

Sizing Power Components of an Electrically Driven Tail Cone Thruster and a Range Extender

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The aeronautics industry has been challenged on many fronts to increase efficiency, reduce emissions, and decrease dependency on carbon-based fuels. This paper provides an overview of the turboelectric and hybrid electric technologies being developed under NASA's Advanced Air Transportation Technology (AATT) Project and discusses how these technologies can impact vehicle design. The discussion includes an overview of key hybrid electric studies and technology investments, the approach to making informed investment decisions based on key performance parameters and mission studies, and the power system architectures for two candidate aircraft. Finally, the power components for a single-aisle turboelectric aircraft with an electrically driven tail cone thruster and for a hybrid-electric nine-passenger aircraft with a range extender are parametrically sized, and the sensitivity of these components to key parameters is presented.

I. Introduction

THE aeronautics industry has been challenged on many fronts to increase efficiency, reduce emissions, and decrease dependency on carbon-based fuels. The NASA Aeronautics Research Mission Directorate has identified a suite of investments to meet long term research demands beyond the purview of commercial investment. Electrification of aviation propulsion through turboelectric or hybrid electric propulsion is one of many exciting research areas which has the potential to revolutionize the aviation industry. This paper will provide an overview of the turboelectric and hybrid electric technologies being developed under NASA's Advanced Air Transportation Technology (AATT) Project, and how these technologies can impact vehicle design. An overview will be presented of vehicle system studies and the electric drive system assumptions for successful turboelectric and hybrid electric propulsion in single aisle size commercial aircraft. Key performance parameters for electric drive system technologies will be reviewed, and the technical investment made in materials, electric machines, power electronics, and integrated power systems will be discussed. Finally, power components for a single aisle turboelectric aircraft with an electrically driven tail cone thruster and a hybrid electric nine passenger aircraft with a range extender will be parametrically sized.

Aircraft or propulsion system studies have been performed for numerous turboelectric and hybrid electric propulsion options. This paper will not serve as an all-encompassing review, but will identify the vehicle-level benefits enabled by propulsion electrification. Previous studies have highlighted the need for advancements in electric drive components (gas turbine generators, electric motors and power system components) in order to exploit the advantages of combining electricity and fuel to drive the aircraft propulsion system. Projected overall vehicle benefits stem from the improvements in aerodynamic and propulsive efficiency balanced by the additional mass and losses of the added electrical components. Typically system studies assume performance levels of electric drive components or include parametric studies of some propulsion drive components. Results are included in this review of drive system key performance parameters derived from parametric analysis of expected propulsion-airframe-integration performance benefits.

The focus of efforts in AATT are for future 150 passenger, single aisle transport planes. Studies show that 40 percent of fleet fuel is used by single aisle 150 to 210 passenger size class vehicles and aircraft larger than 100 passenger account for 87 percent of fleet fuel consumption. The Hybrid Gas Electric Subproject (HGEP) of AATT has been envisioned as a long-term development effort to mature technologies and close gaps in key performance parameters for electric machines and power systems. The subproject investment is partitioned between aircraft

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configuration system studies, power system studies and testing, advancement of electric machines and power electronics, and development of enabling magnetic, insulation, and conductor materials.

II. Turboelectric and Hybrid Electric Propulsion Configurations

The interest in hybrid propulsion for aviation stems from the flexibility electric drive systems can provide to the vehicle design trade space. For illustrative purposes, consider the notional three-dimensional space shown in Fig. 1. The three axes on this figure are the Energy Storage axis (“Storage” axis), the Propulsion-Airframe Integration axis (“Integration” axis), and the Energy Conversion axis (“Conversion” axis). The Storage axis describes the amount of energy stored electrically. Similarly the Integration axis describes the level to which propulsion and airframe systems interact synergistically, and the Conversion axis represents the amount of propulsive energy delivered directly as shaft power compared to that converted and delivered electrically.

At the origin of this cube is a state-of-the-art single aisle transport aircraft with two turbo-fan engines; here all of the energy is stored in jet fuel. These state of the art engines are already equipped with generators that convert part of the shaft energy to electricity used for non-propulsive applications. As you progress out the Storage axis more and more energy is stored in batteries or an equivalent electrical storage system.

The Integration axis represents classes of propulsion-airframe integration that can improve aerodynamic efficiency. This axis is not a continuum, but can be thought of as bins of configuration options such as wing tip propulsors, boundary layer ingestion, and distributed propulsion. Note that these configurations do not require hybrid propulsion; however the advancements in electric drive and power distribution systems open the possibility for these aerodynamic concepts to be implemented in new, efficient vehicle configurations.

At the origin of the Conversion axis no jet fuel is converted into electricity for propulsion purposes. At the maximum of the conversion axis, all of the turbine energy is converted to electricity; this represents a turboelectric drive configuration. Many options are available on the conversion axis. Options include: parallel hybrid, where electric drive and mechanical drive combine at the shaft; series hybrid, where electric drive and turbo-electric drive combine at the bus; and various series/parallel combinations.

The purpose of this notional design space is to emphasize the breath of vehicle and propulsion system configurations that can be considered under the auspices of hybrid propulsion. One could also consider other axes which represent vehicle size and as well as other body styles, such as hybrid wing body.

The NASA Subsonic Fixed Wing Project, the predecessor to Advanced Air Transport Technology Project, sponsored several vehicle studies to target aggressive third generation (N+3) performance goals. These studies found that combinations of improved technology and radical configuration changes were required to meet these aggressive goals. Select results are summarized in Table 1. The studies marked with an asterisk use some form of electric power to improve propulsion performance. The Boeing SUGAR Volt¹ design was an extension of the SUGAR High,² which used a parallel hybrid electric drive concept to augment the cruise portion of the mission by driving the fan with battery powered motors. Although the fuel and emission goals were met, it was found that the overall vehicle energy efficiency was not improved over that of the SUGAR High design. The N3-X³ is a blended wing body type design with a fully

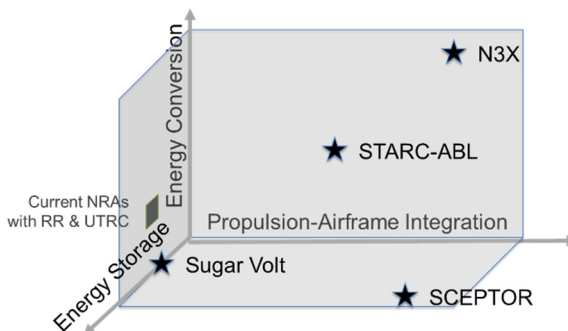


Fig. 1 Hybrid Electric Trade Space

Table 1 N+3 Sponsored Studies for Single Aisle and Larger Aircraft

	Improvements Relative to Baseline ^a		
	Noise Margin ^b	LTO NO _x ^c	Fuel Consumption
N+3 Goals	52 dB	80%	60%
SUGAR High ²	23 to 30 dB	78 %	54%
^d SUGAR Volt ¹	24 to 31 dB	83 to 90%	60%
MIT D8.5 ⁴	60 dB	87%	70%
^d N3-X ³	32 to 64 dB	85%	70%

^a737 to 800 class baseline for SUGAR & MIT, 777 to 200 class baseline for N3-X

^bCumulative relative to Stage 4

^cPercent reduction relative to CAEP/6

^dElectric power used in propulsion system

turboelectric and fully distributed propulsion design utilizing superconducting electric machines and power distribution. Approximately 50 percent of the fuel consumption improvement came from the airframe configuration, and another 20 percent from the turboelectric distributed propulsion. These two studies can be represented at points at the lower left and upper right of the notional hybrid propulsion design space, as seen in Fig. 1. It should be readily apparent that there are many more configuration options to explore.

Although hybridizing an in-line turbine engine does not offer inherent aerodynamic improvement, it could be an attractive first step from an ease of implementation perspective. Electricity is already generated from the turbine engine shafts; replacing the generator with a motor/generator would be straightforward. NASA has ongoing contracts with United Technologies Research Center and Rolls-Royce North America to expand understanding of the parallel hybrid electric propulsion trade space. These studies are exploring mission optimization using battery power to drive fans for taxiing, idle decent, and take-off power augmentation. Concept selection recommendations are expected later in 2016. Additionally, NASA is expanding its exploration of turbo-electric drive propulsion options by a series of studies called Single aisle Turboelectric AiRCraft (STARC). The first STARC configuration looked at distributing propulsion to one motor driven fan only and this electric drive system will be considered in greater detail as one promising transport class aircraft.

A. STARC-ABL Overview

A single-aisle commercial transport concept with a turboelectric propulsion system architecture was developed assuming entry into service in 2035 and compared to a similar technology conventional configuration by Welstead and Felder.⁵ This, STARC-ABL, concept is shown in Fig. 2. The turboelectric architecture consisted of two underwing turbofans with generators extracting power from the fan shaft and sending it to a rear fuselage, axisymmetric, boundary layer ingesting fan. Results indicate that the turbo-electric concept has an economic mission fuel burn reduction of 7 percent, and a design mission fuel burn reduction of 12 percent compared to the conventional configuration. An exploration of the design space was performed to better understand how the turboelectric architecture changes the design space, and system sensitivities were run to determine the sensitivity of thrust specific fuel consumption at top of climb and propulsion system weight to the motor power, fan pressure ratio, and electrical transmission efficiency of the aft boundary layer ingesting fan.

B. SCEPTOR Thin Haul Overview

Several aircraft concepts are being developed at NASA which use a large number of electrically driven propulsors coupled with battery energy storage as the primary power source to enable new types of propulsion airframe integration resulting in efficiency and emissions benefits. The NASA SCEPTOR project has been investigating the benefits of Distributed Electric Propulsion technology, through system studies, development of ground test articles, and more recently on the design of a flight demonstrator to establish and verify some of the potential benefits associated with this technology.⁶ A challenge with this concept is the relatively low specific energy of batteries compared to fuel. Even with a three-fold increase in efficiency, this is a prohibitive mass penalty if one were to simply swap a gasoline engine for an equivalent electric motor and attempt to get the same payload and range performance as the gasoline-powered counterpart. However, this impact is lessened if the mission capabilities of the aircraft are matched to use, rather than design cases. A notional design for a nine passenger aircraft using this technology is shown in Fig. 3.



Fig. 2 STARC-ABL Concept



Fig. 3 SCEPTOR 9 Passenger Concept

III. Overview of Hybrid Gas Electric Subproject

A. Programmatic Background

The AATT project manages a broad range of technology development investments for transport class vehicles. Three focus areas are envisioned to combine to reduce carbon emission and overall use of fossil fuels by looking at: individual and combined effects of aerodynamic efficiencies gain by the use of boundary layer ingestion methods and advanced vehicle designs such as a blended wing body or truss-braced wings, advances in small core technologies for highly efficient (and smaller) gas turbines, and hybrid gas-electric propulsion systems. The investment in hybrid propulsion offers the design freedom necessary to distribute propulsors across the vehicle or exploit vehicle shapes to enable those aerodynamic efficiencies promised in advanced concepts, and also can take advantage of emerging capabilities in energy storage devices to reduce the size of on-board gas turbine engines and reduce the use of fossil fuels by relying partially or wholly on electricity to drive the propulsors.

Hybrid power generation and distributed propulsive power have been identified as candidate transformative aircraft configurations for future commercial transport vehicles which reduce fuel burn and harmful emissions.⁷ However, a technological hurdle exists in that the components for power generation, distribution, and transformation are not currently available in the high power ranges with the necessary efficiency and power density required for transport-class aircraft. Although the wind and marine industries have some overlapping requirements with potential electric aircraft propulsion, the particular combination of high power, high efficiency, and low mass (high specific power) present a unique requirement in the aircraft case. Power generation and distribution using superconducting systems with extremely lower power losses offer intriguing propulsion system benefits for single aisle and larger aircraft.

B. AATT-HGEP Technology Metrics

Within the Hybrid Gas Electric Subproject (HGEP), system studies are ongoing to find configurations of hybrid electric systems which will result in a net fuel burn savings, emission reduction, and noise reduction at the aircraft level. The subproject has defined key performance metrics to inform component and material development investments. For the motor and power electronics system, specific power and efficiency are used as the two key performance parameters (KPPs) of the electric drive system. Specific Power is the ratio of the rated power to mass of the system. Efficiency is the ratio of the output to the input power of the system. Additionally, the system boundaries are carefully and consistently defined to maintain consistent comparisons across technologies.

Key performance parameters serve three purposes. First, hybrid electric aircraft propulsion system performance can be estimated using simplified mass and efficiency models for the power system elements. Second, various motor or inverter types and new technologies can be compared, allowing better investments selections. Finally, the impact of material level investments on motors or inverters can be assessed by estimating the impact to the key performance parameters.

C. AATT-HGEP Investment Strategy

The HGEP Investment Strategy is to use system studies to define a leading hybrid aircraft candidate configuration, make technology investments targeting the tall pole technologies of that configuration, and perform integrated demonstrations to inform both the system studies and the technology requirements. The subproject investment is partitioned between aircraft configuration system studies, power system studies and testing, advancement of electric machines and power electronics, and development of enabling magnetic, insulation, and conductor materials. Where possible key performance metrics are used to guide the technology investments. The work is performed by a mix of industry partners, universities, and NASA civil servants and onsite contractors.

Technology investments are made to support a broad range of aircraft concepts. When selecting the power level for electric machines and inverter investments, the size required for aircraft concepts between 9 and 300 passengers were considered, with propulsion systems using a hybrid or completely electric power for propulsion. An overview chart is shown in Fig. 4. Each bar in the figure represents a size class of aircraft which corresponds to an approximate total propulsive power requirement listed above the bar. The width of the bar represents the range of electric machine sizes that may be expected within this class of aircraft. Selection of configuration (all electric, hybrid electric or turboelectric) affects the electric machine size. The number of propulsive fans also has a large impact. For example, a configuration may have two 10 MW generators and twenty 1 MW motor-driven fans, resulting in machine sizes that vary by an order of magnitude on the same aircraft. It can be seen that 1 MW-level electric machines and power electronics can be used on multiple platforms for example a smaller 19 passenger fully electrified aircraft as well as on larger aircraft up to 150 passenger partially electrified systems. This range of applicability led to the selection of 1 MW level machines the focus of the HGEP technology development subproject.

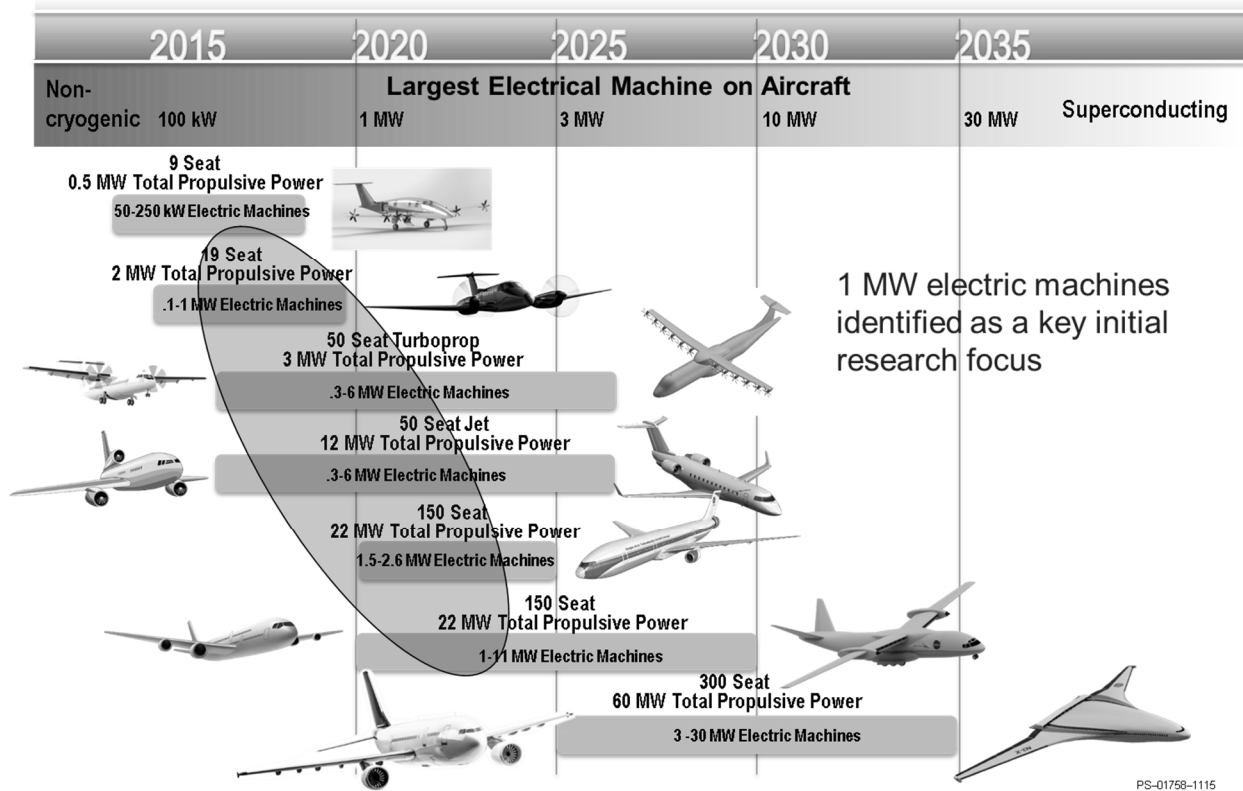


Fig. 4 Electric Machine Size for a Range of Hybrid Aircraft Concepts

IV. Some Key AATT-HGEP Technology Developments

A. High Specific Power 1 MW Electric Machines

The HGEP subproject and its predecessors has ongoing investments in superconducting motor technology over the last decade. HGEP has expanded the investments in advanced motors which do not require superconductors in the last two years, including a NASA Research Announcement (NRA) with the objectives to develop key technologies for and to conduct demonstrations of a highly efficient (> 96 percent) and high power density (13.2 kW/kg) MW-class non-cryogenic motor designed for hybrid gas-electric aircraft propulsion. The key performance parameters are shown in Table 2. The two projects being conducted under the NRA have different approaches, one using a permanent magnet synchronous design and the other an induction motor design. In addition to the hardware and performance demonstrations at the 1 MW level, both of the activities also include studies to evaluate scalability to 10 MW.

Table 2 Motor Key Performance Parameters

	Specific Power (kW/kg)	Specific Power (hp/lb)	Efficiency (%)
NRA Goal	13.2	8.0	96.0

Superconducting motor research is focused on completing a 1 MW demonstration of a fully superconducting motor. A fully superconducting motor uses superconducting cable on both the rotor and the stator of the motor to maximize the specific power and efficiency. This is an advancement over the state of the art, which does not use superconducting wire on the AC (stator) portion of the motors; this is because alternating current results in low performance and high losses for most superconductors. Accordingly, other large superconducting motors that have been demonstrated for the Navy have used copper conductors on the stator of the motor. Under this project a new type of magnesium diboride superconducting wire which uses a twisted multi-filament was developed, and its performance parameters are being measured. This new type of superconducting wire enables the creation of a fully superconducting electric machine with three phase alternating current stator currents in the frequency range required for the large aircraft application.

B. High Specific Power, High Efficiency 1 MW Inverters

HGEP currently has ongoing investments in 1 MW size inverters with the objective to design, build, and test a technology demonstrator for a high efficiency/high specific power MW-class inverter intended to meet the anticipated needs of aircraft electric propulsion drives. As power electronics are a significant contributor to vehicle weight, this technology demonstration will be a key part of the AATT project’s technology development portfolio in the area of hybrid electric propulsion. Investigation are being made in both room temperature and cryogenic inverters.

The configuration being developed uses a 1000 V DC bus input and a three phase AC output and will be compatible with a range of motor types including permanent magnet, induction, and reluctance. The inverter may also be used as an active rectifier. The inverter drive control system is not part of this effort. The key performance metrics of the inverter are shown in the Table 3. Specific power is measured as the ratio of the rated continuous power to the mass of the inverter including power electronics, input and output filters, and packaging. Scalability to the 10 MW level is being evaluated.

Table 3 Inverter Key Performance Parameters

	Specific Power (kW/kg)	Specific Power (HP/lb)	Efficiency (%)
Minimum	12	7.3	98.0
Goal	19	11.6	99.0
Stretch	25	15.2	99.5

C. Advanced Motor Control

In addition to making investments in the inverter to reduce its weight and losses, HGEP is also investing in advanced motor control technologies. By addressing the combination of motor, inverter, and integrated control, additional performance benefits can be achieved beyond what can be accomplished at the component level. In order to facilitate the implementation of advanced controls, drives which have microprocessors that can be directly programmed from the Matlab/Simulink environment are being implemented. This approach allows controller and plant modeling efforts to be directly transitioned to hardware in the loop testing.

V. Sizing Power Components of an Electrically Driven Tail Cone Thruster

The STARC-ABL turboelectric single aisle concept is a tube and wing style aircraft with two turbofans and an electrically powered aft thruster. The configuration has a 7 to 12 percent fuel burn benefit compared to a two turbofan version using the same technology assumptions⁵. The power system transfers electric power from wing mounted turbofans to an aft mounted thruster fan. The motor for the thruster fan runs at a continuous power rating of 3500 hp (2.61 MW). This aft thruster accounts for 20 percent of the thrust at the rolling take off (RTO) point and 44 percent of the thrust at top of climb (TOC) point. A diagram of a notional power system is shown in Fig. 5. Generators in the wing mounted turbofans provide the power; distribution is accomplished by rectification and DC distribution; both the source and return side of the DC distribution is carried on power cables, and a pair of DC breakers are used in each leg. The tailcone fan is driven by an inverter controlled motor. The electric machine parameters used for the generators and motor are 13 kW/kg at 96 percent efficiency. The rectifier and inverter parameters are 19 kW/kg at 99 percent efficiency. These parameters were based on current research work being undertaken to build prototype 1MW hardware that meets these specifications. The cable 170 A/(kg/m) specific ampacity is based on a 0000 gauge copper 1000 V marine cable. An aluminum aircraft cable will have lower mass, however, the ampacity also needs to derated for bundling effects. The circuit protection has a specific power of 200 kW/kg and an efficiency of 99.5 percent which is in line with a recent study⁸ which found a best case DC breaker ratings of 329 kW/kg and 99.77 percent efficiency at 6500 V. Details of the thermal systems design are less mature for this concept, and initial parametric estimates were used. The end to end electrical efficiency of the system is 89 percent and the weight is estimated at 1394 kg (3073 lbm). Details are summarized in Table 4.

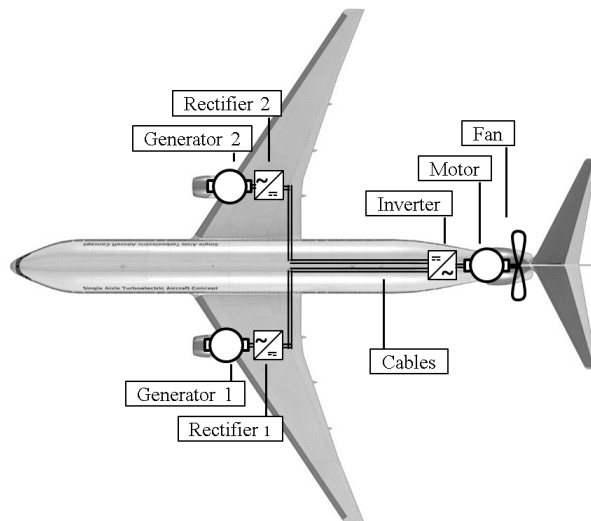


Fig. 5 Notional STARC-ABL Power System

Table 4 STARC-ABL Mass and Efficiency Estimate With Listed Specific Power Assumptions

Component	Quantity	Specific Power	Efficiency (%)	Power (kW)	Weight (kg)	Losses (kW)
Generator (2)	2	13.0 kW/kg	96.0%	1400	215	117
Rectifier (2)	2	19.0 kW/kg	99.0%	1386	146	28
Cable	2	170 A/(kg/m)	99.6%	1380	192	11
Circuit Protection	4	200 kW/kg	99.5%	1373	13.6	28
Inverter	1	19.0 kW/kg	99.0%	2719	143	27
Electric Motor	1	13.0 kW/kg	96.0%	2610	201	109
Thermal System		0.68 kW/kg		291	470	
Total System			89.1%		1394	320

A parametric sensitivity analysis to the specific power of the electric machines, power electronics, and cable voltage was conducted to evaluate of weight sensitivity of the power system to these parameters. Fig. 6 shows the sensitivity of the power system weight to each of the three parameters. In this figure, total system weight is plotted against the specific power (S.P.) of the electric machine (motor and generator) and converter (inverter and rectifier), and the system voltage.

The electric machine specific power was varied from 6 to 20 kW/kg to representing high performance conventional electric machines to a superconducting machine. The converter specific power was varied from 12 to 26 kW/kg representing high performance traction drive power electronics something near the state of the art up to a very advanced wide band gap system. The cable voltage was varied from 600 V, the state of the art, to 5400 V which is in the range used for certain large marine applications.

One observation that can be made is that the power that can be carried on a cable is directly proportional to voltage (assuming the insulation thickness is a negligible portion of the overall cable size and the cable is sized by current carrying capacity). The amount of power that can be carried in a given cable is the most influential parameter in this analysis; using the state of the art voltage here results in an overall system weight twice the notional point design shown in Table 4. A second observation is that increasing the electric machine specific power, to the NRA target levels makes significant progress towards the knee of the weight sensitivity curve in this system. Finally, improvements in the specific power of the converters has the least impact on the system weight; however, improvements in the converter voltage rating are required to enable operation at the high system voltage, and improvements in the converter efficiency will reduce the weight of the thermal management system. Neither of these effects are accounted for in this simple analysis.

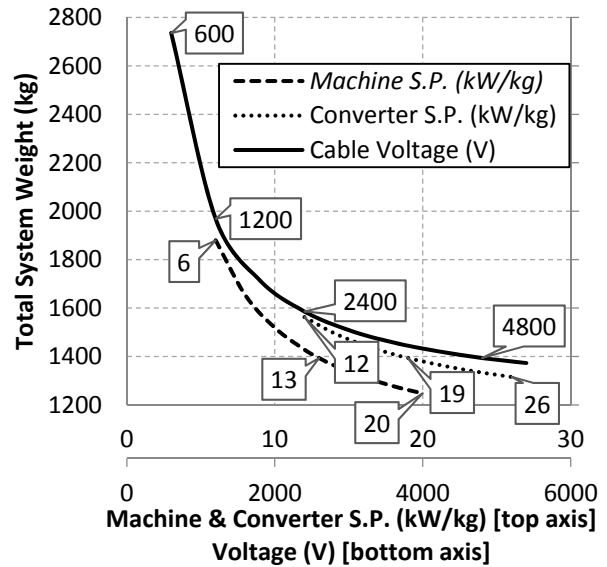


Fig. 6 Tailcone Thruster Power System Weight Sensitivity

VI. Sizing Power Components of a Range Extender

An example of parametric sizing of a range extender will be presented using a notional electric aircraft configuration (Fig. 7) similar to that being developed under the NASA SCEPTOR project. The notional aircraft can carry the pilot and nine passengers and uses electrically driven motors to provide all of the propulsive force. Six 33 kW high lift inverter driven motors are used to blow the wing, shortening the takeoff length and reducing the wing size. Two 150 kW inverter driven wing tip motors are used to provide thrust. The parameters used for the electric machines are 6 kW/kg at 96 percent efficiency and the power electronics are 13 kW/kg at 98 percent efficiency. The primary power source is a battery, which enables the aircraft to fly for approximately one hour without in air fuel use or emissions. The battery specific energy is estimated at 207 W-hr/kg which is based on a 300 W-hr/kg cell level energy density, a 90 percent useful depth of discharge and 30 percent weight increase to account for battery structure and the battery management system. The battery is sized for 20 minutes of full power operating plus 1 hour of cruise power operation totaling 381 kW-hr. A 225 kW range extender, consisting of a turbine and generator connected to the bus with an active rectifier, can be added to increase the maximum flight time and range. Power is distributed using a DC bus with circuit breakers at each inverter, the battery, and the range extender. It is assumed that both the source and return power is transmitted using cables. The cable has 170 A/(kg/m) specific ampacity and the bus voltage is 400 V. A thermal management system is used to transfer heat generated by losses to the airstream with a specific power of 0.68 kW/kg. Details are shown in Table 5.

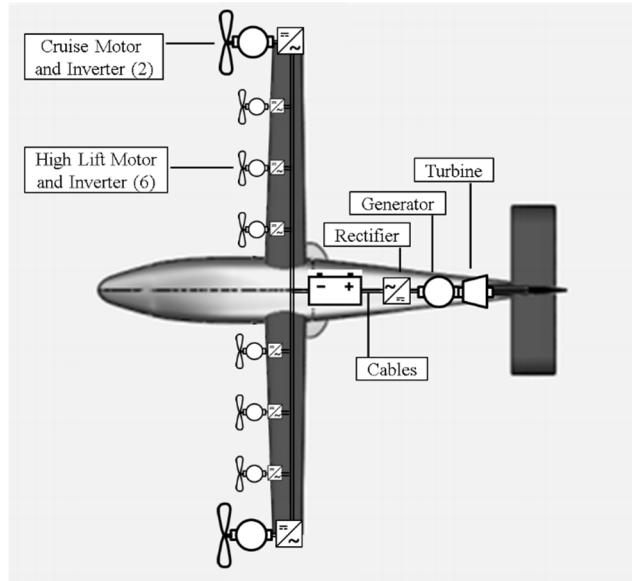


Fig. 7 Electric Plane With Range Extender

Table 5 Power System Weights, Efficiencies and Losses

Component	Quantity	Specific Power	Efficiency	Size	Weight (kg)	Losses (kW)
Battery	1	208 W-hr/kg	93.0%	381 kW	1833	36
Generator	1	6.0 kW/kg	96.0%	230 kW	38.3	10
Rectifier	1	13.0 kW/kg	98.0%	225 kW	17.3	5
Cable (2 pairs × 33 ft), 400 V/477 A)	2	170.0 A/(kg/m)	99.6%	191 kW	112.1	2
Circuit Protection (inverters, battery, rectifier)		200.0 kW/kg	99.5%	754 kW	3.8	0
High Lift Inverter	6	13.0 kW/kg	98.0%	34 kW	15.9	4
High Lift Motor	6	6.0 kW/kg	96.0%	33 kW	33.0	8
Cruise Inverter	2	13.0 kW/kg	98.0%	156 kW	24.0	6
Cruise Electric Motor	2	6.0 kW/kg	96.0%	150 kW	50.0	13
Thermal Management System		0.68 kW/kg	0.0%	83kW	122.6	
Total System			82.1%		2250	83

Sensitivity of the power system weight to the specific energy (S.E.) of the batteries, the bus voltage, and the specific heat rejection (S.H.R.) of the thermal management system was evaluated and is shown in Fig. 8. The useable specific energy of the batteries was varied between 140 to 290 kW-hr/kg, the bus voltage of the cables was varied between 100 and 600 V, and the specific heat rejection of the thermal management system was varied between 0.3 and 1.1 kW of heat rejected per kg. Not surprisingly, the weight of the power system is most sensitive to the battery performance, since it is the dominant mass in the system. The variation in bus voltage from 100 to 600 V reduces the system weight by 375 kg. The improvement in specific heat rejection of the thermal management system from 0.3 to 1.3 kW/kg reduces system weight by approximately 200 kg.

VII. Conclusions

Efforts to provide partially or fully electric propulsion for passenger aircraft are aided greatly by early infusion of electric components into propulsion strings in lower power applications—either in small flight demonstrations or in commercial use. The technology is disruptive to the degree that systems interactions such as controls, cooling, operations, and maintenance will need to be exercised and optimized so that the fuel savings predictions (when combined with advanced vehicle designs) of up to 60 percent when compared to 2013 aircraft can be achieved. A sizing study of the power system has been performed for a turboelectric configuration with a tail cone thruster based on advanced electric machines (13 kW/kg and 96 percent efficiency) and power electronics (19 kW/kg and 99 percent efficiency) which showed that bus voltage and resultant cable weight is a very important driver of power system weight. A second power system sizing study was conducted for a range extender using less advanced motors (6 kW/kg and 96 percent efficiency) and power electronics (13 kW/kg and 99 percent efficiency) for a thin haul commuter range extending turbogenerator. Power system weight, efficiency and losses are estimated for both cases and parametric weight studies were completed.

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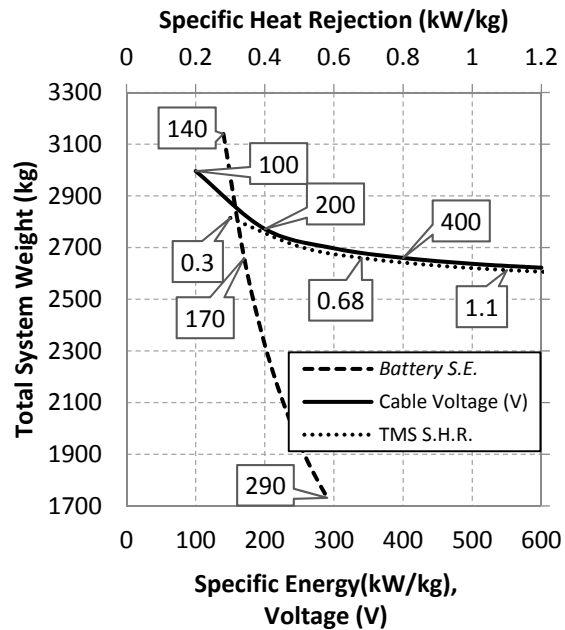


Fig. 8 Range Extender Power System Weight Sensitivity