Using Liquid Natural Gas Fuel to Cryogenically Cool and Enhance a Hybrid Electric Aircraft Power System

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ABSTRACT

A previous system study identified significant increases in range and number of urban air mobility (UAM) missions by replacing the all battery power system of a notional UAM vehicle with an advanced diesel hybrid using conventional diesel or liquid natural gas (LNG) fuels (at constant vehicle design gross weight). Some benefits were realized using the LNG's cryogenic properties to reduce some electrical component losses and cooling requirements. Significant questions were raised concerning volume and thermal management considerations for all studied systems. The notional, baseline vehicle was a hybrid helicopter / airplane design capable of vertical take-off and landing (VTOL), balancing high cruise efficiency with reasonable hover capability. A subsequent power system assessment using the same notional vehicle and mission was performed that identified increased volume and power requirements for the active cooling required. The cooling airflow could also generate additional drag on the vehicle during operation. For the notional vehicle studied, the additional volume identified by the subsequent study would not affect vehicle mold line and therefore drag. However, the additional drag from cooling airflow and the power to circulate it as needed would impact power system and vehicle mission performance. Vehicle and mission models were updated and rerun. Updated results still indicated significant benefits in range and number of UAM missions, but reduced the benefit by 12-15%. Hold time for the hybrid systems also generally increased a few minutes because of reduced power available for charging from the power for required cooling flows. Vehicle weights, thermal loads, and cooling airflows from the updated analyses were similar to previous results.

NOTATION

BMS	=	battery management system
DGW	=	design gross weight
genset	=	fueled engine + generator
ISA	=	international standard atmosphere
L	=	liter
LNG	=	liquid natural gas
NDARC	=	NASA Design and Analysis of Rotorcraft
nmi	=	nautical mile
OGE	=	out of ground effect
UAM	=	urban air mobility
VTOL	=	vertical take-off 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 urban air mobility (UAM). 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. Previous system studies (References 1 & 2) discussed battery versus hybrid, including cryogenic liquid natural gas (LNG). These studies identified substantial range and number of UAM missions performed before recharge / refuel, but also found limitations in the present models that failed to capture potentially important design and performance effects. Therefore, this follow-on study was performed to assess power system volume and thermal management considerations to see the effect on vehicle mission performance estimates.

VEHICLE / MISSION

The notional, baseline vehicle for this study is a hybrid helicopter / airplane design capable of VTOL operations, balancing high cruise efficiency with reasonable hover capability. Figure 1 shows a representative image. Such a design is enabled by advances in distributed electric propulsion technologies. Baseline propulsion and power

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systems are battery, all-electric (assuming, 15 year technologies). Payload capability was selected as one or two passengers (450 lb. or 205 kg maximum total payload) with a 200 pound (91 kg) pilot. Additional background and information can be found in Reference 1.

Figure 1. Notional VTOL vehicle image.

Figure 2 shows a notional layout including some of the major systems to better understand packaging aspects. Since it is believed that active thermal management would likely be required, the battery packs and most power electronics were placed in the main body of the aircraft. This could make battery replacement easier, as well as facilitate design and substitution of the all-battery system with a hybrid system using genset (fueled engine + generator) using energy-dense hydrocarbon fuels. This would also facilitate employing more-highly integrated cryogenic cooled systems that offer other benefits. The added weight of the hybrid system could be offset by reducing the battery size and capability.

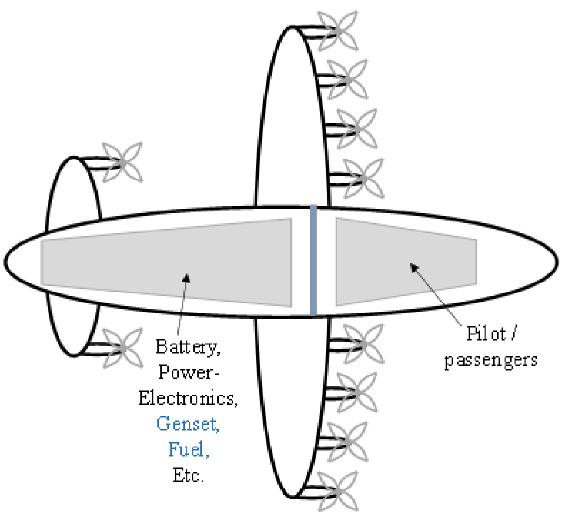

Figure 2. Notional VTOL vehicle layout.

Figure 3 shows the simple mission profile used to size the baseline all-electric, battery aircraft with range set to 150 nautical miles, flying at best range velocity V_{br}. To simulate shorter UAM operations, we assumed repeated mission profiles flying V_{br} at 20 or 50 nautical mile range, which would minimize total energy used.

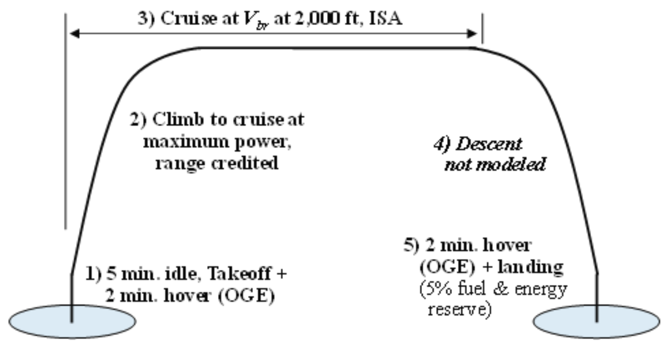

Figure 3. Mission Profile for sizing, maximum range or UAM missions.

PROPULSION AND ENERGY CONCEPTS

Propulsion and energy characteristics used to develop the vehicle characteristics reported here are shown in Table 1, further details can be found in References 1 and 4. Performance levels believed achievable in 15 years were used for this effort. Impressive improvements in electric motor efficiency and power to weight offer an opportunity for new and more capable aviation vehicles. However, widespread adoption of all electric systems is still hampered by the much lower electrical energy density for batteries versus hydrocarbon fuels. This is true even when including the much lower efficiencies of the heat engines employing hydrocarbon fuels.

Table 1. Motive engine and energy storage characteristics (15 year technologies).

Engine type	Power / weight, hp/lb. (kW/kg)	η, %	Fuel energy density, MJ/kg (Wh/kg)	Net energy density, MJ/kg (Wh/kg)
all-electric, battery*	3.4 (5.6)	93	1.75 (486)	1.63 (450)
Diesel cycle	1.06 (1.8)	37	Diesel,43.0 (12,000)	15.9 (4,400)
			LNG, 48.6 (13,500)	18.0 (5,000)

* "Fuel" is lithium battery, cell only average of lithium ion and sulfur technologies. Electric system power to weight for electric motor reported at 8 hp/lb. and power electronics at 6 hp/lb., from Reference 4.

Baseline Propulsion Concept

The baseline vehicle is assumed to be battery, all-electric and its propulsion and power system can be represented by a fairly simple block diagram as shown in Figure 4. Baseline, all-electric, battery propulsion architecture block diagram.. For this further concept assessment, only thermal management for the battery and power electronics were considered, as the electric motors would be mechanically coupled to the rotors and assumed to already have viable cooling systems, with losses, cooling drags and weight included in the electric motor / rotor efficiency and power-to-weight values.

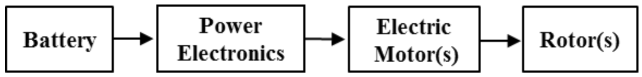

Figure 4. Baseline, all-electric, battery propulsion architecture block diagram.

Advanced Diesel Hybrid Propulsion Concept

The block diagram for the hybrid-electric propulsion and power systems is not much more complicated than the baseline and is shown in Figure 5. The fueled genset can augment battery power for vehicle operations and also be used to recharge the battery, which can affect UAM electric logistic requirements. Thermal management considerations for the electric motors is the same as for the baseline. Thermal management for the conventionally-cooled system includes the fueled genset, vehicle power electronics and the battery.

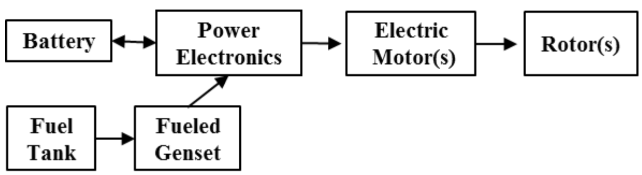

Figure 5. Advanced diesel, series hybrid propulsion architecture block diagram.

Advanced Diesel Hybrid with LNG Cryo-Cooling Assist

Using LNG to cryogenically cool components can be advantageous depending on the vehicle and its propulsion and power system arrangement. The cryogenic LNG is used for the thermal management of the co-located power electronics and genset generator, with the potential to realize electric system performance and weight improvements; while also reducing or eliminating some component cooling airflows. The LNG fuel still has some residual cooling capacity after cooling the genset generator and aircraft power electronics, but was not considered here to reduce other genset cooling requirements. Additional improvements are realized for the overall system from the higher heating value (per fuel weight) of the LNG and slightly greater genset output power for a given fueled engine size (the result from less electric component losses). Offsetting some of these benefits is the LNG tank volume and weight. The LNG fuel density is lower than typical hydrocarbon fuels and is a cryogenic, requiring an insulated tank. To better understand the potential of the LNG hybrid system, a new tool to analyze an integrated propulsion and power system using LNG was developed and is reported in Reference 3. Results from that tool are used to inform this study.

ANALYSIS METHODS

The design code NASA Design and Analysis of Rotorcraft (NDARC, References 5-8) was used to model the various vehicle and propulsion systems, performing vehicle sizing and performance analysis. As described in Reference 8, 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 tilt rotor example distributed with NDARC v1.10. The preliminary models and design methodologies were discussed in greater detail in Reference 1. The models were subsequently updated to account for packaging and thermal management considerations, which are discussed next.

POWER SYSTEM VOLUMES AND MODELING UPDATES

A volumetric larger power system due to components or airflow requirements could have significant effects on vehicle size and mission performance. The significantly larger cooling requirements and additional components for the hybrid systems prompted this subsequent effort. The notional vehicle potentially includes significant volume for the various power system concepts. Based on assumed overall fuselage length, and maximum height and width, internal volume could range from approximately 100-300 ft^3 (2830-8500 L), with potentially about half for the power system. The methodology to estimate airflow cooling flow levels is discussed in Reference 1. To estimate ducting volume, an arbitrary flow velocity of 44 ft./s (13.4 m/s) was chosen to get a flow cross-sectional area and assumed length equal to 3/8 of total fuselage length. Actual thermal loads and airflow rates are given in a later section. Volume estimation methodologies for the various components are discussed next.

Battery and Power Electronics

The baseline power system is all battery, assuming a maximum, C=3 1/hr discharge rate. As sized for the 150 nautical mile range mission, the all-battery concept is only drawing at C=2.2 1/hr during the short-duration high power, takeoff / landing hover and climb mission segments. For the rest of the mission, power draw is less than C=1 1/hr and heat loads are significantly less. Therefore, the same 1.0 kg/L density as suggested in References 9 and 10 for the battery pack [battery and battery management system (BMS)] and an estimated 0.25 kg/L for power electronics (weight based on 20 kW/kg (12 hp/lb.) were used. These relationships were used for the hybrid systems, updating for differences in battery size and for LNG cryo-cooling assist as discussed next.

Conventionally Cooled Diesel Hybrid

The conventionally-cooled hybrid power system uses an energy-dense hydrocarbon fuel and genset to produce the electric power to assist the battery for vehicle operation and battery recharge. The diesel cycle is fairly efficient (for a fueled system), but is heavy and generates significant waste heat that must be actively removed in this installation. As opposed to engine installation directly behind a propulsive fan or rotor, the hybrid is envisioned as a shared or auxiliary system and does not have ready access to cooling airflow. Non-trivial radiator and associated airflow ducting are required.

To quantify the various hybrid system components, the following values were used. Diesel engine volume was estimated at 25 hp/ft3 (0.66 kW/L) from diesel engine data on present and future systems. Diesel fuel density is 7 lb./gal (0.839 kg/L), and negligible additional tank volume assumed. The genset generator was a fixed size (200 hp / 150 kW) for this study; various commercial models were reviewed. For mid-rpm generators, a reasonable volume of 28 L (1 ft^3) was selected. A similar volume was assumed for its controller. The diesel radiator sizing was based on reference 11, with its volume included within the airflow ducting volume.

LNG Cryo-Cooling Assist Hybrid

The LNG cryo-cooling assist hybrid system uses a cryogenic fuel and integrates fuel tank thermal management with some of the hybrid system components to realize some system volume and efficiency benefits. The efficiency benefits are modeled as greatly reduced genset generator and aircraft power electronics losses (with the thermal energy captured in the fuel, not removed via airflow cooling). Information from Reference 3 was used to guide performance assumptions. Estimated benefit ranges from 50-75% reduction in genset generator controller and aircraft power electronics volume; 50% is used in this study. However, the cryogenic LNG fuel tank size is larger than an equal mass of diesel fuel due to insulation and thermal / pressure stabilization. The cryogenic tank has 2 inch (5cm) thick foam insulation and maximum fill is only 90%. Therefore fuel and tank density (based on fuel only) is 2.2 lb./gal (0.26 kg/L) versus LNG's nominal 3.5 lb./gal (0.42 kg/L) density.

Sizing / Volume Results

Table 2 shows the component and overall volumes for the various power system concepts. The hybrid systems are significantly larger than the battery baseline, but should still integrate within their allocated fuselage volume. The additional volume required by the hybrid systems is mainly driven by the ducting and radiators for diesel engine cooling. That requirement is fairly constant across the mission because it is driven by the hybrid genset power level (not vehicle power level). The difference in volume among the battery and hybrid systems would be even more pronounced if the battery baseline ducting could be sized only by cruise. Battery cooling is driven by the relatively short-duration, high power, takeoff / landing hover and optimum climb mission segments. Using cruise to size battery cooling reduces airflow requirements by a factor of eight; but would probably include operational and other penalties to limit battery thermal generation.

Table 2. Power system volumes.

Power system / component	Volume, ft^3 (L)
Battery (baseline)	
Battery & BMS	15 (418)
Power electronics	3 (11)
Airflow ducting*	9 (35)
Total	**27 (464)**
Advanced diesel hybrid	
Battery & BMS	7 (199)
Power electronics	3 (11)
Diesel engine	8 (30)
Fuel tank	4.5 (17)
Genset generator + controller	2 (8)
Airflow ducting	24 (91)
Total	**49 (356)**
LNG cryo-cooling assist hybrid	
Battery & BMS	7 (199)
Power electronics	1.5 (6)
Diesel engine	8 (30)
LNG Fuel tank	14 (53)
Genset generator + controller	1.5 (6)
Airflow ducting	22 (82)
Total	**54 (376)**

Modeling Updates

Based on the volume assessment and thermal load estimates (updated results to be discussed later), the baseline battery power system included a 5 hp (4 kW) load during the short duration, high power mission segments. No drag penalty is included as most airflow-causing drag is during hover or low flight speeds; almost negligible cooling required at cruise. For the conventional cooled hybrid, a 17 hp (13 kW) load was assessed during hybrid genset operation. (That power is sufficient for a 1.1 pressure ratio fan at the required maximum cooling airflow rate.) The genset auxiliary airflow (default is < 1%) is set to the proper ratio to model the appropriate cooling airflow rate and its drag. For the LNG cryo-cool assist hybrid, the load was set to 15 hp (11 kW) and a similar update to the genset auxiliary airflow.

MISSION AND VEHICLE RESULTS

Although the changes seemed fairly small, Table 3 shows their effects are easily seen in mission range and number of UAM missions; previous values are in parentheses. The updates made no noticeable difference to the battery baseline. For the hybrid systems, the additional power required for cooling airflow is the major cause of reduced capabilities and longer hold / recharge times versus pervious results.

Table 3. Maximum range and multiple UAM mission results

Vehicle→	Base line	Conventional hybrid	Cryo-cooling assist hybrid
Maximum range, nmi	150	393 (496)	474 (580)
Multiple UAM missions			
Number of 20 nmi missions	3	6 (7)	7 (8)
Hold time, minutes †	9 ‡	19 (15)	17 (13)
Number of 50 nmi missions	2	4 (4.9)	5 (7)
Hold time, minutes †	13 ‡	21 (15)	17 (12)

Numbers in () are previous answers

† Time on ground between UAM missions to self-recharge battery to full

‡ No self-recharge capability, 2C / 350 kW charger required

Mission Power Levels

Figure 6 shows vehicle power levels (minus that for the cooling airflow) over various mission segments. Results were similar for all power configurations. This was expected as design gross weight (DGW) was maintained across configurations. High climb power minimizes climb segment time and overall mission energy, but limiting climb to 1,000 feet per minute cuts the required power level almost in half with a minimal increase in mission energy. Time to climb would increase from 0.7 to 2 minutes. That could be an important consideration if climb thermal loads limit vehicle operations or defines thermal management system size.

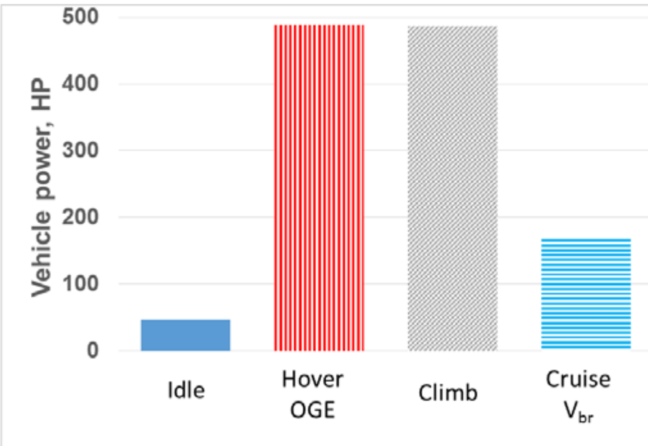

Figure 6. Vehicle mission power levels.

Table 4 gives selected vehicle specifications and did not change significantly from previous efforts (Reference 1). Vehicle DGW and payload were held constant across the different power concepts, with the battery resized based on a maximum C=3 1/hr discharge rate based on genset power available for the hybrid system, to maximize genset fuel capability. This realizes a significant increase in fuel energy and enhanced mission capability; as shown in Table 3 for range and number of missions. The large volume of the LNG tank versus the other power concepts could exclude or severely penalize its use in volume-limited designs.

Table 5 gives thermal load estimates only for the more stringent high / hot (5,000 ft., ISA+20°C) condition and also did not change significantly from previous efforts (Reference 1). The hover and climb segments are the most thermally taxing. The climb is performed here at maximum power, as that is the most efficient and is presently not limited by thermal considerations. As mentioned previously, climb could be performed at lower power levels, but would increase time in climb and slightly increase overall mission energy. Battery cooling requires significantly more airflow for a given thermal load than other components, as the batteries have a significantly lower maximum-use temperature than that assumed for the power electronics or diesel engines.

Three additional observations are worth pointing out concerning the hybrid power systems. One, cooling requirements and airflow are dominated by the diesel engine cooling. A turbocharged diesel was assumed for the genset engine and its power does not lapse with high / hot conditions; it did not operate past its thermal breakpoint. Operation past the thermal breakpoint (higher altitudes or hotter temperatures) would cause the diesel engine and genset output to lapse, changing vehicle mission capability and airflow cooling requirements. Two, battery cooling requirements are similar among the hybrids and the all-battery baseline. The baseline battery is sized for 150 nautical mile range, so its battery pack is only at C=2.2 1/hr discharge during takeoff / landing hover. For the hybrid systems, the battery was sized for maximum C=3 1/hr discharge to minimize battery weight and size. This results in similar battery heat generation for the hybrid vehicles, even though total battery draw is at 40% less power (the remaining hover power required is being supplied by the genset). Three, as noted in blue below, the LNG cryo-cooling assist hybrid thermal loads for power electronics are significantly less than the other concepts, as well as slightly less for the genset. Cryo-cooling realizes higher efficiency for the electrical components (aircraft power electronics, genset generator and its controller). In addition to lower thermal losses, any heat that is produced is put into the fuel, as opposed to requiring cooling airflow. In turn, this slightly reduces the overall required power for cooling air.

Table 4. Selected Vehicle Specifications.

Vehicle → Parameter ↓	Battery Baseline	Conventional cooled hybrid	Cryo-cooling assisted hybrid
Design gross weight (DGW), lb. (kg)	3,681 (1,673)	3,681 (1,673)	3,683 (1,674)
Empty weight, lb. (kg)	3,026 (1,376)	2,816 (1,280)	2,818 (1,281)
Disk loading / wing loading, lb./ft^2	10 / 50	10 / 50	10 / 50
Genset Weight, lb. (kg), % DGW	0	247 (112), 7%	217 (99), 7%
Nominal fuel weight, lb. (kg), % DGW	0	210 (95), 6%	210 (95), 6%
Fuel Energy, MJ	0	4,096	4,629
Fuel + tank volume, gallon, (L)	0	30.7 (116)	96.1 (364)
Battery + BMS weight, lb. (kg), % DGW	921 (419), 25%	437 (199), 12%	437 (199), 12%
Battery energy, MJ	609	290	290
Battery volume, gallon, (L)	80.4 (304)	38.3 (145)	38.3 (145)
Sea level maximum rated power, hp (kW)	578 (431)	578 (431)	578 (431)
Propulsion engines and power electronics weight, lb. (kg), % DGW	311 (141), 8%	311 (141), 8%	311 (141), 8%

Table 5. High /Hot (5,000 ft. ISA+20°C) Thermal Load Estimates

Mission segment →	1) hover (OGE)	2) climb (start)	2) climb (end)	3) cruise
Battery Baseline				
Battery Cooling				
Thermal load, hp (kW)	35 (26)	35 (26)	35 (26)	5 (3)
Cooling airflow, ft^3/min. (l/s)	2668 (1259)	2652 (1252)	2535 (1196)	335(158)
Power electronics				
Thermal load, hp (kW)	10 (7)	10 (7)	10 (7)	4 (3)
Cooling airflow, ft^3/min. (l/s)	325 (153)	324 (153)	328 (155)	119 (56)
Conventionally-cooled hybrid				
Battery Cooling				
Thermal load, hp (kW)	30 (22)	30 (22)	30 (22)	0 (0)
Cooling airflow, ft^3/min. (l/s)	2290 (1081)	2290 (1081)	2290 (1081)	0 (0)
Power electronics				
Thermal load, hp (kW)	10 (7)	10 (7)	10 (7)	4 (3)
Cooling airflow, ft^3/min. (l/s)	325 (153)	325 (153)	325 (153)	121 (57)
Hybrid Genset Cooling				
Thermal load, hp (kW)	118 (88)	118 (88)	118 (88)	118 (88)
Cooling airflow, ft^3/min. (l/s)	3921 (1851)	3921 (1851)	3976 (1877)	3976 (1877)
LNG cryo-cooling assist hybrid				
Battery Cooling				
Thermal load, hp (kW)	29 (21)	30 (22)	30 (22)	0 (0)
Cooling airflow, ft^3/min. (l/s)	2189 (1033)	2253 (1064)	2154 (1017)	10 (5)
Power electronics*				
Thermal load, hp (kW)	2 (2)	2 (2)	2 (2)	1 (1)
Hybrid Genset Cooling				
Thermal load, hp (kW)	110 (82)	110 (82)	110 (82)	110 (82)
Cooling airflow, ft^3/min. (l/s)	3651 (1723)	3651 (1723)	3702 (1748)	3702 (1748)

* Cooling for power electronics by LNG fuel (no additional airflow required)

CONCLUSIONS

A previous system study identified significant increases in range and number of urban air mobility (UAM) missions by replacing the all battery power system of a notional UAM vehicle with an advanced, diesel hybrid using conventional diesel or liquid natural gas (LNG) fuels. Further benefits were realized using the LNG's cryogenic properties to reduce some electrical component losses and cooling requirements. Significant questions were also raised concerning volume and thermal management considerations for all studied systems. A subsequent power system assessment was performed that identified increased volume and power requirements for the active cooling required. The cooling airflow could also generate additional drag on the vehicle during operation. For the notional vehicle studied, the additional volume identified by the subsequent study would not affect vehicle mold line and therefore drag. However, the additional drag from cooling airflow and the power to circulate it as needed would impact power system and vehicle mission performance. Vehicle and mission models were updated and rerun. Updated results still indicated significant benefits in range and number of UAM missions, but reduced the benefit by 12-15%. Hold time for the hybrid systems also generally increased a few minutes because of reduced power available for charging to power cooling flows required. Vehicle weights, thermal loads, and cooling airflows from the updated analyses were similar to previous results.

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