Hybrid Electric Turboprop Commercial Freighter Opportunity

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As the era of electric and hybrid electric aviation is dawning, there is an opportunity to reduce cost, energy use, and emissions of air transportation. In this paper, the case is made for the potential efficiency benefits that can be gained with hybrid electric propulsion. Initial economic, mission profile, and propulsion system concepts are provided for a large turboprop aircraft defined as the Hybrid Electric Turboprop Commercial Freighter (HETCOF). Market analysis establishes HETCOF has the potential to serve a large market share, but the cost requirements for a new purpose-built freighter are challenging relative to a repurposed narrow body aircraft currently operating in the market. Comparing HETCOF to a genericized large turboprop freighter the payload capacity is reduced by 40% for the Technology Readiness Level (TRL) 5+ configuration but is equivalent to the baseline for the TRL 1-2 configuration. All HETCOF configurations result in increased efficiency and subsequent block fuel, block energy, and block emissions reductions. An integrated power/thermal/and energy storage system is provided and analyzed using key performance parameters to estimate weights and losses at three TRL values. Analysis substantiates that for a concept like this to have economic and energy benefits, many TRL 1-2 level technologies are needed. Relevant ARPA-E programs and NASA technologies being developed to enable the benefit are also described. The most significant result of this paper is that the HETCOF concept closes with reduced fuel burn, energy use, and emissions while retaining some or all of the cargo capability of the baseline aircraft across TRL level assumptions, which enables this platform to be used for near term introduction with increasing benefits as technology matures.

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I. Introduction

Transportation of people and goods is an important part of our economy and social structure. Aerospace research has always been focused on efficiency, with every new aircraft architecture increasing overall efficiency by 2-3% over periods of decades of development. As the era of electric and hybrid electric aviation is dawning, there is an opportunity to reduce cost, energy use and emissions of air transportation if the mission requirements can be met.

This paper explores that opportunity in the context of large turboprop aircraft for domestic freight operations that is defined as the Hybrid Electric Turboprop Commercial Freighter (HETCOF). Two papers by Pham et al. [1,2] describe the aircraft concept using a prior approach to the power, thermal, and electrical energy storage system sizing. This paper focuses on a more detailed description and analysis of an integrated power and thermal system (Fig. 1).

The size of the HETCOF payload and range is comparable to older narrow body aircraft that are typically used for the domestic freight market. A cost requirement analysis is provided to inform economic requirements. Technical factors that can directly impact the addressable market include noise and emissions, because most jurisdictions limit operations based on noise levels, and some are now also limiting operations based on emissions.

Technical constraints are significant when considering a large hybrid electric aircraft. The key new technology discussed in this paper is an integrated hybrid electric propulsion system and its associated power, energy, and thermal management components. This paper provides an example integrated system layout for this application. Rather than specifying technologies for each component, key performance parameters and sizing for each component are used based on three different Technology Readiness Levels (TRL)s. This methodology allows independent innovators to meet those component requirements using whichever technology or approach they find suitable.

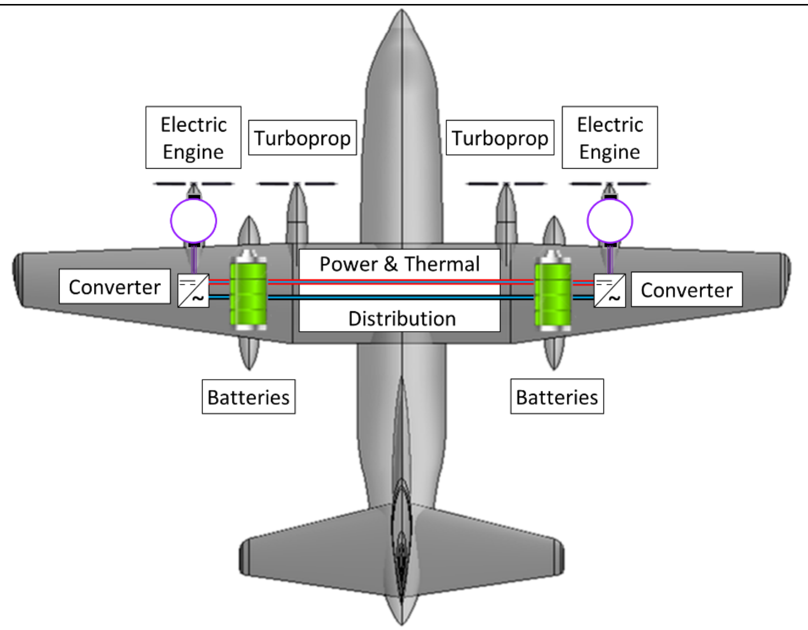

Fig. 1 - HETCOF propulsion system diagram.

II. Motivation

Aircraft overall efficiency is approximated by the product of thermodynamic efficiency, the ability to turn chemical energy into rating shaft power, and propulsive efficiency, the ability to turn rotating shaft power into thrust. Propulsion for current state of the art aircraft such as the Boeing 787 and Airbus 350 have reached impressive Thermodynamic Efficiencies of greater than 55% and propulsive efficiencies of greater than 70%, effectively leading to overall efficiency from chemical energy to thrust approaching and exceeding 40% [3]. Although 40% overall efficiency for flight is an incredible achievement, reflecting on billions of dollars in investment in research, it still reflects that over half the chemical energy used is not efficiently used to propel the aircraft. In a world were sustainable transportation and reduction in CO_2 emissions are important, there is a need to strive for better.

Thermodynamic efficiency in combustion engines is fundamentally determined by material capabilities that limit the temperature and pressure in the combustor and turbine; these are the key limiting factors in the achievement of higher thermodynamic (Carnot) efficiency. Although turbines already use advanced alloys and ceramic matrix composite (CMC) materials, further advances in material technology take time and are not expected to meet net zero goals by 2050 [ref.]. The NASA Hybrid Thermally Efficient Core (HyTEC) project, certain FAA CLEEN projects, and ARPA-E's advanced alloys research ULTIMATE program [4] all are investing technology to increase turbine efficiency, however the rate of increase is slow since turbines are a relatively mature technology.

Propulsive efficiency is dictated by the combination of the propulsion system and aircraft. Typical aircraft under design and construction today are certified for Extended-range Twin-engine Operations Performance Standards (ETOPS) which has proven that twin-engine aircraft are operated as safely as four-or more engine aircraft. Twin-engine aircraft have an operational advantage that they have reduced maintenance requirements over four engine designs. In addition, having larger engines leads to higher thermodynamic efficiency, as turbines are generally more efficient at larger scales due to the higher bypass ration and relative size of tip clearance compared to compressor or turbine blade dimensions. In contrast, multiple small engines in distributed propulsion configuration have the potential to achieve higher propulsion efficiency, but smaller combustion engines at lower power rating are often less thermodynamically efficient, potentially negating any propulsive advantage.

Electrified aviation has unique features which can be applied to overcome some of these challenges. Similarly to a combustion engine system, propulsion efficiency can be separated into powertrain efficiency and propulsive efficiency. For a fair comparison, the electrified powertrain analysis needs to include the products of the efficiencies of the battery system, the power conversion system(s), the cabling, and the electric motor. Unlike to thermal engines, electric motors can be produced at different ratings with similar efficiencies. In general, electric powertrains are significantly more efficient and reach levels of 90-95%. This allows for advanced propulsion concepts such as distributed electric propulsion (DEP) which allows for a better distributed airflow over the wing and higher propulsion efficiency [5].

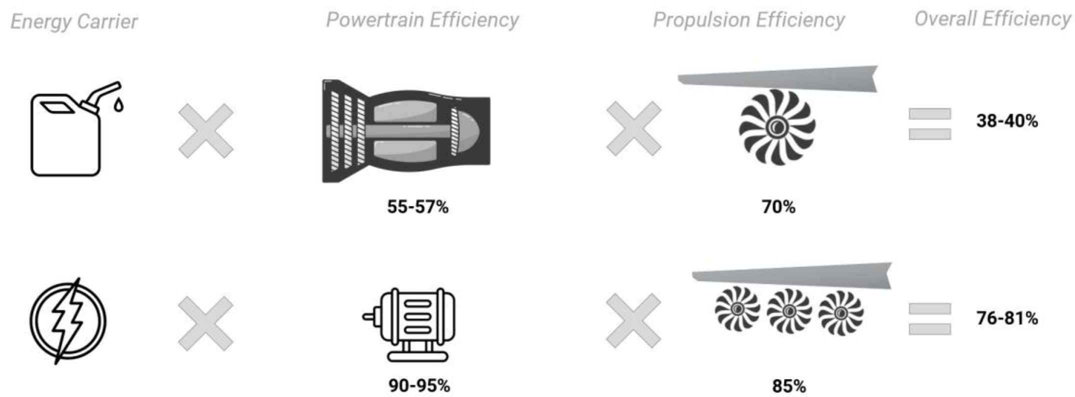

Fig. 2 - Comparison of thermal and electric propulsion overall efficiency potential.

Fig. 2 illustrates how electrified architectures have the potential to significantly increase the efficiency of propulsion. Electrification of transportation has proven to lead to both more sustainable and economical options by increasing the efficiency of the propulsion system greatly [5]. This increased efficiency results in transportation options that require less energy for the same range, and thus have the potential to effectively decrease operating cost [6]. This is substantiated by noting that an Electric Vehicle (EV) such as a Tesla P100D vehicle with 100kWh battery (~2.7 gallons fuel equivalent) can achieve 315 miles range, approaching 116 MPG. Therefore, finding pathways to electrified flight could lead to significant energy savings. As the costs of jet-A and electricity (production) are similar, it is apparent that electrified architectures could also lead to disruptive improvements in Cost per Average Seat Mile (CASM), and lower operational expenses.

III. Addressing the Barriers

The next challenges to address are the cost of the electric architecture, and the weight of the system. The Breguet equation shows possible aircraft range and payload, given aircraft maximum take-of-weight (MTOW), energy carrier mass, and propulsion efficiency. To enable electrified aviation, significant innovations are needed to increase both the efficiency and especially the mass of the components that make up the energy carrier and powertrain systems.

Fig. 3 shows a diagram of a notional propulsive drivetrain, for a variety of vehicle types, using icons to signify ARPA-E programs that have been launched to support transformational technology concepts. The schematic illustrates paths that include battery energy storage (direct electrification) as well as sustainable fuels-to-electricity conversion (indirect electrification) that lead to electrified propulsion. Hybrid versions of these architectures are also possible, and are likely to provide redundant independent paths to safe operation.

Indirect electrification approaches are supported through the creation of sustainable fuels through the GREENWELLS [7] program, along with on-board power generation or auxiliary power units (APU)s with high power density and efficiency from the REEACH [8] program. Given the expectation that sustainable fuels will be more expensive than traditional Jet-A further emphasizes the need to simultaneously develop a leap in efficiency in order to mitigate the potentially higher energy cost [9].

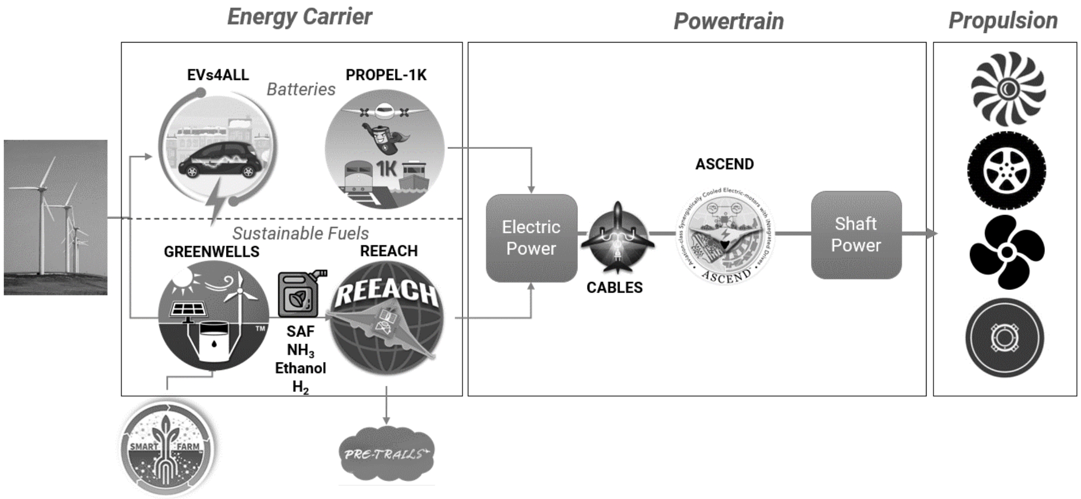

Fig. 3 - ARPA-E programs on direct or indirect Electrified architectures.

IV. Market Size and Cost Requirements

A. Market Size

The dedicated air cargo and freight market has the potential to be a critical early pathway for emerging technologies in low to zero emission propulsion [10]. Air cargo provides a critical link to the global supply chain, transporting high value and time sensitive goods (e.g., computer chips, manufacturing equipment, robotics, luxury goods, and medical equipment). The air cargo market in 2021 transported over $6 trillion in goods and represented 35% of global trade valuation while making up less than 1% of total freight volume [11]. The combined US domestic and international air cargo market makes up a significant portion of total freight ton miles (FTM) with 28% of the world share in 2023 [12].

Fig. **4** presents a heat map of the narrowbody cargo domestic market identifying the operational density by payload and distance in 2019. The blue call-out box isolates the space the HETCOF is anticipated to have full-electric range coverage, with a majority of the network appearing to be covered in terms of operations. Table 1 further breaks down the cumulative operations by distance ranges for this market, showing 28% of operations occur up to 250 miles, 53% of operations up to 500 miles, and 73% of operations up to 750 miles. The range coverage up to 750 miles is also consistent with the network maps for FedEx and UPS, with broad distance coverage from their respective mega-hubs (FedEx – Memphis, TN, and UPS – Louisville, KY). Taken together, these results indicate broad market coverage for the all-electric thresholds of the HETCOF.

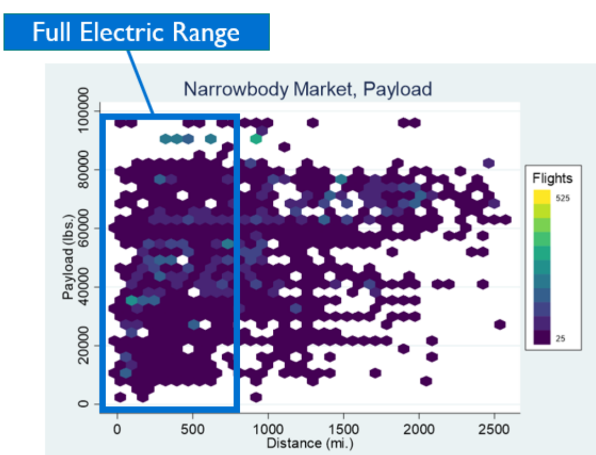

Fig. 4 - Operations Heatmap of Narrowbody Market by Payload and Distance Range [10]

Table 1 - Narrowbody Cargo Operations by Distance Ranges [10]

Distance Band	Narrowbody Cargo Operations	
	Count of Flights	Cumulative Total 2019 Flights
0-250 miles	34,352	28%
251-500	31,098	53%
501-750	24,279	73%
751-900	8,062	80%
901-1100	9,970	88%
1101-1500	7,447	95%
1501-2000	8,068	99%
2001-2500	582	100%
2501-3000	7	100%
2019 Total	123,865	100%
Relevant Flights (<750)	89,729	73%

Source: BTS T-100

B. Cost Requirements

To better understand the potential range of cost requirements for the HETCOF concept, a breakeven analysis was conducted to identify areas where the lifecycle costs of the concept aircraft are roughly equivalent to the lifecycle costs for a competitor aircraft. Expected cost equivalence between the aircraft is determined by the level at which cost decreases from one source (e.g., fuel/energy) balance cost increases from other sources (e.g., maintenance or capital expenditures).

The breakeven analysis measures and compares the total operational lifecycle costs from an operator's perspective between two aircraft (excluding disposal costs). This analysis is conducted on a per-aircraft level assuming a 25-year useful life of the aircraft. Given the B737-8 is a conversion (from passenger to freight) aircraft, the starting age is set to 27, whereas the HETCOF concept aircraft is purpose-built and enters service new (age 0). All other operating costs, such as crew salaries, route and landing charges etc., were assumed to be equal between the B737 conversation aircraft and HETCOF and were not included in the calculations. Additional second order costs associated with electrification were not included at this time but are worth future consideration; these additional costs include aircraft infrastructure upgrades to meet electrification requirements, spare batteries and battery storage, and labor costs associated with battery technicians (training and salaries).

The breakeven results at a range of distances are listed in Table 2. Positive percentages on purchase and maintenance cost change indicate that at a given fuel burn reduction level, costs could increase for either capital or maintenance and the HETCOF would still breakeven relative to the conversion aircraft. The highest average distance range (750 miles) show the strongest cost-effectiveness results for the HETCOF. The key takeaway is that the 250 mile variant (TRL 5+) doesn't total cost savings (purchase + fuel + maintenance), whereas the 750 mile (TRL 1-2) does.

Table 2 - Breakeven Cost Analysis Results

Fuel Burn Change	*Distance Range – 250 Miles*		*Distance Range – 500 Miles*		*Distance Range – 750 Miles*	
	Purchase Price Change	**Maintenance Cost Change**	**Purchase Price Change**	**Maintenance Cost Change**	**Purchase Price Change**	**Maintenance Cost Change**
-30%	0%	-86%	0%	-35%	0%	34%
-30%	-20%	0%	-13%	0%	17%	0%
-30%	-30%	41%	-20%	21%	10%	14%
-40%	0%	-71%	0%	-16%	0%	53%
-40%	-17%	0%	-6%	0%	27%	0%
-40%	-30%	56%	-20%	41%	15%	24%
-50%	0%	-56%	0%	-4%	0%	73%
-50%	-13%	0%	1%	0%	37%	0%
-50%	-30%	71%	-20%	60%	20%	33%

Note: Results based on 700 annual operations, negative values indicate reduction in costs.

To examine input assumptions for utilization rates and fuel price values in more detail, annual operations were increased – evaluated at 700, 1,110, and 1,500 -while separately, fuel prices were increased from $2.18 to $5 per gallon; to gauge the impacts on the breakeven analysis space. These results for the two separate scenarios are presented in Fig. **5** showing improved cost effectiveness with increases in utilization rates or fuel price levels. For the utilization rate test, an average distance range of 750 miles per operation and a 40% reduction in fuel is assumed, which pushes the breakeven line up and to the right, significantly increasing the range of potential cost increases for both capital and maintenance. The fuel price test assumes an average distance of 750 miles per operation at the three fuel reduction scenarios, also moving the breakeven lines up and to the right in parallel with each other, increasing the range of potential cost increases to still breakeven.

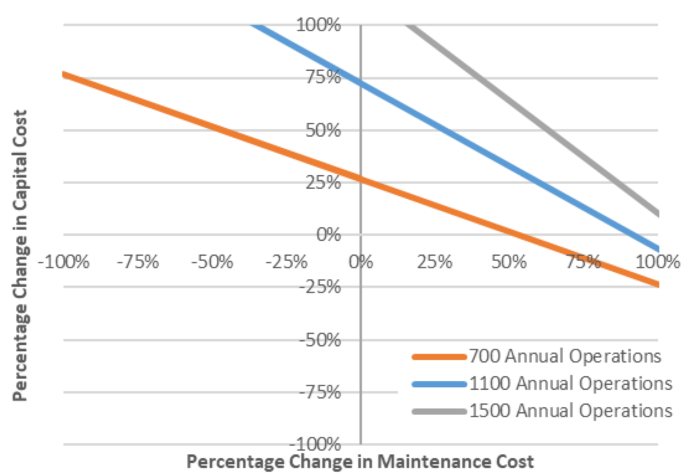

Fig. 5 - Breakeven rates at different operational levels for HETCOF vs B737F, 750mile range, 40% fuel reduction.

A number of factors were evaluated to find the most economically beneficial operational scenarios. There is significant room for improved cost-effectiveness, based on increased utilization rates of the HETCOF aircraft, or higher future fuel prices. A clear pattern emerges when considering the results at the three distance range assumptions where the HETCOF is most competitive, when the annual level of block hours is increased for the two aircraft. The reason for this is straightforward: increasing the level of utilization of the HETCOF improves the cost-effectiveness of the aircraft, allowing it to take advantage of improved energy efficiency and lower maintenance costs over a larger number of block hours performed, lowering the impact of higher relative capital costs. The use of a repurposed aircraft for HETCOF was not evaluated, but may be another way to reduce the initial capital cost.

V. Intended Mission Profiles

The HETCOF is intended to operate in a regional air freight market. The majority of operations will be in areas without significant overwater flights. The intent is to be able to operate in an all-electric mode up to 750 nautical miles, and hybrid electric mode to a standard maximum range of 2,400 nautical miles. Meeting these goals will require substantial technology improvements in energy storage, power system, and thermal systems.

When developing the concept of operations for a hybrid-electric aircraft concept, power/energy management is an integral consideration throughout the mission profile. The powertrain system must be sized appropriately to meet power requirements for All Engine Operating (AEO) and One Engine Inoperative (OEI) takeoff, top-of-climb rate of climb, 2nd Segment OEI climb gradient, and descent, along with meeting a 20% minimum state-of-charge limit after completing the design and reserve missions.

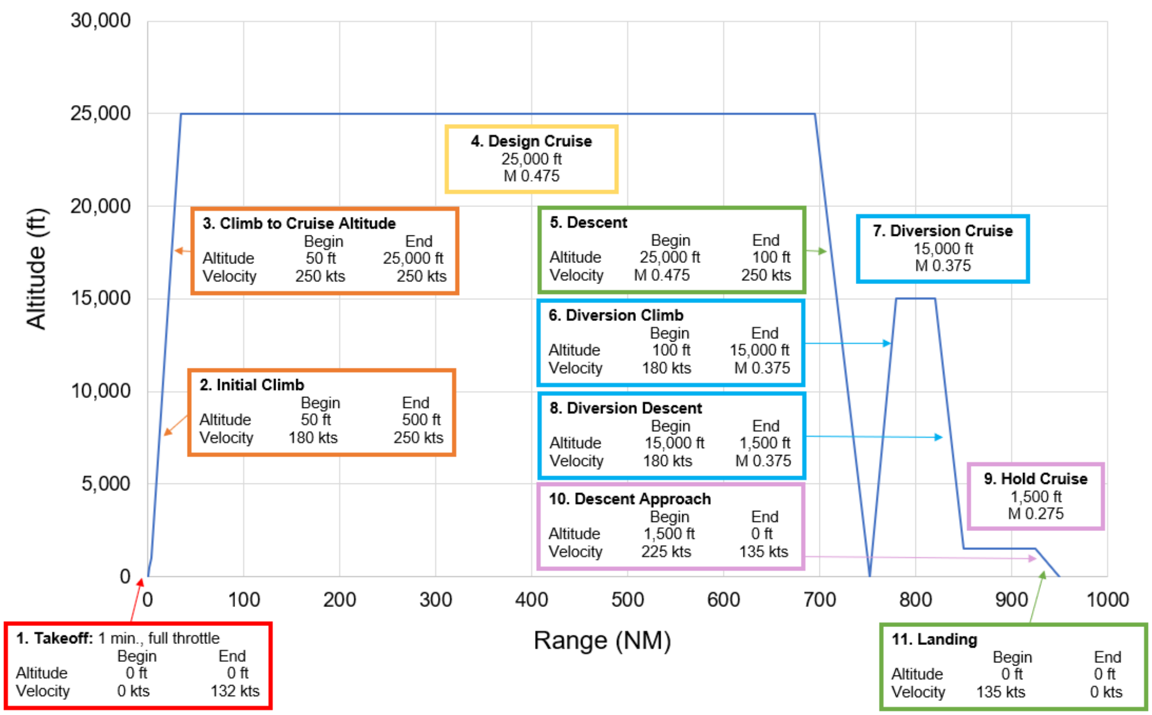

Fig. 6 - Economic mission profile for the hybrid electric turboprop commercial freighter.

For the economic mission profile (Fig. 6), the HETCOF assumes all-electric cruise operations for a 750 nautical mile design range; wherein the majority of the power is provided by the high-power electric system, and the parallel gas turbine engines are set to idle power to reduce the risk of operating outside the re-light envelope when reigniting the turbines. For lower electric motor output power, the economic mission range of 750 NM can be met with hybrid-electric operations, where the power-split is dependent on the cruise power requirements. All-electric ground operations are optional, where taxi and takeoff can be done with both power systems at maximum takeoff, sea-level static thrust, or with the electric power system set to idle. The takeoff field length is based on the maximum motor power, where higher power results in lower required takeoff field length, which is desirable for short takeoff and landing operations. Initial climb is done with both propulsion systems at maximum climb power to achieve the best rate-of-climb speed (V_Y), which is maintained up to cruise altitude. All-electric cruise is done with the majority of the power provided by the Electrified Aircraft Propulsion (EAP) system (>85%) where the turbines are set to idle as discussed previously.

For the design mission (Fig. 7), hybrid cruise allows for reduced power draw from the electrical system, which is set to a lower power setting. This can result in reduced required battery weight and increased fuel load, where the 2,400 NM design range is met by setting the gas turbine system at 100% normal rated power, with the differential made up with the electric power system.

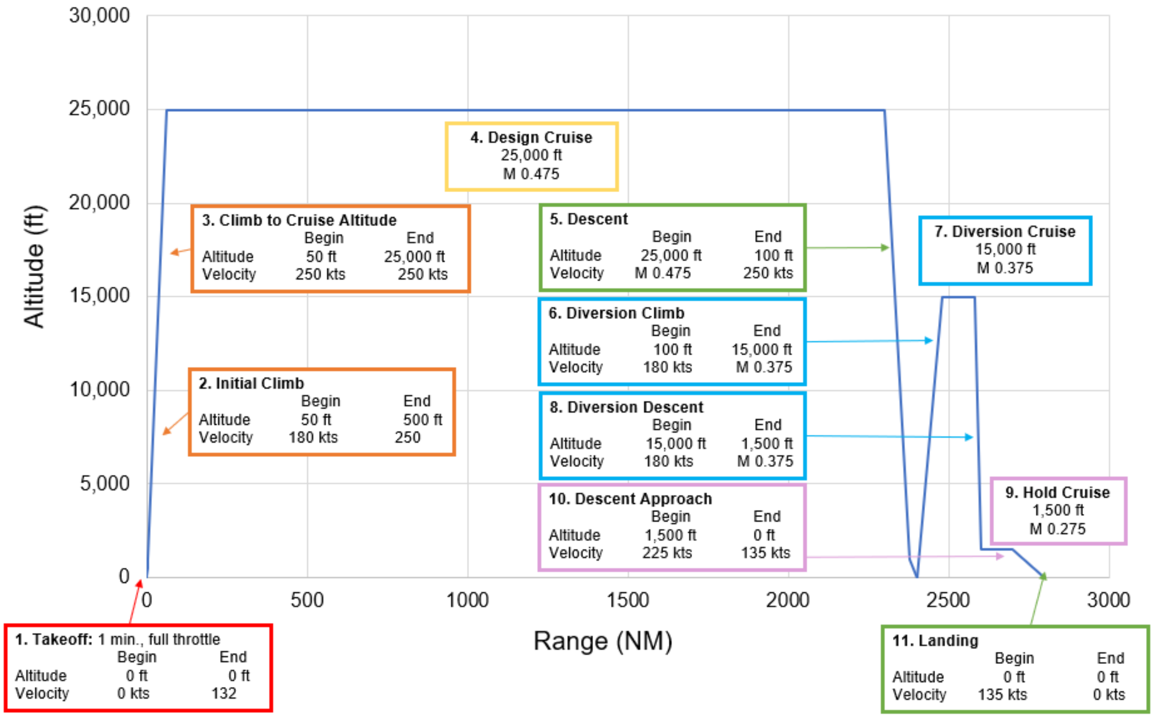

Fig. 7 - Design mission profile for 2400 nm hybrid-electric cruise.

Descent for both mission profiles is done without electric power and with the conventional gas turbine engines set to idle, with the electric-driven propeller set to windmilling configuration, which allows for minimal battery charging throughout descent (3-5% charge.) The diversion portion assumes hybrid-electric missed approach and climb, but diversion cruise on the conventional turbine engines for 100 NM to the alternate airport, with a 30-minute hold time at a lower altitude. This is to conserve the available battery capacity, and avoid a significant battery weight penalty for the diversion mission, by ensuring the minimum state of charge limit is not exceeded. For sizing, percent landing weight is set to 97.6% and performed only using the conventional gas turbine power systems at idle power. At landing, the charge should be no less than the 20% minimum SOC limit.

VI. Aircraft Concept and Enabling Technology

The Hybrid Electric Turboprop Commercial Freighter (HETCOF) aircraft concept combines electrified aircraft propulsion (EAP) under development by NASA, ARPA-E, universities, and industry, using an existing, widely produced reference airframe. Pham et al [1,2] describe the aircraft concept using a prior approach to the power, thermal, and electrical energy storage system sizing. This paper focuses on a more detailed description and analysis of an integrated power and thermal system, as shown in Fig. 8. We consider this system using key performance parameters to approximate configurations at Technology Reediness Level (TRL) 5+, TRL 3-4, and TRL 1-2. Relevant NASA and ARPA-E activities at these TRL levels are discussed in the power and thermal key performance parameter sections.

A. Integrated Power and Thermal Management System Configuration

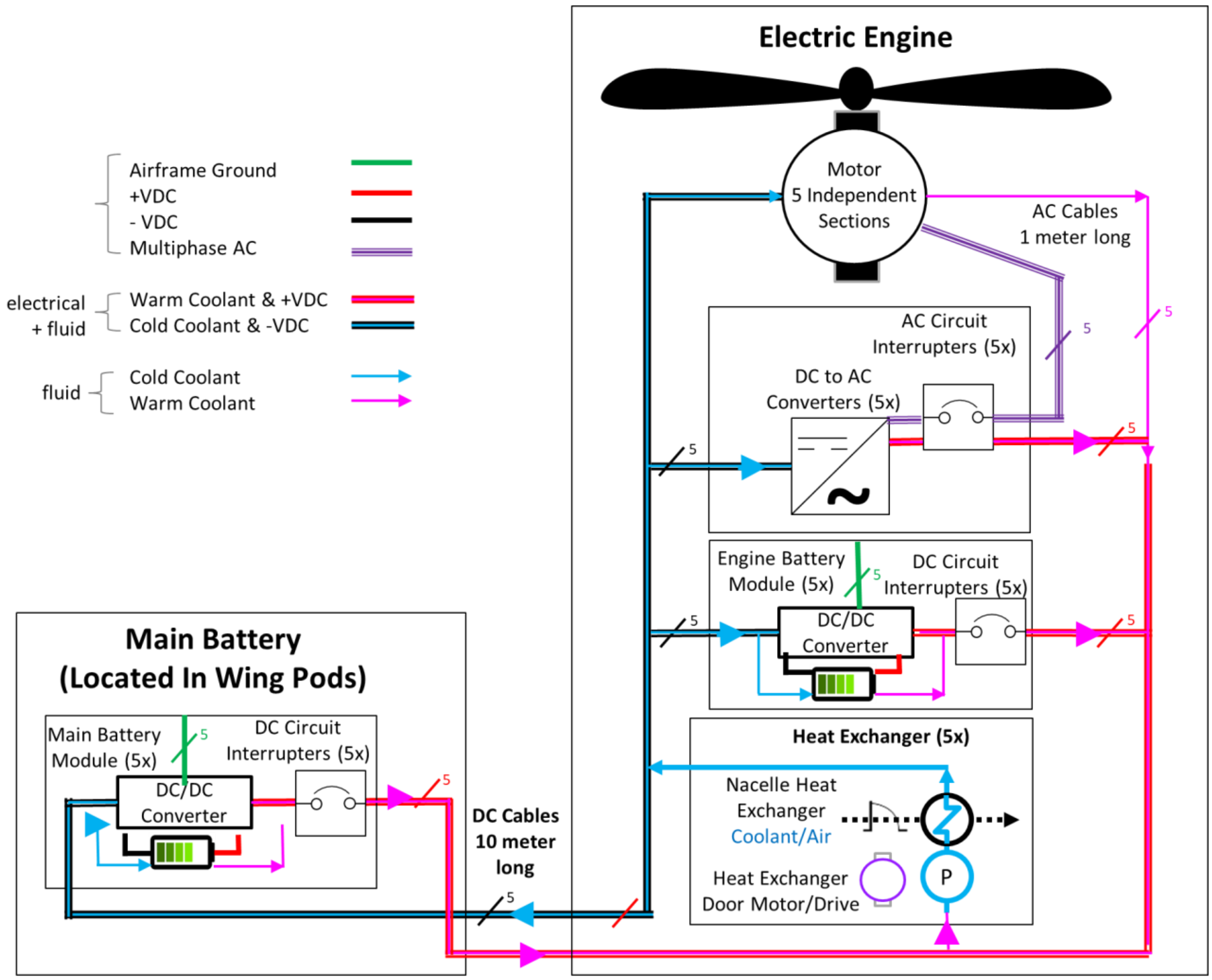

Fig. 8 - HETCOF power and thermal diagram.

B. Electrical Power System Key Performance Parameters and Performance Estimates

1. *Electrical Key Performance Parameters*

The power and thermal analysis conducted in the paper is done based on key performance parameters (KPPs). The power system KPPs define the weight and electrical efficiency or loss performance of the electrical power system, and are estimated at three TRLs as listed in Table 3.

Table 3 - Electrical power system key performance parameters.

	Specific Mass	Efficiency

	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level	Units	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level	Units
Electric Machines								
Electric Engine Motor (EEM)	15	25	50	kW/kg	98.0%	99.0%	99.5%	%
Power Conversion								
DC to AC Converter	20	30	40	kW/kg	97.0%	99.0%	99.5%	%
Battery DC/DC Converter	6.7	10	13.3	kW/kg	97.0%	98.0%	99.0%	%
Circuit Interrupters								
AC Circuit Interrupters	200	300	600	kW/kg	99.5%	99.7%	99.9%	%
DC Circuit Interrupters	100	150	300	kW/kg	99.5%	99.7%	99.9%	%
Cables								
AC Distribution Cable	10	2	0.5	kg/m/MW	0.08%	0.04%	0.02%	loss/m
DC Distribution Cable	10	2	0.5	kg/m/MW	0.08%	0.04%	0.02%	loss/m
Batteries								
Rechargeable Battery	250	750	1500	Wh/kg	95.0%	97.0%	98.0%	%

The KPPs in Table 3 are derived from a number of the following publications. The Electrical Power System components specific power and efficiency ranges are based on the Subsonic Single Aft Engine (SUSAN) aircraft concept studies [13], but are updated by work completed since its publication. Specifically, the electric machine values are updated considering Tallerico [14, 15, 16], Jansen [17], and Pastra [18]. KPPs for power conversion components are updated by Kowalewski [19], Granger [20], Garrett [21], and Hall [22]. Values for circuit protection equipment come from the sizing paper written by Pastra [19]. Cable information is provided by Dever [23, 24], battery KPPs are generated using the sizing paper Tiede [25], and motor and battery sizing is based on Pham [1,2].

1. *ARPA-E Energy Storage and Powertrain developments*

ARPA-E programs are focused on the maximum performance column of Table 3. Direct electrification technology is supported by programs like EVS4ALL [26] and PROPEL-1K [27], which develop technologies for lower-cost, fast charging, and higher energy density energy storage systems. The recently announced Pioneering Railroad, Oceanic and Plane Electrification program (PROPEL-1K) is focused on the development of energy storage systems with a target energy density of 1000 Wh/kg and a volumetric energy density of 1000 Wh/l, at the pack level [27]. Transformational technologies for energy dense and highly efficient conversion of electricity into shaft power are supported by the CABLES [28] and ASCEND [29] programs.

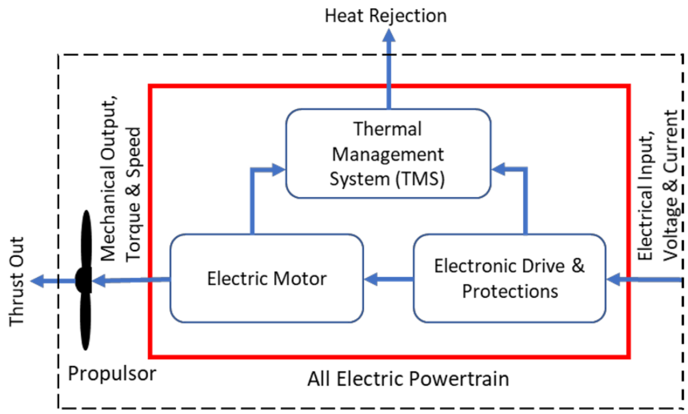

Fig. 9 - Aviation-class Synergistically Cooled Electric-motors with iNtegrated Drives (ASCEND) powertrain subsystem optimization.

The CABLES program identified that for MW class electric aircraft, transformational breakthroughs in the area of high voltage transmission would be necessary. High voltage operation at altitude has always been challenging as partial discharge can occur, which can damage equipment. The program targets development of innovative solutions of 10kV cable technology that could operate at 10km altitude (~30kft).

ASCEND powertrain improvements encompass the subsystem, and include improved energy density of the electric machines, the power electronics, and the cooling system, combined as illustrated in Fig. 9. This powertrain can both operate in motor and generator mode.

This comprehensive view of the powertrain is important, as the performances of each of these elements are correlated. I.e. a very high energy density motor could be developed if an extreme cooling system would be available, but clearly this would be challenging to put on an aircraft. The combined subsystem perspective allows for the global optimization of the combined relevant areas: motor/generator, power electronics, thermal management. The goal of this program is to achieve a combined energy density of >12kW/kg while achieving an efficiency of >93%, although many of the projects exceed these goals; for example, an advanced powertrain developed by Hinetics is targeting 40 kW/kg and 99% efficiency.

2. Electrical Power System Sizing, Weights, and Losses

The weight and heat loss estimates for one electric engine and its associated battery system are presented in Table 4.

Table 4 - Weight and loss estimates for one full electric engine and associated battery system.

		Power (kW)			**Weight (kg)**			**Heat Load (kW)**	
	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level
Electric Engine Shaft Power Required	1650	2100	4400						
Motor	1650	2100	4400	110	84	88	33	21	22
AC Cables (3ph x 1m)	1683	2121	4422	17	4	2	1	1	1
AC Circuit Interrupters	1684	2122	4423	8	7	7	8	6	4
DC/AC Converters	1693	2128	4427	85	71	111	51	21	22
Engine Battery DC Circuit Interrupters	175	213	443	2	1	1	1	1	0
Engine Battery DC/DC converter	180	218	448	27	22	34	5	4	4
DC Cables (2x10m)	1744	2149	4449	174	43	22	14	9	9

Main Battery DC Circuit Interrupters	1794	2171	4472	18	14	15	9	7	4
Main Battery DC/DC converter	1803	2177	4476	269	218	337	54	44	45
DC Cross Strap Cables	897	1085	2236	179	43	22	N/A	N/A	N/A
Totals/Engine				**710**	**465**	**617**	**177**	**113**	**112**

Calculations for Table 4 are completed as follows. The calculation begins with the required engine shaft powers for the three configurations (Row 1), which are described in the *Aircraft Concept and Enabling Technology S*ection above. The required motor power (Row 2) is the same as the shaft requirement, because the motor is rated by shaft power. The 'Weight' columns for each of the three motor TRLs are calculating using the motor required power divided by the Specific Mass (in kW/kg) for the motor at the corresponding TRL listed in Table 3; and the 'Heat Load' values are calculated by multiplying the required motor power by (1 – Efficiency) for each motor TRL, as listed in Table 4.

Once the Weight and Heat Load calculations are done the row is complete, and the calculations for the next row, which correspond to the next upstream component in the EPS (the AC Cables) is done. First, the 'Power' for the three AC Cable TRLs is calculated, by adding the previous-component (that of the motor) losses (Heat Load) to its power. With the AC cable 'Power' calculation complete, the 'Weight 'and 'Heat Load' for the AC Cables is calculated using the same approach applied to the motor, using Table 3 'AC Distribution Cable' data.

The remainder of Table 4. is calculated in similar fashion, with the exception of two components: the Engine Battery DC/DC converter, which is sized at 10% of the Main Batter Power rating, and the Engine Battery DC Circuit Interrupters, which are sized based on the Engine Battery DC/DC converter minus losses. The 'Totals' are merely the sums of the Weight and Heat Load columns. Weight and Loss Estimate for Batteries are listed in Table 5.

Table 5 - Weight and loss estimate for batteries.

	Energy (kW-hr)			Weight (kg)			Heat Load (kW)		
	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level	TRL 5+ Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level
Main Battery	5064	6532	13428	20256	8709	8952	90	65	90
Engine Battery	15	18	37	60	24	25	9	7	9
Subtotal	5079	6550	13465	20316	8733	8977	99	72	98
Total				**21916**	**9706**	**10234**	**453**	**298**	**323**

In Table 5., 'Weight' and 'Heat Load' values are calculated for the Main Battery and the Engine Battery using a similar approach as that employed in Table 4, one notable difference being that the Specific Mass in Table 3. used to calculate the 'Weight' is in W-hr/kg, instead of kW/kg. The 'Subtotal' row is simply the summed weights for that column, while the 'Total' row includes summed Weights and Heat Loads of two engines, plus those of the Batteries and the DC cross Strap cable.

3. Electrical Power System – Concluding Comments

Notable items included in the EPS analysis are the summaries of the power system configuration, sizing, and component weights. Notable aspects of the EPS design include independent left/right systems, which are cross strapped to enable recovery in case of emergency; and five-times redundancy within each system.

C. Thermal System Key Performance Parameters and Performance Estimates

1. Thermal Key Performance Parameters

To quantify the weight, power draw, and drag impact of a realistically sized and redundant thermal management system (TMS) architecture on the HETCOF aircraft, a KPP approach was taken similar to that of the EPS. A set of KPPs was developed to define the thermal performance, fluid performance, power consumption, and weight of each component in the HETCOF TMS. These were assigned values corresponding to three levels of TMS component performance corresponding to different TRL ranges. This illustrates the change in TMS impact as technology progresses from the current state of the art to future levels. A concurrent paper describes the TMS KPP methodology and data sources in more detail in Stalcup et al.[31].

The levels are based on NASA's Technology Readiness Level scale and are summarized in Table 6. To assign values to each KPP at each TRL range, data from several sources were compiled to provide a broad assessment of current and future TMS component performance. When compiling this data, focus was given to component designs that are specific to aeronautical applications. In some cases, data was not available in the given TRL range for aeronautical applications, so other sources were considered from similar automotive or space applications.

Table 6 - Thermal management system key performance parameter levels.

KPP Level	KPP Level Description	Sources for KPP Values
TRL 1-2	Future projections	• Projections based on higher TRL level data and analysis • Published analysis of TRL 1-2 technologies
TRL 3-4	Current research	• Testing and analysis from NASA internal technology development • Testing and analysis from NASA-funded technology development • Other published test data or analysis of TRL 3-4 technologies
TRL 5+	State of the art	• Commercial product datasheets • Commercial product test data • Other published test data or analysis of TRL 5+ technologies

For the TRL 5+ KPP level, representing the state of the art, sources include commercial off-the-shelf (COTS) product datasheets, specifications, and manuals; published and NASA-internal test data for COTS products; and other published data and analysis of TRL 5+ technologies from journal articles, conference papers, whitepapers, etc. For the TRL 3-4 KPP level, representing current research, sources include test data and analysis from NASA internal technology development; test data and analysis from NASA-funded technology development, including multiple Small Business Innovation Research (SBIR) programs and projects funded under the Aeronautics Research Mission Directorate (ARMD); and other published data and analysis of TRL 3-4 technologies. For the TRL 1-2 KPP level, values are projections of future technology development based on the other two KPP levels.

The KPPs presented here are specific to single-phase liquid cooling solutions. They are defined and values are assigned within the following categories: heat acquisition, heat transport, and heat rejection. Heat acquisition KPPs characterize the thermal and fluid performance of cooling of motors/generators, converters, battery modules, and circuit interrupters. Heat transport KPPs characterize the power draw and weight of fluid pumps. Heat rejection KPPs characterize the thermal and fluid performance and weight of ram-air heat exchangers. These KPPs are defined so that they represent the minimum number of parameters needed to characterize the weight, power draw, and drag of the TMS. They are also defined so that they can be directly utilized for high-level thermal/fluid modeling and analysis.

Table 7 - Thermal management system key performance parameters.

	TRL 5+	TRL 3-4	TRL 1-2	Unit	TRL 5+	TRL 3-4	TRL 1-2	Unit	TRL 5+	TRL 3-4	TRL 1-2	Unit	TRL 5+	TRL 3-4	TRL 1-2	Unit
	Cooling Effectiveness				Heat Load/Pumping Power											
Heat Acquisition																
Motors/Generators	0.20	0.27	0.32	-	2.5E2	5.0E2	1.0E3	-								
Converters	0.12	0.26	0.33	-	2.5E3	1.0E5	4.0E5	-								
Batteries	0.70	1.80	2.10	-	1.0E5	1.0E6	2.0E6	-								
Circuit Interrupters	0.12	0.26	0.33	-	2.5E3	1.0E5	4.0E5	-								
	Efficiency				Specific Power											
Heat Transport																
Pump	0.50	0.55	0.60	-	$15P^{0.3448}$	$17P^{0.3448}$	$19P^{0.3448}$	W/kg								
	Effectiveness				Heat Load/Pumping Power				Heat Load/Drag Power				Specific Heat Rejection			
Heat Rejection																
Ram Air HX	0.50	0.60	0.70	-	2500	3000	3500	-	33	33	46	-	5.0E3	5.0E3	7.0E3	W/kg

The KPPs and their values derived from the complied data are presented in Table 7. For heat acquisition components, the thermal performance KPP is defined as a cooling effectiveness:

$$\varepsilon_{cooling} = \frac{\left(\frac{Q}{\Delta T}\right)}{\dot{m}c_p} = \left(\frac{T_{out}-T_{in}}{T_{hotspot}-T_{in}}\right)_{steady} \quad (1)$$

where Q is the heat load from the component, ΔT is the temperature difference between $T_{hotspot}$ the hotspot of the component and T_{in} the inlet coolant temperature, $\dot{m}$ is the coolant mass flow rate, c_p is the isobaric specific heat of the coolant, and T_{out} is the outlet coolant temperature. When evaluating the cooling effectiveness for a given design, in general four quantities are needed: the heat load, hotspot and inlet temperatures, and the mass flow rate. In steady state conditions, only three temperatures are needed and the effectiveness will always be less than unity. For pumps, efficiency is defined as the end-to-end efficiency including motor and motor controller (if applicable) losses. Pump specific power is defined as a function of the pump output power. For heat exchangers, the effectiveness is the traditional definition

$$\varepsilon_{HX} = \frac{T_{1,out}-T_{1,in}}{T_{2,in}-T_{1.in}} \quad (2)$$

where 1 refers to the fluid with the smaller heat capacity rate (typically air) and 2 refers to the fluid with the larger heat capacity rate (typically coolant). With this set of values, the TMS can be sized, performance can be estimated, and the weight, power, and drag impacts can be quantified.

D. Thermal System Weight / Loss Analysis

This analysis involved calculating various flow parameters for each component shown in the power and thermal diagram in Fig. 8. These parameters were then used to determine the size of the pumps and the heat exchangers needed for the electric engines of the aircraft. The KPPs listed in Table 4, Table 5, and Table 7 were utilized to predict the temperatures, flow rates, and pressure drops from each component within the HETCOF. The design heat load for each component was determined by adding a 25% margin to the heat load values listed in Table 4 and dividing by five to account for the five independent sections of the electric motor.

This analysis assumes that the heat exchanger delivers coolant, i.e., PGW 60/40 at 40°C to the main battery module, engine battery module, DC to AC converters, and the electric motor. The inlet temperature, cooling effectiveness value, and maximum hotspot temperature of the component are used to determine the outlet temperature at which coolant flows into the downstream components (i.e., DC and AC circuit interrupters). The average temperature of the inlet and outlet is used to find the specific heat of the PGW 60/40, which leads to calculating the design mass flow rate ($Q = \dot{m}c_p\Delta T$). The pressure drop of each component is then calculated by dividing the pump power by the design volume flow rate. Pump power is calculated by dividing the design heat load by the cooling effectiveness of the component, while the design flow rate is dependent on the design mass flow rate and the average fluid temperature. This process was used to calculate the same values for each component within the fluid loop.

The parameters mentioned above were all used to calculate the weight, power requirement, and drag at cruise conditions for three different configurations (i.e., TRL levels). The mass of the wing heat exchanger was determined by dividing the total design heat load of all the components by the specific heat rejection of the heat exchanger. Similarly, the mass of the wing pump was found by dividing the power output of the wing pump by the pump's specific power listed in Table 7. The calculated total mass values are listed below in Table 8. The output power of each wing pump was found by multiplying the sum of the pressure drop of the motor and heat exchanger by the sum of the volume flow rates of components flowing into the heat exchanger. The input power of each wing pump was calculated by dividing the output power of each pump by the pump's efficiency values from Table 7. Since the HETCOF uses five independent motors and two electric engines, the values for output power and input power of each wing pump were multiplied by 10 to obtain the total output and input power of the wing pumps as shown in Table 9. A similar method was used to determine the total mass of the wing heat exchangers, and wing pumps.

Table 10 shows the total drag power for each configuration which was calculated by dividing the total design heat load by the heat load/drag power values from Table 7. The total mass, total output power, and total drag power each decrease progressively from TRL 5-6 down to TRL 1-2. As mentioned in the previous section, TRL 5-6 includes values for current state-of-the-art technologies while TRL 3-4 represents technologies that are currently being researched. TRL 1-2 represents values that are expected to be achieved in the future as electric propulsion technology advances. Thus, TRL 1-2 is expected to have the greatest performance at even greater efficiency than the other configurations, hence, significantly less drag, total mass, and power requirement as shown in Tables 5-7.

Table 8 - Total mass for the wing heat exchangers and pumps for various configurations.

Component	Number	Total Mass (kg) TRL 5-6 Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level
Wing HX	10	143.84	143.19	65.33
Wing Pump	10	62.93	38.91	8.09
TOTAL		**206.77**	**182.10**	**73.42**

Table 9 - Power requirements for the wing pump for various configurations.

Power Required for Wing Pump	TRL 5-6 Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level
Total Output Power (W)	10,334	6,004	647
Total Input Power (W)	20,669	10,917	1,079

Table 10 - Drag power produced for various configurations.

Component	Number	TRL 5-6 Tech Level	TRL 3-4 Tech Level	TRL 1-2 Tech Level
Drag Power (W)	10	21,793	21,695	9,941

E. Integrated MW-Class Aircraft Performance Assessment

This analysis focused on quantifying the vehicle-level performance impacts of electrification on the integrated HETCOF concept, where the baseline vehicle concept is based on the LTF defined in Ref. [2] for the economic and design mission profiles. Based on the power and thermal management system sizing specifications provided in Table 3, Table 4, and Table 5, the EAP component weights were factored into the operating empty weight of the integrated HETCOF concept.

The extended design structure matrix for the hybrid-electric concept analysis depicts how weight allocation, design/mission requirements, and EAP system performance were iterated upon to determine the resulting fuel savings and battery energy required for a given mission.

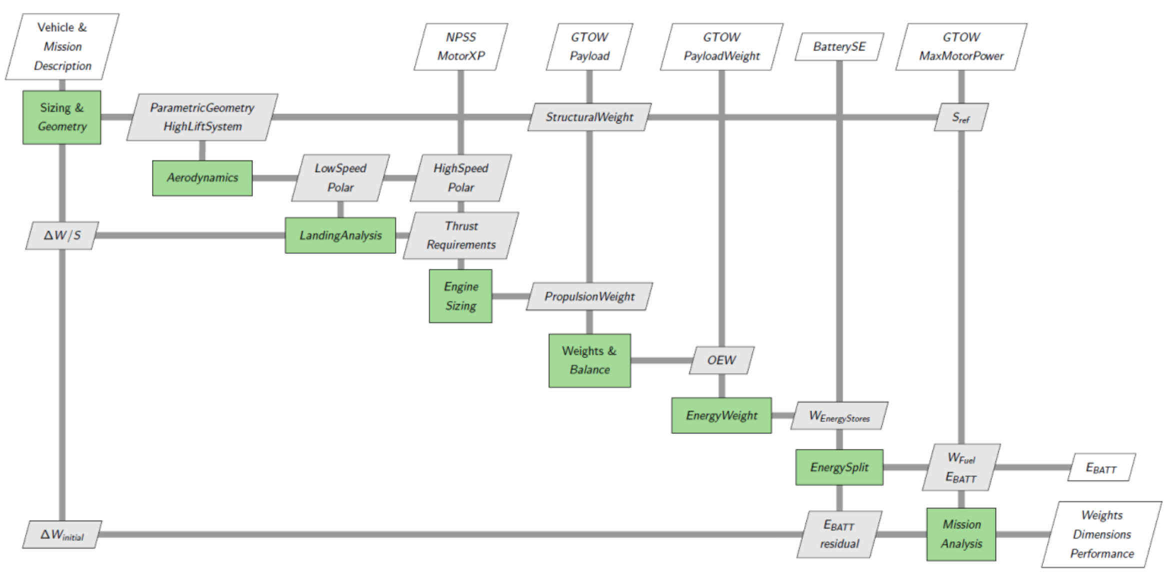

Fig. 10 Integrated modeling & simulation environment for hybrid-electric aircraft synthesis and mission analysis [1].

Figure 10 depicts the integrated modeling and simulation environment for synthesis of parametric, physics-based vehicle models that utilize dual-sided, parallel gas turbine and electrified powertrain drive systems. This is imperative to capture the power and weight parameters from the electrical power system and TMS sizing in previous sections. In (3), the energy required for each flight phase was calculated as a function of the electric system run time, electric motor power, and propeller efficiency.

$$E_{BATT_{phase}} = P_{EAP_{phase}}(t_{phase}\eta_{EAP})\eta_{prop} \quad (3)$$

where in (4) the energy split for each phase between the conventional fuel and electric battery energy sources is iteratively adjusted using Newton-Raphson methods with underrelaxation to minimize the residual battery energy.

$$E_{BATT,new} = \alpha E_{BATT,guess} E_{BATT}\left(\frac{d(E_{BATT,resid})}{d(E_{BATT})}\right)^{-1} \quad (4)$$

Where $d(E_{BATT,resid})/d(E_{BATT})$ is the derivative of the battery energy residuals with respect to the available battery energy. The value of α is set to 0.8 to stabilize the convergence process and control the step-size. The battery capacity required is calculated as a function of the battery specific energy density and matched to the allocated energy storage weights determined in Table 5 and energy allocation is matched to the target design range and battery charge depletion of 20% minimum state-of-charge.

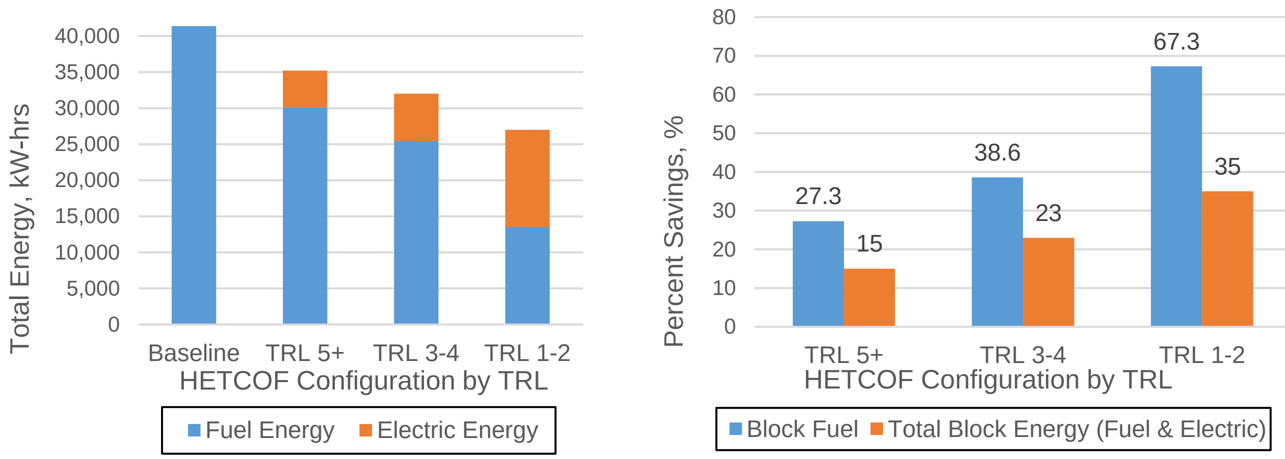

Fig. 11 Design mission block fuel and energy a) Total b) Percentage saved

Figure 11 summarizes the results of the vehicle benefit assessment, where performance benefits are quantified in terms of block fuel burn and block energy reduction. Block fuel refers to the fuel required for the mission, which does not include taxiing or reserves, whereas the block energy is to total energy required for the mission including both fuel-based energy and electric energy; the weighted sum of the energy from the electrical storage systems (batteries, capacitors, etc.) and conventional Jet A fuel. The estimated baseline energy use was equivalent to 41,385 kW-hr assuming conventional Jet-A1 fuel, where the gas turbine propulsive efficiency was approximately ~40% assuming heat losses from combustion and based on state-of-the-art turboprop component efficiencies. The EAP system efficiency was an aggregate of the component efficiencies, where the HETCOF powertrain exhibited significantly improved thermal conversion efficiencies that resulted in block energy savings for the 750 NM design mission, where the TRL 1-2 representative configuration was capable of all-electric cruise operations. The baseline energy consumption per nautical mile (ECNM) is 55.77 kWh/NM where increasing savings are realized with higher degree of electrification during cruise and improved EAP technology projections.

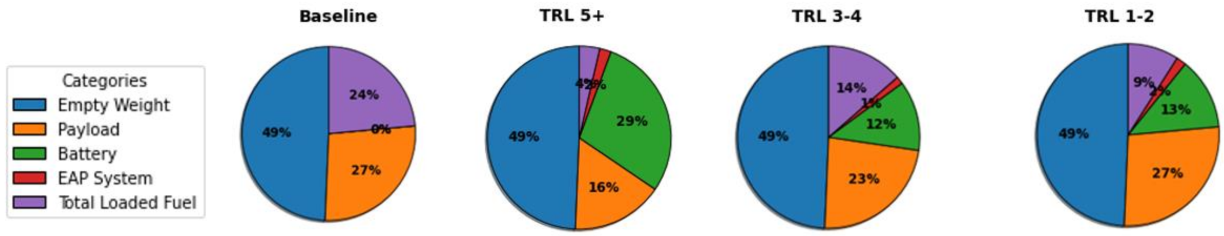

Fig. 12 HETCOF weight composition for representative configurations.

Figure 12 depicts the weight breakdown for the integrated HETCOF aircraft concept – approximately 49% of the aircraft weight is referred to as 'empty' weight which includes the fixed useful load, fixed equipment, furnishings, airframe structures, powerplant installation and dry weights, avionics, de-icing system, and other necessary components of the aircraft without cargo/payload loading. The operating empty weight for the hybrid-electric aircraft concepts include the EAP system weight and electric battery storage, while the total fuel loaded for this concept was based reserve fuel allocation and design mission energy requirements. HETCOF technology configurations relative to the genericized large turboprop freighter with a maximum gross takeoff weight of 70,295 kg capable of facilitating 19,050 kg of payload. However, as the operating empty weight increases with addition of the electrified power and energy system, the allocation for total fuel and payload capacity is penalized by 40%. With decreased TRL level, power and energy density of the electrified powertrain and energy storage systems is improved, leading to a reduced penalty with regards to the payload.

Table 11 Aircraft performance sensitivities to power / thermal system sizing.

Vehicle-Level Performance Metrics **Cruise Power-Split**	**TRL 5+ Tech Level** 25% Electric	**TRL 3-4 Tech Level** 50% Electric	**TRL 1-2 Tech Level** All-Electric
Design Mission Energy Use, kWh			
Fuel Energy	30,121	25,540	13,535
Electric Energy	5,079	6,550	13,465
Total Fuel & Electric	35,200	32,000	27,000
Fuel Burn Reduction per NM, kg-fuel/NM Relative to Baseline	-1.26	-1.77	-3.10
Energy Consumption per NM, kWh/NM	46.93	42.67	36
Max. Payload Capacity, kg	11,350	16,400	19,050
Payload Capacity Reduction, %	-40%	-15%	None
Total Block Energy Savings, %	15%	23%	35%
Block Fuel Savings, %	27.3%	38.6%	67.3%
CO_2 Emissions Reduction per NM, kg-CO_2/NM	-3.98	-5.59	-9.8

Table 11 lists the results of the vehicle benefit assessment for the representative technology configurations where the baseline, reference four-turboprop concept was used to baseline the savings in fuel and energy consumption. The percent differences for block fuel and energy savings scale with decreasing TRL levels, where improved battery specific energy results in reduced penalty to fuel energy storage and payload capacity. The reduction in CO_2 emissions per nautical mile relative to the conventional baseline is -4 to -10 kg-CO_2/NM and block fuel savings for a 750 NM ranging from 27% to 60%, which is significant savings when factoring fuel costs. For the 750 NM mission, this can result in CO_2 emissions reductions of 3,000 to 7,500 kg-CO_2 with improved payload capacity up to maximum for farther term EAP technology improvements. While this preliminary aircraft performance analysis only focuses on the 750 NM mission and the trade-offs between the fuel and payload capacity, future studies will look at optimization of the power/energy management throughout the mission to improve range capabilities.

VII. Conclusion

A significant market exists for the Hybrid Electric Turboprop Commercial Freighter (HETCOF) if the performance and operational requirements can be achieved through technical and system integration advancements beyond the state of the art. The cost requirements are a challenge for initial market penetration; however, the analysis shows that under certain conditions the total cost of ownership and operation may be less than converted narrowbody aircraft that currently serve the market.

For a target range of 750 NM, the HETCOF configurations demonstrate that vehicle benefits scale with improved electrified aircraft propulsion system performance, resulting in reduced CO_2 emissions by a magnitude of 4 to 10 kg-CO_2/NM, block fuel savings of 27% to 67%, and block energy savings of 15 to 35%. Maximum payload capacity compared to a genericized large turboprop freighter increases with improved specific power/energy densities starting at 60% of the baseline for Technology Readiness Level (TRL) 5+, increasing to 85% for TRL 3-4, and reaching full capacity for TRL 1-2. These results substantiate how technological advances in energy storage specific energy and thermal management systems mitigate the weight penalty incurred by electrification.

An integrated power and thermal management system was presented along with the key performance parameters (KPPs) that need to be met for various performance levels. Analysis shows that for a concept like this to have economic and energy benefits many TRL 1-2 level technologies would be needed. Work is ongoing and ARPA-E, NASA, and through industrial efforts to make progress towards the KPPs needed for this concept however substantial further work is required in technology development, integration of the power, thermal, and energy storage systems, and ultimately integration and test on an aircraft.

The most significant result of this paper is that the HETCOF concept can close with reduced fuel burn, energy use, and emissions while retaining some or all of the cargo capability of the baseline aircraft across TRL level assumptions, which enables this platform to be used for near term introduction with increasing benefits as technology matures.

Acknowledgments

This work has been supported by NASA's Convergent Aeronautics Solutions (CAS) Project/Subsonic Single Aft Engine (SUSAN) activity, the NASA Electrified Powertrain Flight Demonstration (EPFD) Project, and the ARPA-E ASCEND program. Economic analysis was done by Volpe Center - Department of Transportation.

References

[1] Pham, D.D.T.V., Recine, C. and Jansen, R.H., "Sizing and Performance Analysis of a MW-Class Electrified Aircraft Propulsion (EAP) System for a Parallel Hybrid Turboprop Concept." In 34th Congress of the International Council of the Aeronautical Sciences (ICAS). 2024.

[2] Pham, D., Bowles, J.V., Zilliac, G.G., Listgarten, N., Go, S. and Jansen, R.H., "Parametric Modeling and Mission Performance Analysis of a True Parallel Hybrid Turboprop Aircraft for Freighter Operations." In AIAA AVIATION FORUM AND ASCEND 2024, p. 3581. 2024.

[3] Epstein, A. H. (2014) 'Aeropropulsion for commercial aviation in the twenty-first century and research directions needed', *AIAA journal*. American Institute of Aeronautics and Astronautics, 52(5), pp. 901–911.

[4] ARPA-E, "Ultrahigh Temperature Impervious Materials Advancing Turbine Efficiency (ULTIMATE)", DE-FOA-0002337, 5 June 2020, https://arpa-e.energy.gov/technologies/programs/ultimate

[5] Kirk, K, "Electrifying transportation reduces emissions AND saves massive amounts of energy", Yale Connections, 7 August, 2022.

[6] Borlaug, B., Salisbury, S., Gerdes, M. and Muratori, M., "Levelized cost of charging electric vehicles in the United States." Joule 4, no. 7 (2020): 1470-1485.

[7] ARPA-E, "Grid-free Renewable Energy Enabling New Ways to Economical Liquids and Long-term Storage (GREENWELLS)", DE-FOA-0003234, 25 January 2024, https://arpa-e.energy.gov/technologies/programs/greenwells

[8] ARPA-E, "Range Extenders for Electric Aviation with Low Carbon and High Efficiency (REEACH)", DE-FOA-0002240, 31 January 2020, https://arpa-e.energy.gov/technologies/programs/reeach

[9] de Bock, H.P., Tew, D.E., Rahman, Z., Lecoustre, V. and Cox-Galhotra, R.A., 2023, June. Progress Toward Climate-Friendly Aviation in the ARPA-E ASCEND and REEACH Programs. In *Turbo Expo: Power for Land, Sea, and Air* (Vol. 86939, p. V001T01A039). American Society of Mechanical Engineers.

[10] Wishart, J. M., Jansen, R. H., Mahavier, K., Coppinger, K, "Hybrid Electric Turboprop Commercial Freighter (HETCOF) Market Study," *AIAA SciTech 2025 Forum*, January 2025, Orlando Florida.

[11] International Air Transportation Association. "The Value of Air Cargo." IATA, Montreal, Canada, 2021. Available: https://www.iata.org/contentassets/62bae061c05b429ea508cb0c49907c4c/air-cargo-brochure.pdf

[12] International Air Transportation Association. "Air Cargo Market Analysis." IATA, Montreal, Canada, December 2023. Available: https://www.iata.org/en/iata-repository/publications/economic-reports/air-cargo-market-analysis-deember-2023/

[13] Haglage, J.M., Dever, T.P., Jansen, R.H., and Lewis, M.A., "Electrical System Trade Study for SUSAN Electrofan Concept Vehicle," AIAA 2022-2183, AIAA SciTech Forum, San Diego, CA & virtual, 3-7 January 2022.

[14] Tallerico, T., Anderson, A., Scheidler, J.J., Jansen, R. and Sixel, W., "Concept design of a 5 MW partially superconducting generator." In AIAA AVIATION 2023 Forum, p. 4505. 2023.

[15] Tallerico, T.F., Anderson, A.D. and Scheidler, J.J., "Design optimization studies of partially superconducting machines based on NASA's high efficiency megawatt motor." In 2021 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), pp. 1-29. IEEE, 2021.

[16] Tallerico, T.F. "NASA Reference Motor Designs for Electric Vertical Takeoff and Landing Vehicles." In 2021 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), pp. 1-41. IEEE, 2021.

[17] Jansen, R.H., Kascak, P., Dyson, R., Woodworth, A., Scheidler, J., Smith, A.D., Stalcup, E., Tallerico, T., de Jesus-Arce, Y., Avanesian, D. and Duffy, K., "High efficiency megawatt motor preliminary design." In 2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), pp. 1-13. IEEE, 2019.

[18] Pastra, C.L., et al. "Specific Power and Efficiency Projections of Electric Machines and Circuit Protection Exploration for Aircraft Applications." 2022 IEEE Transportation Electrification Conference & Expo (ITEC). IEEE, 2022.

[19] Kowalewski, S.R., Blystone, J., Maroli, J.M., Granger, M., Avanesian, D., Belovich, E., Liederbach, G. and Miller, W., "NASA's X-57 High Lift Motor Controller: Detailed Design, Test Results, and Outcomes." In AIAA AVIATION FORUM AND ASCEND 2024, p. 4134. 2024.

[20] Granger, M.G., Avanesian, D., Jansen, R., Kowalewski, S.R., Leary, A., Bowman, R., Dimston, A., Stalcup, E. and Miller, W.A.,"Design of a High Power Density, High Efficiency, Low THD 250kW Converter for Electric Aircraft." In AIAA Propulsion and Energy 2021 Forum, p. 3332. 2021.

[21] Garrett, M., Avanesian, D., Granger, M., Kowalewski, S., Maroli, J., Miller, W., Jansen, R. and Kascak, P., "Development of an 11 kW lightweight, high efficiency motor controller for NASA X-57 Distributed Electric Propulsion using SiC MOSFET Switches." In 2019 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), pp. 1-8. IEEE, 2019.

[22] Hall, C., Pastra, C.L., Burrell, A., Gladin, J. and Mavris, D.N., "Projecting Power Converter Specific Power Through 2050 for Aerospace Applications." 2022 IEEE Transportation Electrification Conference & Expo (ITEC). IEEE, 2022.

[23] Dever, T.P. and Jansen, R.H., "Cable Key Performance Parameters for Megawatt Electrified Aircraft Propulsion Conceptual Aircraft Model." In 2022 IEEE Transportation Electrification Conference & Expo (ITEC), pp. 748-753. IEEE, 2022.

[24] Dever, T., Lantz, T. and Jansen, R., "Cable Key Performance Parameter Projections for Megawatt Electrified Aircraft Propulsion Models." In AIAA SCITECH 2024 Forum, p. 1328. 2024.

[25] Tiede, B., O'Meara, C., and Jansen, R. "Battery Key Performance Projections based on Historical Trends and Chemistries." 2022 IEEE Transportation Electrification Conference & Expo (ITEC). IEEE, 2022.

[26] ARPA-E, "Electric Vehicles for American Low-Carbon Living (EVs4ALL)", DE-FOA-0002760, 16 June 2022, https://arpa-e.energy.gov/technologies/programs/evs4all

[27] ARPA-E, "Pioneering Railroad, Oceanic, and Plane ELectrification with 1K Energy Storage Systems (PROPEL-1K)", DE-FOA-0003162, 17 October 2023, https://arpa-e.energy.gov/technologies/programs/propel-1k

[28] ARPA-E, "Announcement of Teaming Partner List for an upcoming FOA: Solicitation on Topics Informing New Program Areas: Connecting Aviation by Lighter Electric Systems (CABLES)", RFI-0000050, 2020, https://arpa-e.energy.gov/technologies/exploratory-topics/aviation-power-distribution.

[29] ARPA-E, "Aviation-Class Synergistically Cooled Electric-Motors with Integrated Drives (ASCEND)", DE-FOA-0002238, 31 January 2020

[30] Stalcup, E. J., Dever, T. P., and Sachs-Wetstone, J. J., "Thermal Management Key Performance Parameter Development and System Analysis for the SUSAN Electrofan Aircraft," *AIAA SciTech 2025 Forum*, January 2025 (to be published).