.8)	730 (544)	714 (532)	713 (532)	499 (372)	366 (273)
Thermal load, hp (kW)	9.3 (6.9)	51.1 (38.1)	50.0 (37.3)	49.9 (37.2)	34.9 (26.0)	25.6 (19.1)
Cooling airflow, ft^3/min. (l/s)	262 (124)	1,445 (682)	1,414 (667)	940 (444)	657 (310)	456 (215)
Electric: 30 year technology						
Power, hp (kW)	132.5 (98.8)	730 (544)	714 (532)	713 (532)	499 (372)	366 (273)
Thermal load, hp (kW)	4.0 (3.0)	21.9 (16.3)	21.4 (16.0)	21.4 (16.0)	14.9 (11.1)	11.0 (8.2)
Cooling airflow (lo T), ft^3/min. (l/s)	112.5 (53.1)	619 (292)	606 (286)	403 (190)	281 (133)	195 (92)
Cooling airflow (hi T), ft^3/min. (l/s)	38.2 (18.0)	210 (99)	206 (97)	172 (81)	120 (57)	77.5 (36.6)

Table 8. Multi-Mission range extender (100 nmi)

Technology level ↓	Hardware weight, lb. (kg)	Fuel, lb. (kg)	Total, weight, lb. (kg)
15 year diesel	634 (288)	167 (76)	801 (364)
gas turbine	253 (116)	201 (91)	454 (207)
battery	-	1,393 (633)	1,393 (633)
30 year diesel	571 (259)	160 (73)	731 (332)
gas turbine	206 (93)	193 (88)	399 (181)
battery	-	775 (352)	775 (352)

Medium utility: The medium utility vehicle also uses gas turbine engines, which in their larger size, have even better power to weight and efficiency than the multi-mission's engine. Combining the capable engines with high fuel energy density gives this vehicle impressive capabilities (including high / hot operation). Electric motor size was determined by matching the 4,000 ft, 95°F hover OGE capability for the baseline's two 1,600 hp (1,193 kW) gas turbines with two 1,200 hp (895 kW) electric motors. The reduction in energy density for 15 year technology resulted in a non-viable vehicle, as shown in Figure 4. Thirty year technology enables significant payload at 100 nautical mile range, but payload drops quickly as range increases. Energy storage technology would have to at least double the 30 year technology goal to regain similar payload / range as the baseline. Vehicle power and thermal load calculations are given in Table 9 for the 100 nautical mile range vehicles at DGW. The all-electric vehicles size engine power to meet hover OGE capability and operate at similar, high power levels for climb, the latter defines the maximum cooling requirements. Other trends are similar to those previously discussed for the other vehicles.

Table 9. Medium Utility thermal load

Mission segment → Vehicle, parameter ↓	1 idle	2 hover OGE	3 climb	4 Vmax cruise	5 Best range cruise	6 endurance
Electric: 15 year technology						
Power, hp (kW)	356 (265)	2,098 (1,565)	2,284 (1,703)	2,280 (1,700)	1,393 (1,039)	1,058 (789)
Thermal load, hp (kW)	24.9 (18.6)	147 (110)	160 (119)	160 (119)	97.5 (72.7)	74.0 (55.2)
Cooling airflow, ft^3/min. (l/s)	704 (332)	4,155 (1,961)	4,523 (2,135)	3,005 (1,418)	1,582 (747)	1,317 (622)
Electric: 30 year technology						
Power, hp (kW)	356 (265)	2,098 (1,565)	2,284 (1,703)	2,280 (1,700)	1,394 (1,040)	1,058 (789)
Thermal load, hp (kW)	10.7 (8.0)	62.9 (46.9)	68.5 (51.1)	68.4 (51.0)	41.8 (31.2)	31.7 (23.6)
Cooling airflow (lo T), ft^3/min. (l/s)	302 (142)	1,781 (840)	1,939 (915)	1,288 (608)	787 (372)	564 (266)
Cooling airflow (hi T), ft^3/min. (l/s)	102 (48.3)	604 (285)	658 (310)	550 (260)	336 (159)	224 (106)

Range extender results for the multi-mission vehicle are shown in Table 10 using vehicle cruise power levels from Table 9. The gas turbine range extenders are substantially lighter than the diesel or battery options for both 15 and 30 year technology levels. The gas turbine range extender would significantly improve payload and range for the 15 year technology case especially, if some nominal battery weight could be removed. It would also be effective to increase range for the 30 year technology case. Other trends are similar to those previously discussed for the multi-mission vehicle.

Table 10. Medium Utility range extender (100 nmi)

Technology level ↓	Hardware weight, lb. (kg)	Fuel, lb. (kg)	Total, weight, lb. (kg)
15 year diesel gas turbine battery	1775 (807) 709 (322) -	469 (213) 564 (256) 3,905 (1775)	2,244 (1,020) 1,273 (579) 3,905 (1775)
30 year diesel gas turbine battery	1599 (727) 576 (262) -	450 (205) 541 (246) 2,169 (986)	2,049 (931) 1,118 (508) 2,169 (986)

Conclusions

Propulsion options and technologies were reviewed, models developed, and vehicle sizing and mission analysis performed to assess the potential capabilities and estimate ancillary requirements for replacing traditional propulsion options with more and all-electric propulsion systems. Electric motor power is unaffected by altitude or hot days (if not limited by thermal management considerations), which can enable unique capabilities during operation. The range of single-main rotor helicopter vehicles studied ranged from a Spartan light utility (1-3 person capacity) to a highly capable, ten passenger [total of 3,000 pound (1,364 kg) payload], medium utility class. Electric motor, power electronic and battery energy storage for 15 and 30 year technology projections were used. Payload and range capability for all-electric vehicles are presently limited by the relatively low energy density for battery or other systems, versus over an order of magnitude greater energy density for hydrocarbon fuels. As vehicle size and capability grow, relative energy requirements also increase, resulting in further energy capacity shortfalls for all-electric systems. Only the light utility vehicle retained significant payload capability at 100 nautical mile range assuming 15 year technology. Thirty year technology battery energy storage projections are sufficient to obtain similar performance to the baseline for the light utility. But results for the other classes suggest a further doubling of energy density (at least by weight) is required to approximate original vehicle payload and range capabilities. The high efficiency projected for future electrical systems suggest that their airflow requirements for cooling will be five to ten times less than the airflow rates that air-breathing systems require for reacting with fuel, even considering the low exhaust heat quality for electrical systems. Hydrocarbon-fueled range extenders can be prudently used to recover range and payload lost due to battery energy density limitations; the largest improvements realized for larger systems that can effectively utilize the combined relatively high efficiency and power to weight for a gas turbine engine combined with a high energy density fuel. To enable more and all-electric systems, work must continue to achieve performance levels suggested from previous technology assessment efforts, as well as identify vehicles, missions and systems that are best suited to take advantage of their unique characteristics.

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