Technical and Environmental Assessment of All-Electric 180-Passenger Commercial Aircraft

by

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Abstract

Aviation emissions contribute to climate change, and all-electric aircraft offer an opportunity for zero in-flight emissions. Over the past decade, more than 50 all-electric conceptual, experimental, and commercial aircraft have been researched, with a particular focus on light aircraft. These designs are reviewed, along with progress in battery technology. An all-electric aircraft design and optimization program, TASOPTe, has been developed from an existing version for conventionally-powered aircraft, TASOPT. Both programs are largely based on first-principles, enabling the design of aircraft with unusually short design ranges. A series of optimized 180-passenger aircraft based on the Airbus A320neo configuration are designed and evaluated at 200-1600 nmi design ranges with 2-10 propulsors and 400-2000 Wh/kg batteries. The performance of these all-electric aircraft is compared to advanced conventionally-powered aircraft optimized for the same design ranges. Optimized all-electric aircraft are found to use two or four propulsors, depending on the design range and specific energy assumed. The design range limits for each specific energy are determined, which are restricted by aircraft weight and performance penalties. A factor of four increase in battery pack specific energy from current values of 200 Wh/kg to 800 Wh/kg enables 500 nmi flights. However, a lower design range of 300 nmi provides improved energy and environmental performance. The required grid power generation circumstances for commercial all-electric aircraft to become net environmentally beneficial is determined for each specific energy assumption. The entire energy conversion chain, including charging, transport, and discharging of electrical energy, is considered. Despite the higher total energy use, narrow-body all-electric aircraft have the potential for lower equivalent CO₂ emissions if the electrical grid transitions toward renewable energy. This is largely enabled by the complete elimination of all high-altitude emissions, which would remove associated non-CO₂ warming.

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Nomenclature

Acronyms and Abbreviations

AC	Alternating Current
AEA	All-Electric Aircraft
AGWP ₁₀₀	100-year Absolute Global Warming Potential
Al-air	aluminum-air
BAU	Business-As-Usual
BHL	Bauhaus Luftfahrt e.V.
BLI	Boundary Layer Ingestion
BMS	Battery Management System
CO ₂	carbon dioxide
CO ₂ e	carbon dioxide equivalent
DEP	Distributed Electric Propulsion
ECS	Environmental Control System
HRE	Highly Renewable Energy
HT	Horizontal Tail
HTS	High-Temperature Superconducting
ISA	International Standard Atmosphere
LG	Landing Gear
Li-air	lithium-air
Li-ion	lithium-ion
Li-S	lithium-sulfur
Li-Se	lithium-selenium
LSA	Light-Sport Aircraft
LTO	Landing and Takeoff
MEA	More-Electric Aircraft
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NB	Narrow-Body
nmi	nautical miles
NO _x	nitrogen oxides
NPV _{3%}	Net Present Value at a 3% Discount Rate
NREL	National Renewable Energy Laboratory
OAG	Official Airline Guide
ODM	On-Demand Mobility
OEI	One Engine Inoperative
PMAD	Power Management and Distribution

SSPC	Solid State Power Controller
TASOPT	Transport Aircraft System OPTimization
TASOPTe	Transport Aircraft System OPTimization – electric
ULA	Ultra-Light Aircraft
USD	U.S. Dollar
VAN	Variable Area Nozzle
VT	Vertical Tail
VTOL	Vertical Takeoff and Landing
Zn-air	zinc-air

Symbols

b	wing span [m]
D	drag [N]
DOD	depth-of-discharge [%]
E	energy [Wh]
E^*	specific energy [Wh/kg]
E/P	energy to productivity ratio [-]
f	battery mass fraction [-]
FPR	fan pressure ratio [-]
g	acceleration due to gravity [m/s^2]
I	current [A]
k	oxygen to active battery mass ratio [-]
L	lift [N]
L/D	lift to drag ratio [-]
$l_{LG,main}$	main landing gear length [m]
$l_{LG,nose}$	nose landing gear length [m]
l_v	wing to vertical tail aerodynamic center distance [m]
M	Mach number [-]
$m_{aircraft}$	aircraft mass [kg]
m_b	battery mass [kg]
$n_{w,LG,main}$	number of main landing gear wheels [-]
$n_{w,LG,nose}$	number of nose landing gear wheels [-]
P	power [W]
P^*	specific power [W/kg]
$P_{aircraft}$	aircraft power [W]
PAX	passengers [-]
P_b	battery power [W]
$PFEI$	payload fuel energy intensity [kJ/kg-km]

R	range [m, nmi], resistance [Ω]
S	wing planform area [m^2]
SOC	state-of-charge [%]
S_v	vertical tail planform area [m^2]
t	time [s]
U	voltage [V]
U_{oc}	open-circuit voltage [V]
v_∞	flight speed [m/s, kt]
v_{stall}	stall speed [m/s, kt]
$W_{LG,main}$	main landing gear weight [t]
$W_{LG,nose}$	nose landing gear weight [t]
W_{ML}	maximum landing weight [t]
W_{MTO}	maximum takeoff weight [t]
W_{pay}	payload weight [t]
z	active to total battery mass ratio [-]
$\eta_{overall}$	overall aircraft efficiency [-]
η_p	polytropic efficiency [-]

Chapter 1

Introduction

Climate change, due to aviation and other sources, poses risks for humans and the ecosystem in the form of rising sea levels, more frequent extreme weather episodes, changes in disease vectors and crop productivity, loss of biodiversity, and increased heat stress [1]. Aviation contributes to climate change, as it was responsible for 2.5% of global CO₂ emissions in 2016 [2]. Moreover, airline traffic projections by Airbus and Boeing indicate that aviation will continue its historical growth through 2036 at approximately 4.5% per year [3, 4]. Due to this growth, aviation-related CO₂ emissions are expected to double or triple by 2050.

An almost unique feature of aviation is that a significant portion of the aviation-attributable climate warming is due to non-CO₂ emissions, especially contrails and contrail-cirrus clouds. Contrails are white line-shaped clouds that form behind aircraft. They have about the same radiative impact as all aviation-related CO₂ emissions, thereby approximately doubling the net climate impact of aviation [5]. In turn, aircraft that do not combust fuel and thus do not emit water vapor at high-altitude, would have the potential for greatly reducing the climate impacts of aviation. Furthermore, studies have shown that the air quality impacts of aviation, which are caused by fuel combustion, have led to approximately 16,000 premature mortalities per year [6]. All-electric aircraft have the potential to avert the negative externalities of aviation without deterring societal and economic globalization.

Historically, decreases in fuel consumption have been achieved by advancing aircraft technologies, such as the development of high-bypass ratio turbofans and winglets. These efforts have resulted in continuous economic and environmental benefits. However, marginal evolutionary improvements in aircraft propulsion and aerodynamics ($\sim 1\%$ p.a. fleet average) are outstripped by aviation growth ($\sim 4.5\%$ p.a.). Additionally, recent

emissions regulations, such as the 2016 global aviation CO₂ emissions standard, provide regulatory stimuli to reduce the environmental footprint of air transportation [7]. As exemplified in Table 1, ACARE and NASA have also set forth a series of emission reduction objectives for Europe and the U.S., respectively. Driven by these motivating factors, advanced aircraft technology would enable aviation to flourish in the future. One such novel concept, the focus of this work, is battery-powered all-electric aircraft.

Table 1. ACARE Flightpath 2050 and NASA N+3 goals for emission reduction [8, 9].

Emission	Flightpath 2050^a	N+3^b
Noise	-65% ^c	-71 dB ^d
LTO NO_x	0 ^e	-75% ^f
NO_x	-90%	-
CO₂	-75%	-
Fuel Burn	-	-70% ^g

^a 2050 implementation, relative to state of the art aircraft in 2000

^b 2035 implementation

^c perceived noise of flying aircraft

^d relative to FAA Stage 4 noise regulation

^e emission-free taxiing

^f relative to CAEP 6

^g relative to state of the art aircraft in 2008

There are multiple reasons this concept may lead toward air transportation with reduced environmental impacts. First, unlike gas turbine technology, electric propulsion is not limited to the same thermodynamic efficiency limits. Thus, all-electric aircraft have the potential to achieve a higher on-board energy conversion efficiency (e.g. $\sim 85\%$ rather than $\sim 50\%$), thereby significantly reducing the energy required per flight [10]. Second, these aircraft would likely use a system of electric motor-ducted fans, which, unlike gas turbines, have efficiencies that are nearly constant with scale [11]. Hence, using more numerous, smaller motor-fan assemblies allows for distributed electric propulsion (DEP), which may be lighter and quieter, offers increased redundancy and propulsion efficiency, and facilitates overall efficiency improvements during off-design stages of flight. Finally,

battery-powered aircraft would not release emissions in-flight. While CO₂ would still be released at ground level to charge batteries in the near-term, the climate impact of aviation would be diminished through avoidance of high-altitude water vapor emissions and the resulting contrails. In the long-term, electricity supplied from emission-free sources may further reduce the environmental impacts.

Other options to reduce the environmental consequences of aviation include using biofuels and more fuel-efficient aircraft routing, but both of these options are of limited impact compared to the scale of global aviation growth [12, 13]. Additionally, any future air transportation system that remains reliant on in-flight fuel combustion, even “clean” fuels like hydrogen, will still produce contrails, which have a significant effect on global climate change. This work evaluates a technological change that would reduce atmospheric aviation emissions and allow for independence from the current fossil fuel economy.

Chapter 2

Electric aircraft overview

In recent years, the aerospace industry has seen the emergence of aircraft electrification. This concept has led to fundamental changes to aircraft design, construction, and operation. Aircraft manufacturers have begun incorporating electric technologies into their aircraft with more-electric aircraft (MEA), such as the Airbus A380 and Boeing 787 [14]. In MEA, the hydraulic, mechanical, and/or pneumatic systems are replaced with electrical systems in an effort decrease weight and increase reliability. More recent research has shifted toward turboelectric, hybrid-electric, and all-electric aircraft, all of which are forms of electric propulsion [15]. This section discusses possible electric aircraft configurations and present a review of past and present all-electric aircraft research and development.

2.1. Propulsion system arrangements

Similar to ground-based electric vehicles, various hybrid-electric and turboelectric aircraft designs have been investigated, often without batteries due to the lack of opportunity for regenerative braking [16]. Shown in Figure 1 is a visualization of the various options for electric aircraft propulsion.

Hybrid-electric types can be defined based on which devices supply power and how the powertrain is arranged. The primary options are series hybrid, parallel hybrid, and series/parallel hybrid. A series hybrid-electric configuration has an electrical coupling, such as an electric generator and battery both supplying electrical power to an electric motor [18]. A parallel hybrid-electric configuration has a mechanical coupling between power supplying components, such as a shared gas turbine and electric motor shaft. A series/parallel hybrid is combination of the preceding two options. Examples of series and parallel hybrid-electric aircraft concepts are the Airbus/Rolls-Royce E-Thrust and Boeing

SUGAR Volt and, respectively [19, 20]. Another concept, which is close to commercialization, is the 12-passenger Zunum Aero series hybrid-electric aircraft [21].

In a turboelectric configuration, a gas turbine drives an electric generator, which provides electrical power to an electric motor. An example turboelectric aircraft concept is the NASA N3-X [22]. Additionally, a partial-turboelectric aircraft uses a combination of electric and gas turbine propulsion.

Figure 1. Electric aircraft propulsion system topologies. Modified from [17].

The designs mentioned thus far provide comparatively modest environmental benefits given they still entail high-altitude emissions and non-CO₂ impacts. In contrast, all-electric aircraft use only electrical energy and power for propulsion, so no in-flight emissions occur. A variety of additional terminologies are used in aviation literature to describe this aircraft concept, including “battery-electric”, “electric-propulsion”, “full-

electric”, “fully-electric”, and “universally-electric” aircraft. In this work, all-electric aircraft (AEA) is used, with the only energy source being stored electrical energy (e.g. batteries). In reference to the propulsor specifically being electrically powered, “all-electric propulsor” or “all-electric engine” is appropriate.

2.2. All-electric aircraft under study

Amongst the options for electrification, AEA will likely be last to reach commercial aviation, primarily due to battery technology limitations. Nonetheless, in the past decade AEA have been widely researched. Shown in Table 2 is a survey of all-electric airplanes that have previously been or are currently being evaluated. Only aircraft with fixed wings (airplanes) are included, not rotorcraft, such as the CityAirbus or Volocopter 2X. Also excluded are solar powered aircraft, such as the Aero Electric Sun Flyer or PC-Aero Elektra One, or gliders, such as the Lange Antares 20E or Pipistrel Taurus Electro.

As indicated in Table 2 by the seat counts, electric propulsion is currently targeted at smaller aircraft. This is due to a variety of reasons. First, flights for these aircraft are typically expected to have short ranges, thus current battery technology is less of a limitation. Second, projects of smaller scale pose less cost and risk for aircraft manufacturers. Finally, greater benefits can be realized in transitioning to electric propulsion from internal combustion engines for small aircraft (e.g. $\eta_{\text{thermal}} \approx 25\%$) than from turbofans for large aircraft (e.g. $\eta_{\text{thermal}} \approx 50\%$).

2.2.1 VTOL aircraft

Telecommunications advancements and increased smartphone usage have led to the emergence of on-demand mobility (ODM) in automobile transportation [23]. ODM providers connect customers with transport service in real-time. Lyft and Uber, two of the largest ODM providers, now service the majority of cities in the U.S. and many cities worldwide. This concept has now moved into the aviation industry, led by Uber Elevate,

Table 2. Survey of all-electric airplanes. Data Compiled from [24-82].

Aircraft	Location	Seat Count ^a	Range [nmi]	Cruise Speed [kt]	Status ^c (Last Update)	Type
Pipistrel eVTOL (unnamed)	Ajdovščina, Slovenia	TBA	52	130	Dev	VTOL
Zee.Aero Z-P1	Mountain View, CA, USA	1	-	-	Dev	VTOL
Flight of the Century Long-ESA	Aliso Viejo, CA, USA	1	-	-	Demo (2012)	Light
Lazair eLazair	Hammondsport, NY, USA	1	4 ^b	38	Demo (2011)	ULA
APEV Demoichellec	Peynier, France	1	13 ^b	38	Demo (2012)	ULA
APEV Pouchelec	Peynier, France	1	19 ^b	38	Demo (2012)	ULA
Electravia MC15E Cri-Cri	Vaumeilh, France	1	25	100	Demo (2015)	Light
Electravia BL1E Electra	Vaumeilh, France	1	27	49	Demo (2007)	ULA
Airbus Electric Cri-Cri	Toulouse, France	1	30 ^b	60	Demo (2010)	Light
Yuneec-Flightstar Espyder E280	Cable, CA, USA	1	33 ^b	33	Canc (2013)	LSA
Airbus A ³ Vahana	Santa Clara, CA, USA	1	43	95	Dev	VTOL
NASA Puffin	Hampton, VA, USA	1	43	130	Con (2010)	VTOL
LSA MC30E Firefly	Redange, Luxembourg	1	82 ^b	89	Demo (2011)	ULA
Airbus E-Fan	Toulouse, France	1	86	86	Canc (2017)	Light
NASA X-57 Maxwell	Edwards, CA, USA	1	87	152	Dev	Light
JAXA Hornisse Type 2B	Tokyo, Japan	2	-	-	Dev	VTOL
Aurora eVTOL (unnamed)	Manassas, VA, USA	2	35	108	Dev	VTOL
Extra 330LE	Hünxe, Germany	2	57 ^b	170	Demo (2016)	Light
Liaoning Ruixiang RX1E	Shenyang, China	2	65 ^b	65	Prod	LSA
Autonomous Flight Y6S	Sevenoaks, UK	2	70	61	Dev	VTOL
Sonex Electric Sport Aircraft	Oshkosh, WI, USA	2	76	115	Dev	LSA
ACS-Itaipu Sora-e	Putim, Brazil	2	77	103	Demo (2015)	LSA
Pipistrel WATTsUP	Ajdovščina, Slovenia	2	81	85	Demo (2014)	LSA
Pipistrel Alpha Electro	Ajdovščina, Slovenia	2	81	108	Prod	LSA
Evektor SportStar EPOS	Kunovice, Czech Republic	2	92 ^b	92	Dev	LSA
Liaoning Ruixiang RX1E-A	Shenyang, China	2	97	59	Prod	LSA
DeLorean DR-7	Laguna Beach, CA, USA	2	104	130	Dev	VTOL
Yuneec E430	Cable, CA, USA	2	130 ^b	52	Canc (2013)	LSA
EVA X01	Toulouse, France	2	162	-	Dev	VTOL
ACS Z-300	Putim, Brazil	2	162	120	Dev	VTOL
Lilium Jet	Gilching, Germany	2	162	162	Dev	VTOL
EAC ElectraFlyer-X	Cliffside Park, NJ, USA	2	174 ^b	87	Canc (2012)	LSA
Joby S2	Santa Cruz, CA, USA	2	174	174	Dev	VTOL
Pipistrel Panthera	Ajdovščina, Slovenia	2	216	198	Dev	Light
IFB-Stuttgart e-Genius	Stuttgart, Germany	2	243	65	Demo (2015)	Light
Beyond Aviation Electric Cessna 172	Broomfield, CO, USA	2	244 ^b	122	Canc (2012)	Light
ACS LOONG-e	Putim, Brazil	2	351	118	Dev	LSA
SKYLYS Aircraft AO	Dover, DE, USA	3	81	108	Dev	VTOL
Joby S4	Santa Cruz, CA, USA	4	-	-	Dev	VTOL
AirSpaceX MOBi	Birmingham, MI, USA	4	62	130	Dev	VTOL
Carter Electric CarterCopter Air Taxi	Wichita Falls, TX, USA	4	98	152	Dev	VTOL
HopFlyt	Lusby, MD, USA	4	174	120	Dev	VTOL
Pipistrel Taurus G4	Ajdovščina, Slovenia	4	243	87	Demo (2011)	Light

Aircraft	Location	Seat Count ^a	Range [nmi]	Cruise Speed [kt]	Status ^c (Last Update)	Type
Eviation Alice	Kadima, Israel	9	521	240	Dev	NB
328 (Martin Hepperle) ^d	Braunschweig, Germany	28	109	162	Con (2012)	NB
328-LBME ² (Martin Hepperle) ^d	Braunschweig, Germany	28	786	138	Con (2012)	NB
Stanford Aluminum-Air Aircraft	Stanford, CA, USA	30	1150	287	Con (2016)	NB
Airbus VoltAir	Ottobrunn, Germany	68	900	270	Con (2012)	NB
Electrified ATR 72-500	Munich, Germany	68	883	241	Con (2012)	NB
Stanford Lithium-Air Aircraft	Stanford, CA, USA	114	2376	447	Con (2015)	NB
Wright One	Los Angeles, CA, USA	150	261	-	Dev	NB
BHL Ce-Liner	Munich, Germany	189	900	436	Con (2014)	NB

^a passenger seat count for narrow-body aircraft, total seat count otherwise

^b range estimated with cruise speed and endurance

^c Canc: cancelled project, Con: conceptual design, Demo: demonstration design, Dev: currently in development, Prod: currently in production

^d intermediate designs between 328 and 328-LBME² not shown

who envision vertical takeoff and landing (VTOL) aircraft for aviation ODM [83, 84].

VTOL aircraft are capable of taking off and landing without a runway, allowing for use away from airports. As shown in Table 2, there are 16 different all-electric VTOL with fixed wings currently in development. These aircraft are designed primarily for travel within urban areas, thus all are limited in passenger capacity (<5 PAX), maximum range (<200 nmi), and design cruise speed (<200 kt).

2.2.2. Light aircraft

A variety of ultra-light aircraft (ULA), light-sport aircraft (LSA), and other light aircraft have been studied as well. Many of these were demonstrator aircraft, such as the NASA Green Flight Challenge competitors, IFB-Stuttgart e-Genius and Pipistrel Taurus G4 [51]. Some projects, including the Airbus E-Fan, Beyond Aviation Electric Cessna 172, Electric Aircraft Corporation ElectraFlyer-X, Yuneec-Flightstar Espyder E280, and Yuneec E430, were cancelled before reaching production. Currently the two-passenger Sonex Electric Sport Aircraft, Evektor SportStar EPOS, Pipistrel Panthera, and ACS LOONG-e aircraft designs are in development, with plans for future production. Additionally, the NASA X-57 Maxwell is currently under construction. This aircraft will enable the investigation of

distributed electric propulsion by using 12 high-lift electric motors with folding propellers on the wing leading edge and 60 kW wingtip cruise motors [85, 86]. Finally, the increasingly popular Pipistrel Alpha Electro trainer aircraft and recently developed Liaoning Ruixiang RX1E and RX1E-A are the only AEA currently in production.

2.2.3. Narrow-body aircraft

Most relevant to this work are narrow-body AEA. A visualization of the design missions for these aircraft is shown in Figure 2. Currently 2 regional airliners, the 9-passenger Eviation Alice and 150-passenger Wright One, are being developed by startup aviation companies. The other 7 narrow-body AEA listed in Table 2 are conceptual designs that are highly dependent on future technology assumptions. The focus of this work is an AEA designed for a maximum of 180 passengers (PAX). The only previously researched AEA of this size is the BHL Ce-Liner, which features a C-wing and two aft-mounted ducted fans [87]. Thus, this is the primary design from aviation literature used for comparisons.

Figure 2. Design missions of previously studied narrow-body all-electric aircraft. Not shown is the 114 PAX, 2376 nmi Stanford Lithium-Air Aircraft.

2.3. Battery technology status

For AEA to become feasible, the critical development required is battery technology, especially the specific energy and power. These terms represent the energy and power per unit mass of battery, respectively. Recently battery research has come to the forefront, largely due to the growing popularity of electric vehicles. Projects, such as the DOE Battery500, aim to accelerate the development of advanced batteries [88]. Li-ion batteries are the state of the art battery type, but other battery chemistries, specifically Li-S, have emerged as contenders for aviation applications.

2.3.1. Tradeoffs

The battery chosen for a given application is dependent on many battery properties, as illustrated in Figure 3. The mass properties, specific energy and power, are crucial for aircraft performance. However, energy density [Wh/L] is key as well, as aircraft have a limited wing and fuselage volume available for energy storage. Though not considered in this work, other parameters are also of importance. The cycle life, calendar life, cost, and charge rate capability all impact the economic and operational feasibility of AEA. Finally, airlines consider the safety and operating temperature range to be of utmost importance.

Figure 3. Battery tradeoffs. Modified from [89, 90].

2.3.2. Li-ion overview

Many different types of Li-ion batteries currently exist. The anode and cathode composition define the Li-ion battery type. Nearly all current anodes are either graphite or lithium titanate oxide (LTO). While LTO anodes have a higher discharge rate capability and better stability, graphite anodes have a higher specific capacity [Ah/kg], Researchers are seeking to increase the specific capacity in graphite anodes through silicon addition [91].

Table 3. Common cathode options for Li-ion batteries. Data from [95, 96, 97, 98].

Li-ion Type	Chemical Description	Specific Capacity [Ah/kg]		Voltage [V]		Electric Vehicle Applications
		Typical	Theoretical	Avg.	Mid.	
LCO	Lithium cobalt oxide LiCoO_2	150	274	3.8	3.9	N/A Note, original B787 battery
LMO	Lithium manganese oxide LiMn_2O_4	120	148	4.1	4.0	2011/2013 Nissan Leaf 2012 Mitsubishi i-MiEV 2013 Ford Focus EV
NCA	Lithium nickel cobalt aluminum oxide $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$	190	278	3.7	3.7	2014 Tesla Model S 2015 Mercedes-Benz B-Class ED 2016 Tesla Model X
NMC	Lithium nickel manganese cobalt oxide $\text{LiNi}_x\text{Mn}_y\text{Co}_{1-x-y}\text{O}_2$	170	278 (NCM 333)	3.7	3.8	2014 BMW i3 2015 Chevrolet Spark EV 2017 Nissan Leaf, Tesla Model 3
LFP	Lithium iron phosphate LiFePO_4	160	170	3.4	3.4	2011 Chevrolet Spark EV eBuses

The cathode options are listed in Table 3. Early Li-ion batteries used LCO and early electric vehicle batteries used LMO, but now NCA, NMC, and LFP are the most popular options. The highest specific energy batteries available commercially use NCA, such as the Panasonic NCR18650A cells in current Tesla battery packs [92]. Batteries with NMC have slightly lower specific energies than those with NCA, but offer improved cycle lives and safety. Batteries with LFP are reliable, relatively low cost, and offer long

cycle lives and high-power capabilities, but have low specific energies. It is believed that NMC-type batteries will dominate over the next decade [93]. These batteries have their own design space, shown in Figure 4. It is desirable to move away from the LCO region, as cobalt (Co) is expensive and sourced from regions with questionable mining ethics [94].

Many Li-ion batteries today are actually Li-ion polymer (LiPo) batteries, and feature a semisolid polymer electrolyte. Solid-like and solid-state Li-ion batteries are actively being researched worldwide for increased safety and potentially improved mass and volume properties as well [99, 100, 101].

Figure 4. Lithium nickel manganese cobalt oxide battery design space. Modified from [102, 103].

2.3.3. Li-S overview

Li-S batteries feature a sulfur cathode and lithium anode. Sulfur is abundant and non-toxic, so this battery chemistry would offer high energy economy and environmental friendliness. It also has a high theoretical specific energy of 2567 Wh/kg. However, many issues currently restrict this technology, including the low electrical conductivity of sulfur, excessive volumetric expansion during discharge, and parasitic lithium polysulfide

intermediate reactions [104, 105]. Solutions to these issues are available, such as conducting agents, robust structures, and electrolyte additives, respectively. However, these solutions add weight, thus penalizing the specific energy. Current Li-S batteries also have limited cycle lives presently.

2.3.4. Li-air overview

One of the other often-mention battery chemistries for aviation, Li-air, is not considered in this work. Though it has the largest theoretical specific energy of all secondary batteries, many practical issues restrict implementation. Li-air batteries would require an air feed system, and pressurization, as the available battery capacity increases with pressure [106]. Additionally, they have poor rate capabilities (e.g. order of mW/kg) and would require high performance O₂-selective membranes to prevent contamination [107, 108]. Finally, Li-air batteries gain mass and expand, resulting in structural design difficulties.

2.3.5. Theoretical battery parameters

Based on the chemical reaction of each battery chemistry, theoretical values for the battery specific energy and energy density can be determined, as shown in Table 4. The limitations of the Li-ion battery chemistry are clearly observed, though these theoretical values would increase with silicon addition to the graphite anode [91]. Li-S batteries are the most promising option that do not gain mass during discharge, while Li-air batteries have the highest theoretical values. Li-metal batteries, not discussed previously, use a lithium anode. These batteries offer mass and volume improvements over Li-ion batteries, but current cycle lives are not suitable for aviation [109]. The other battery chemistries listed in Table 4 may be reasonable for aviation, but are not used in this work and are only listed for reference.

Table 4. Theoretical parameters for potential aviation batteries.

Battery Type	Discharge Reaction	Nominal Cell Voltage [V]	Cathode Specific Capacity [Ah/kg] ^a	Specific Energy [Wh/kg] ^b	Energy Density [Wh/L] ^c	Ref. ^d
Li-ion ^e	$Li_{1-x}C_6 + Li_xMO_2 \leftrightarrow C_6 + LiMO_2$	3.4-4.1	148-278	396-607	~1000	Table 3
Li-metal	$Li_{1-x} + Li_xMO_2 \leftrightarrow LiMO_2$	3.4-4.1	148-278	578-1054	>1000	Table 3
Li-S	$2 Li + S \leftrightarrow Li_2S$	2.2	1167	2567	2189	[110]
Li-air	$2 Li + \frac{1}{2} O_2 \leftrightarrow Li_2O_2$	3.0	1168	3505	3492	[110]
Li-Se	$2 Li + Se \leftrightarrow Li_2Se$	2.0	577	1155	1824	[111]
Al-air	$4 Al + 6 H_2O + 3 O_2 \leftrightarrow 4 Al(OH)_3$	2.71	1031	2793	3147	[107]
Zn-air	$2 Zn + O_2 \leftrightarrow 2 ZnO$	1.65	659	1087	3736	[110]

^a Discharged state (calculated)^b All active materials, including oxygen (calculated). Without oxygen, values for metal-air batteries are Li-air: 11584 Wh/kg, Al-air: 8075 Wh/kg, Zn-air: 1353 Wh/kg.^c Charged anode and discharged cathode (calculated)^d References for nominal cell voltage^e Graphite anode

2.3.6. Theoretical all-electric aircraft range

Similar to the Breguet range equation for conventional aircraft, the all-electric aircraft range can be estimated with an assumed specific energy and aircraft parameters.

The range [m] of an aircraft is

$$R = v_{\infty} t, \quad (1)$$

where v_{∞} [m/s] is flight speed and t [s] is flight time. The flight time for a battery-powered all-electric aircraft is approximated as

$$t = \frac{m_b E^*}{P_b}, \quad (2)$$

where m_b [kg] is battery mass, E^* [J/kg] is battery (pack) specific energy, and P_b [W] is battery power. The required battery power is

$$P_b = \frac{P_{\text{aircraft}}}{\eta_{\text{overall}}}, \quad (3)$$

where P_{aircraft} [W] is aircraft power and η_{overall} [-] is overall aircraft efficiency. The aircraft power is

$$P_{\text{aircraft}} = v_{\infty} D, \quad (4)$$

where D [N] is aircraft drag. Assuming lift equals weight, the aircraft drag is

$$D = \frac{m_{\text{aircraft}} g}{L/D}, \quad (5)$$

where m_{aircraft} [kg] is aircraft mass, g [m/s²] is acceleration due to gravity, and L is lift [N]. Substituting (4) and (5) into (3), the battery power is

$$P_b = \frac{v_{\infty} m_{\text{aircraft}} g}{\eta_{\text{overall}} L/D}. \quad (6)$$

Rearranging, the flight speed is

$$v_{\infty} = \frac{P_b \eta_{\text{overall}} L/D}{m_{\text{aircraft}} g}. \quad (7)$$

The battery mass fraction f [-] is

$$f = \frac{m_b}{m_{\text{aircraft}}}. \quad (8)$$

Substituting (2), (7), and (8) into (1) and rearranging, the constant mass aircraft range is defined as

$$R = \frac{\eta_{\text{overall}} E^* L/D f}{g}. \quad (9)$$

For a mass gaining aircraft the rate of mass gain [kg/s] is

$$\frac{dm}{dt} = \frac{k z P_b}{E^*}, \quad (10)$$

where k [-] is the fraction of oxygen mass gained to active battery mass (chemistry based) and z [-] is the active to total battery mass ratio. Thus, the product of k and z is the oxygen mass gained to total battery mass fraction. Note the P_b divided by E^* is the rate of battery use [kg/s]. Substituting (6) into (10) and rearranging,

$$\frac{dm}{m_{\text{aircraft}}} = \frac{k z v_{\infty} g}{\eta_{\text{overall}} E^* L/D} dt. \quad (11)$$

Using (1) and integrating,

$$\ln \left(\frac{m_{\text{final}}}{m_{\text{initial}}} \right) = \frac{k z g R}{\eta_{\text{overall}} E^* L/D}, \quad (12)$$

where m_{initial} [kg] is initial aircraft mass and m_{final} [kg] is final aircraft mass. The final aircraft mass is

$$m_{\text{final}} = m_{\text{initial}} + f k z. \quad (13)$$

Substituting (13) into (12) and rearranging, the mass gaining aircraft range is defined as

$$R = \frac{\eta_{\text{overall}} E^* L/D}{g} \frac{\ln(1 + f k z)}{k z}, \quad (14)$$

where E^* [J/kg] is specific energy based on initial battery mass. The specific energy [J/kg] based on the final battery mass is

$$E^*_{\text{final}} = \frac{E^*}{1 + k z}. \quad (15)$$

Note that the flight speed does not directly impact the range for any electric aircraft, as shown in (9) and (14), but it may impact the overall efficiency and lift to drag ratio.

As shown by Figure 5, the range of AEA with current technology assumptions is limited in relation to conventional aircraft. For example, Li-S batteries can only achieve around 1000 nmi subject to modest assumptions for future battery and aircraft technology. Li-air batteries have the potential for a longer range, but must overcome other practical issues, such as low specific power.

3.3.7. Packing efficiency

Shown in Figure 6 is a summary of state-of-the-art, projected, and theoretical cell specific energies for various lithium-based battery chemistries. It is crucial to note the difference between cell and pack specific energy. Battery manufacturers typically specify cell values, while pack values are important at the vehicle level. Current electric vehicles have a 65-75% packing efficiency, which is the ratio of cell to pack mass [78, 92, 97, 112, 113, 114, 115, 116]. However, it is expected that AEA will have values greater than 80%, as more focus will be placed on mass minimization rather than impact safety [113, 117, 118].

Figure 5. All-electric aircraft range limitations. Two commonly proposed battery chemistries for aviation and various technology assumptions are displayed. Discharged specific energies are used for Li-air, which has $k = 2.305$.

Figure 6. Specific energies of lithium-based batteries. State of the art Li-ion, Li-metal, and Li-S batteries are manufactured by Panasonic [119], SolidEnergy [109], and Oxis Energy [120], respectively.

Chapter 3

Aircraft sizing methodology

Specification, performance, and optimization of all-electric aircraft was performed with Transport Aircraft System OPTimization – electric (TASOPTe). This program was developed specifically for this work. TASOPTe is an electric propulsion-based version of the Transport Aircraft System OPTimization (TASOPT) code, which was developed at MIT to evaluate conventionally-fueled aircraft [121]. TASOPT was utilized to design the D8 “double bubble” aircraft, and is currently used by multiple research groups [122].

Both TASOPT and TASOPTe are multidisciplinary design optimization (MDO) programs that can simultaneously optimize the airframe, propulsor, and operation of a given transport aircraft. The key benefit of these programs is the use of first-principles methods rather than reliance on empirical data, which can have limited ranges of validity. This allows for confidence in the results of innovative designs. Only where necessary are historical correlations used, particularly for some non-structural aircraft equipment and secondary structure weights [121]. The design space is limited to tube-and-wing aircraft topology, but unconventional aircraft features can be included, such as boundary layer ingestion, strut-braced wings, “double bubble” fuselages, and composite materials [122].

3.1. Common TASOPT and TASOPTe features

Though TASOPT has been heavily modified for all-electric aircraft analysis, many features remain unchanged. The methodology of TASOPT is well-documented [121, 123, 124], so only a high-level summary of the unmodified features is provided here.

3.1.1. Inputs and outputs

Aircraft are designed using basic input parameters, some of which can be selected for optimization. The fuselage dimensions are specified using basic dimensional inputs (e.g.

length, radius, etc.), but the majority of inputs are dimensionless. For example, inputs for the airframe, propulsor, and aircraft operation include the fan pressure ratio, non-structural weight fractions, and cruise Mach number, respectively. Using dimensionless inputs aids in designing various size aircraft with the same underlying shape and weight assumptions.

In addition to design parameters, aircraft design constraints may also be stipulated. These include maximum balanced field length, minimum top-of-climb gradient, maximum wing span, and maximum energy storage (jet fuel or battery) volume. These constraints are implemented via optimizer penalty functions.

To evaluate performance, aircraft missions must be specified. The parameters that define each mission include, range, passenger count and weight (payload), and takeoff/landing altitude and temperature. A single design mission is always specified, and optional off-design missions (e.g. shorter range) may also be assessed. Optimization is optionally performed using mission-averaged weights across a set of defined design and off-design missions.

Using the design inputs and constraints, aircraft sizing is completed based on the design mission, and then performance is computed for off-design missions. If optimization variables are selected, then the result is an optimized aircraft, rather than just a sized aircraft. In either case, outputs include key dimensions and weights (e.g. fan diameter and battery weight), along with a complete flight profile and mission energy requirements.

3.1.2. Aerodynamic performance

Rather than traditional wetted-area or full 3D CFD approaches, wing airfoil performance is determined from a family of precomputed transonic airfoils. Performance for the airfoil family is calculated using 2D viscous/inviscid CFD for a range of airfoil thicknesses, lift coefficients, and Mach numbers. Similarly, fuselage profile drag is found using compressible viscous/inviscid CFD with axisymmetric simplifications. The use of CFD

presented here allows accurate and widely applicable results to be obtained without a large computational expense. Traditional wetted area approaches with supervelocity corrections are utilized to obtain the drag of minor components, such nacelles. Trefftz-Plane analysis is used to determine induced drag [121].

3.1.3. Airframe structure and weight

The primary structural airframe elements are treated as simple geometric shapes, with the material gauges sized for each element at critical loading cases. The fuselage is modeled as a pressure vessel with spherical or ellipsoidal endcaps, which has additional bending and torsion loads. The wing is modeled as a double piecewise linear taper planform with sweep. It is assumed to be cantilevered or optionally have a strut support at the planform panel-break. The wing cross-section is modeled as a structural box with front and rear shear webs and curved top and bottom spar caps. The tails use the same model as the wing, except for the optional strut. The sized material gauges, along with specified material densities, provide the primary structure weight. The floor weight is determined from a payload-loading analysis. Weights of the secondary structure (e.g. slats, flaps, etc.) and non-structural aircraft equipment (e.g. windows, seats, etc.) are estimated with historical weight fractions and are assumed to be proportional to the passenger count (payload) or cabin size, as appropriate [121].

3.2. Electrical and propulsion system architecture

Though TASOPTe is largely based on TASOPT [121], substantial modifications have been made that allow for the analysis of all-electric aircraft. The primary differences are a consequence of the fundamentally distinct energy storage and propulsion system. Rather than gas turbines, all-electric aircraft use electric motor-ducted fan assemblies. A schematic of the electrical and propulsion system architecture is shown in Figure 7. Propulsion is provided by ducted fans, which are connected to AC electric motors.

Intermediate motor-fan gearboxes may optionally be included. Electrical power is provided to the electric motors from the battery through the power management and distribution (PMAD) system. Power offtakes are required for aircraft subsystems (e.g. anti-icing, avionics, etc.) and the electrical cooling system. Each component in the electrical and propulsion system has an associated weight and efficiency. The weight calculations are discussed in the following sections, while constant efficiencies are assumed for each component, except the batteries. Though no system of this type currently exists, NASA is researching a similar system in the NASA Electric Aircraft Test bed (NEAT) [125].

Figure 7. Electrical and propulsion system architecture for a single propulsor. Modified from [22, 126, 127, 128, 129].

3.2.1. AC electric motors

The AC electric motors may be specified as conventional or high-temperature superconducting (HTS). In either case, the particular type used is the brushless DC motor, also known as the electronically commutated motor. The name of this motor type can be misleading, as the power supply is DC, but a DC/AC inverter (controller) allows for variable frequency AC motor operation. Not using brushes or commutators has many benefits, including less maintenance, higher reliability, and the ability to operate in reverse as a generator. Conventional motors are assumed to use strong permanent magnets, while HTS motors use wound HTS coils [130, 131, 132, 133].

The electric motor weight is scaled with shaft power, with HTS motors having more favorable scaling exponents [134, 135]. The motors and electrical system are sized for takeoff, which is the most power demanding condition. Specific power benefits can be achieved with high power and/or HTS motors, rather than low power and/or conventional motors. For example, 1 and 10 MW conventional motors have specific powers of 2.2 and 2.8 kW/kg, respectively, while 1 and 10 MW HTS motors have specific powers of 10 and 22 kW/kg, respectively. For comparison, the combined shaft power of modern turbofans is near 10 kW/kg, and state of the art lightweight electric motors (Siemens, 0.25 MW) have achieved 5 kW/kg [136]. Considering the higher efficiencies also possible in a superconducting system, HTS motors are appropriate for commercial aviation at the 180 PAX scale, where motor power requirements are of 10 MW magnitude. NASA estimates that electric motors of this type will be available around 2050, which drives the expected entry into service [137].

3.2.2. PMAD system

In the present context, the PMAD consists of DC/DC converters, cables, DC/AC inverters, buses, and solid state power controllers (SSPCs). The battery output DC voltage is stepped up with a DC/DC converter before the main cable transmission to limit currents. Just prior to the electric motors, the DC voltage is inverted to AC voltage with an inverter, which also acts as a controller. SSPCs allow loads to be removed from the system if a fault is detected, allowing protection from short circuits and overloads [138]. Each of these electrical system components has an associated weight. The total cable weight is determined based on an assumed value of cable weight/length and the length between the fuselage and each propulsor. The weights of the other components are determined using specified specific powers and calculated powers at the respective components.

3.2.3. Electrical system cooling

The heat from the electric motors must be dissipated, so a cooling system is included. Cooling for a conventional electrical system is fulfilled with a water-cooled radiator. The weight in this case is determined from an assumed specific power and a calculated heat removal requirement [135]. A cryocooler is used for cooling in a HTS system, with the weight determined from cryocooler scaling trends [126, 139].

3.2.4. Aircraft subsystems power offtakes

Unlike conventional aircraft that offtake power from the low-pressure gas turbine spool, all-electric aircraft draw power directly from the battery for aircraft subsystems (e.g. ECS, flight controls, etc.). More-electric aircraft, such as the Boeing 787 and Airbus A380 require up to 2 kW/seat, which is expected to increase to 4-5 kW/seat [14, 140, 141]. The required power offtake is estimated from the design aircraft passenger count and maximum takeoff weight (W_{MTO}), with 1 kW/PAX and 0.50 W/N assumed, respectively.

3.2.5. Ducted fans

The ducted fan model in TASOPTe has a 1D flowpath simulation, which was developed from the gas turbine flowpath simulation in TASOPT. Diffuser, fan, and nozzle pressure ratios are specified for the design point (cruise). Fan stage polytropic efficiencies are determined using one of two methods. In the first, a linear relationship between the polytropic efficiency (η_p) and fan pressure ratio (π_f) is represented by

$$\eta_p = 0.909 - 0.282 (\pi_f - 1.284). \quad (16)$$

The constants in Eq. (16) were determined using low design FPR (1.294) test data and an assumed stator and duct efficiency of 0.985 [142]. A second, more complex model generates polytropic efficiency contours, as shown in Figure 8. This fan map was calibrated using the same low FPR test data.

Figure 8. Calibrated fan polytropic efficiency contours for a 1.294 FPR fan. Increased flutter margin is provided by using a VAN with a 15% increase in nozzle area during takeoff (TO) in reference to the design cruise (CR) nozzle area.

A variable area nozzle (VAN) may optionally be included. Without a VAN, the takeoff condition approaches the flutter boundary (surge/stall for a higher FPR fan), as shown in Figure 8. In this region, low efficiency and damage to the fan may occur. The VAN weight penalty is represented by an increase in the fan exhaust cowl weight, which is proportional to the increase in nozzle area from the design condition [143]. However, the VAN weight is highly dependent on the design and mechanism for area variation [144]. Ongoing work with shape memory alloy actuation may lead to lower weight VANs in the future [145, 146].

The fan weight, including rotor blades, hub, spinner, stator blades, outer casing, and support struts, is using fan scaling trends [147, 148]. Preliminary weight calculations for a 2.5 m diameter fan agree with the WATE++ simulations for similar size PW4462 and PW4168 fans [124].

3.2.6. Motor-fan gearboxes

Between the electric motor and ducted fan, a gearbox may optionally be incorporated. A conventional motor is generally assumed to not need a gearbox, as the efficiency remains constant across a wide range of speeds. However, a gearbox is likely required for a HTS motor, as the high efficiencies often stated for HTS motors occur at higher speeds (~ 10000 rpm) than typical speeds for high fan efficiency (2000-5000 rpm) [149, 150, 151].

Epicyclic gearing is assumed with a sun input, carrier output, and fixed ring. For this configuration, the gear ratio theoretically approaches 6:1 when 3 to 9 planetary gears are used. Similar to the Pratt & Whitney PW1000G turbofan, a gearbox with 5 planetary gears is assumed. With constraints on the number of teeth for all of the gears, the maximum gear ratio is 4.33:1, which is assumed to be suitable for a HTS system.

The gearbox weight is determined using the specified gear ratio and calculated maximum torque [152, 153]. This calculation is based on historical trends, with a future weight decrease assumption. Similar trends have been mentioned in other aviation literature [71, 154].

3.2.7. Distributed electric propulsion

In TASOPT, it is assumed that at most one propulsor per wing would be used, as the aircraft industry trend is to use two ultrahigh bypass ratio fans for high propulsive efficiency. However, electric aircraft can achieve high propulsive efficiency through the use of many small propulsors, also known as distributed electric propulsion (DEP). Thus, TASOPTe is robust to the number of wing mounted propulsors permitted.

3.3. Battery specification and operation

A key aspect of TASOPTe is battery performance modelling. During discharge, battery capacity decreases until reaching a physical or prescribed limit. The performance

(efficiency) of a battery depends on the rate of discharge, which varies throughout the mission. Many analyses neglect battery efficiency or assume values of 98% or greater [10, 134, 155, 156]. This implies that the rate of discharge has no impact on battery performance, which is fundamentally incorrect. AEA capabilities, especially takeoff and balanced field length, are limited due to battery performance. This section describes how batteries are specified and operated within TASOPTe.

3.3.1. Discharge models

The battery is modeled as a lumped internal resistance-voltage source with the voltage and power estimated as

$$U = U_{oc} - I R \quad (17)$$

and

$$P = I U. \quad (18)$$

The required power (P) is set by the mission operating point, which then determines the current (I) and voltage (U) if the open-circuit voltage (U_{oc}) and resistance (R) are known. The open-circuit “no load” voltage is the voltage in the absence of current and may vary with state-of-charge (SOC) and temperature. The resistance is the sum of the cell ionic and electronic resistances and may vary with current, SOC, temperature, and age. It is common practice to neglect the effect of current and age on resistance for conceptual design, and it is assumed that the battery has temperature control. Thus, the open-circuit voltage and resistance are functions of SOC only. SOC represents the remaining capacity normalized by the nominal (maximum) available capacity. As a battery is discharged, the SOC decreases from a maximum of 100% to a minimum of 0%, though a partial range is typically used. Similarly, the depth-of-discharge (DOD) is the used capacity normalized by the nominal capacity and ranges from 0 to 100%.

Figure 9. Li-ion and Li-S battery discharge models. The open-circuit voltage models have the same general form, but the Li-S model has a lower magnitude and is piecewise in nature. The resistance models vary substantially in magnitude and form. The Li-S model has abrupt changes due to varying polysulfide reactions occurring during distinct phases of discharge.

The functions of open-circuit voltage and resistance against SOC are termed battery discharge models (BDM) in this work. Numerous BDM are available from literature, especially for the well-established Li-ion battery chemistry [131, 157, 158, 159]. The two primary BDM used in this work are illustrated in Figure 9. Rather than using older models from literature, these BDM were fit to battery test data. The Li-ion models were extracted from a fit of 9 recent electric vehicle tests performed by the Advanced Vehicles group at the Idaho National Laboratory [96]. The Li-ion batteries for these electric vehicles were all of the LMO or NMC type and represent state of the art transportation batteries. The Li-S models were fit to Oxis Energy Ltd. cell test data [160]. As shown by Figure 9, the shape and magnitude of the open-circuit voltage and resistance varies considerably for different battery chemistries. To account for battery technology improvement, the resistance model can be scaled an assumed technology factor. For convenience, the models used to generate Figure 9 are shown in Eq. (19) and (20) for Li-ion and (21) and (22) for Li-S batteries.

$$R = 0.00197 + \frac{0.000110}{SOC} \quad (19)$$

$$U_{oc} = 3.55 + 0.100 e^{-300(1-SOC)} + 0.593 SOC - 0.00792 \frac{1-SOC}{SOC} \quad (20)$$

$$\begin{aligned} R &= 0.459 - 0.431 SOC & SOC > 0.790 \\ R &= 0.119 & 0.790 \geq SOC \geq 0.768 \\ R &= 0.0513 e^{0.896 SOC} - 0.0755 e^{1.81 SOC} + 0.0509 e^{2.39 SOC} & SOC < 0.768 \end{aligned} \quad (21)$$

$$\begin{aligned} U_{oc} &= 2.50 - \frac{1.16(1-SOC)}{2 SOC - 1} - 0.0888 SOC & SOC > 0.801 \\ U_{oc} &= 2.07 - 0.0149 \frac{1-SOC}{SOC} - 0.440 e^{-15.0(1-SOC)} & SOC \leq 0.801 \end{aligned} \quad (22)$$

Note that other analyses use the empirical Peukert's Law to determine the change in available capacity at various discharge rates. However, this equation was developed for lead-acid batteries, and is not applicable to the lithium-based battery chemistries relevant for aircraft [161].

3.3.2. Battery specification

Specific energy and power, two often-mention battery parameters, are set at inputs. However, it is important to define under what conditions the energy is used and the power is drawn. Battery manufacturers state the specific energy at a specified C-rate and SOC, which represents the ‘nominal’ condition of the battery. Typically, the chosen C-rate is 1/5 or 1/3 and the SOC is 50%. The C-rate [1/h] is defined as the current [A] divided by the nominal capacity [Ah] and represents the rate of discharge. Thus, a C-rate of unity indicates that the battery discharges in approximately one hour.

The specific power definition is not as clearly defined. As Larminie states, ‘it is a highly variable and rather anomalous quantity, since the power given out by the battery depends far more upon the load connected to it than the battery itself’ [132]. Multiple reasonable power choices could be used to define this parameter, including the maximum possible output power or the available power at the nominal battery condition. However,

these values would over and under represent the true battery power capability, respectively. In this work, the specific power is defined using the USABC peak power definition at 80% SOC [162]. The power at this point is that which decreases the battery voltage to 2/3 of the open-circuit voltage, due to resistance losses.

Figure 10. Example Ragone plots for Li-ion and Li-S batteries. The battery discharge models from Figure 9 are used. Representative state of the art values for specific energy and power are assumed, specifically, 200 Wh/kg and 1200 W/kg for Li-ion and 300 Wh/kg and 600 W/kg for Li-S. The unusual Li-S curvature appears due to its unique open-circuit voltage and resistance models.

3.3.3. Ragone plots

With the BDM, specific energy, and specific power defined, it is possible to examine the tradeoff between available energy and power capability. This is illustrated on a Ragone plot, as in Figure 10. This plot is generated by time integrating a range of powers to find the corresponding available battery energy for each power. Approximately, the horizontal position, vertical position, and curvature depend on the specific energy, specific power, and BDM assumptions, respectively. At higher rates of discharge, the available energy decreases due to higher resistance losses.

3.3.4. Battery operation

The power drawn from the battery is determined by the propulsion system requirement, which varies during the mission. The battery SOC is integrated throughout the mission from an assumed initial value of unity to a prescribed end value. The remaining battery operating parameters (e.g. voltage, current, efficiency, etc.) are determined at each mission point based on the required power and current SOC. The total mission energy requirement is calculated by integrating the battery power drawn throughout the mission.

3.3.5. Reserve requirements

The reserve “fuel” requirement for AEA is not well-defined, but clearly some battery capacity must remain unused in case of an aborted landing, hold, or diversion. For AEA, the reserve metric is end SOC. Previous analyses have assumed 10 to 25% SOC at the end of the mission [132, 163, 164]. In this work, the end SOC is set to 30%, representing 30 minutes battery discharge at a C-rate of 0.4 and 10% SOC left unused for maintaining battery health and a longer cycle life.

3.3.6. Charge and swap

One of three options for battery handling may be specified. First, the ‘swap’ option allows the battery to be sized for each individual mission, analogous to fueling a conventional aircraft. Second, the ‘full charge’ option indicates that the same battery, corresponding to the design mission, is always used and the SOC begins at one. Finally, the ‘partial charge’ is similar to the ‘full charge’ option, but the SOC begins at less than one. This option is useful if minimum charging time is desired between missions.

3.3.7. Auxiliary batteries

The option for an auxiliary takeoff battery is implemented in TASOPTe. It is assumed to be non-mass gaining (not metal-air) and the same for all missions (not swapped). This additional battery should have a high rate capability, allowing for an increased maximum takeoff power and decreased takeoff and balanced field length.

3.4. Mission flight profiles

The flight trajectory for a traditional gas turbine powered aircraft includes ‘cruise climb’ due to aircraft weight reduction as fuel is burned. However, the weight remains constant during AEA flight, or even increases in the case of metal-air (e.g. Li-air, Al-air) batteries, which can result in ‘cruise decent’. Variable flight trajectory is implemented in TASOPTe that can account for increasing weight throughout the mission.

3.5. Landing gear length and weight

In TASOPT and other studies, landing gear (LG) weight is scaled with W_{MTO} . Common values for nose and main LG weight fractions are approximately 1% and 3%, respectively [165, 166, 167]. However, the underlying assumption with this method is that aircraft

weight is largest at takeoff. While this holds true for conventional aircraft, AEA may gain mass throughout flight if metal-air batteries are used. Thus, the maximum landing weight (W_{ML}) is better suited for AEA analysis in TASOPTe.

Furthermore, various trends for LG weights are available from aviation literature. Most of these trends present LG weights or LG weight fractions primarily as a function of W_{MTO} [168, 169, 170, 171, 172]. However, Raymer presents LG weights as a function of W_{ML} and other parameters [173]. Modified versions of these main and nose LG weight [t] equations are

$$W_{LG,main} = 0.0214 W_{ML}^{0.888} l_{LG,main}^{0.4} n_{w,LG,main}^{0.321} v_{stall}^{0.1} \quad (23)$$

and

$$W_{LG,nose} = 0.0178 W_{ML}^{0.646} l_{LG,nose}^{0.5} n_{w,LG,nose}^{0.450}. \quad (24)$$

To arrive at Eq. (23) and (24) no kneeling (ability to vertically translate) is assumed, along with an ultimate landing load factor of 4.5, and 2 main LG shock struts. Both equations are scaled to 85% of their original values in [173] to fit modern aircraft data. The required inputs are W_{ML} [t], nose and main LG lengths [m], number of nose and main LG wheels [-], and stall speed [m/s]. W_{ML} and stall speed are determined during the aircraft sizing process. However, the number of main LG wheels is dependent on W_{ML} and the nose and main LG lengths are dependent on the aircraft and propulsor dimensions.

A survey of over 50 aircraft with W_{ML} between 40 and 160 t indicated that below 79 t current aircraft use two dual-wheels for the main LG, such as on the Airbus A320 and Boeing 737. Above this value, two four-wheel trucks (bogies) are typical, such as on the Airbus A310 and Boeing 767. Thus, below and above 79 t it is assumed that 4 and 8 main LG wheels are required, respectively. Nearly all current aircraft with W_{ML} of 40-160 t use a tricycle arrangement with dual nose wheels.

As noted by Seitz, rather than constraining the propulsor size, it is more appropriate to size the LG appropriately [174]. Two requirements set the LG length, including maintaining a minimum ground clearance and avoiding propulsor damage in the case of a nose LG collapse. The first of these is illustrated in Figure 11. Per FAA AC150, the minimum ground clearance (Δz_{clear}) is 0.4572 m (18 in) [175]. The wing vertical and horizontal placement (Δz_{wing} and y_o), main LG and propulsor spanwise placement ($y_{\text{LG},\text{main}}$ and $y_{\text{eng},\text{in}}$), nacelle-wing offset (Δz_{nace}), and wing dihedral (Γ) are specified values. Thus, the main LG length ($l_{\text{LG},\text{main}}$) is set during the sizing process based on the nacelle diameter (d_{nace}).

Figure 11. Main landing gear length parameters. Landing gear length is partially set by the minimum nacelle ground clearance (Δz_{clear}). All other parameters shown are specified, except the nacelle diameter (d_{nace}), which is determined during aircraft sizing. Modified from [176].

3.6. Vertical tail sizing

AEA may use DEP, thus using more than two electrically-powered propulsors. One of the often-mentioned benefits of DEP is the possibility for a smaller vertical tail (VT). In TASOPTe the VT can be sized via a specified volume coefficient or through maintaining one engine inoperative (OEI) yaw trim. The VT volume coefficient is

$$V_v = \frac{S_v l_v}{S b}, \quad (25)$$

where S_v , l_v , S , and b represent the VT planform area, wing to VT aerodynamic center distance, wing planform area, and wing span, respectively. Various values can be assumed for V_v , such as 0.074 [171], 0.09 [173], and 0.10 [168]. V_v is approximately 0.085 and 0.094 for the geometry of an A320 and B737, respectively.

Figure 12. VT volume coefficient with varying propulsor spacing and count. The propulsor spacing is measured from center to center of the propulsors. Due to a finite wing length, the propulsor spacing is limited with more than four propulsors.

To analyze the potential VT sizing benefits of DEP, an effective V_v is calculated for the OEI yaw trim VT sizing option as well. Based on preliminary AEA sizing results, this effective V_v is plotted in Figure 12 as a function of the propulsor spacing and propulsor count. An assumed innermost propulsor placement, that of an A320, is used here. As expected, benefits in VT sizing are seen with a smaller propulsor spacing and an increased propulsor count. However, the calculated A320 V_v is used in this work.

The number of propulsors is varied in this work, as discussed later. Preliminary results indicated that the propulsor spacing has a minimal effect on aircraft performance. To allow for sufficiently clean inlet airflow and reduce the risk of multiple propulsor failure, the dimensionless propulsor spacing is set to 2.0. The innermost propulsor placement is an optional optimization variable, but many other considerations drive this placement. Increasing the propulsor distance from the fuselage has the following qualitative advantages (+) and disadvantages (-):

- + Less risk of fuselage damage due to a blade or disk failure
- + Less cabin noise
- + Less interference drag from fuselage interaction
- + Increased wing bending moment relief in air
- + More ground clearance and potentially shorter landing gear
- Increased wing bending moment on ground
- Possibly increased wing flutter
- Propulsor mounting difficulties due to a shorter outboard chord
- Increased electrical system weight due to longer cabling
- Increased OEI yawing moment
- Center of gravity moved aft

Chapter 4

Aircraft configuration, mission, and technology assumptions

The overall aim is to devise all-electric aircraft designs as a function of key technology assumptions (e.g. batteries). Design characteristics and performance are then compared with conventional aircraft designed with the same technology assumptions where relevant.

4.1. Top-level requirements

The specific aircraft under study is based on the geometry of an Airbus A320neo. Basic sizing parameters (e.g. fuselage length, wing sweep, etc.) were acquired from publically available aircraft data or appropriate estimates [177]. An A320 was chosen as the design basis in order to properly isolate and observe the benefits of electric propulsion applied to a modern, widely-used commercial aircraft configuration.

An A320 seats a maximum of 190 PAX, with typically 164 PAX in a 1-class configuration and 150 PAX in a 2-class configuration [177]. Considering the A320 PAX counts and previous studies at MIT involving the D8 “double bubble” concept, the design payload is 180 PAX assuming 97.5 kg/PAX [178]. The contingency reserve charge (end SOC) is set to 30%. The balanced field length is limited to 2438.4 m (8000 ft) at ISA sea level, which is a typical runway length for wide-body aircraft. The wing span is constrained to 35.97 m (118.0 ft), which conforms with the FAA Group III and ICAO Code C airport gate limitations [179].

An A320 is designed for Mach 0.78 cruise at an altitude of approximately 11 km. However, for very short missions (e.g. 200 nmi), optimized AEA fly at lower “cruise” altitudes (e.g. 8 km). Maintaining Mach 0.78 results in excessive fuselage drag and poor aircraft performance, causing convergence issues in some cases. Considering this, the design aircraft speed is maintained at 448 kt, corresponding to the original A320 design speed at M0.78 and 11 km.

4.2. Electrical and propulsion system components

As previously discussed, a HTS electrical and propulsion system is used for weight and efficiency benefits. Future gearboxes (gear ratio of 4.33:1) and HTS motors are expected to have high efficiencies of 98.0% and 99.5%, respectively [151, 156]. Table 5. lists the weight and efficiency assumptions for the PMAD.

Table 5. PMAD weights and efficiencies.

Component	Specific Power [kW/kg]	Efficiency [%]	References
Solid State Power Controller	44	99.7	[22, 180, 127]
DC/DC Converter	26	99.5	[126, 180, 181, 182]
Transmission Cable	7 [kg/m]	99.9	[181, 183, 184]
DC/AC Inverter (Controller)	26	99.5	[126, 180, 181]

4.3. Battery parameters

Two BDM, shown in Figure 9, are available for analysis. The Li-ion BDM model is used for all AEA designs in this work, and the Li-S BDM is also used for a subset of cases to evaluate the impact of the discharge profile on battery and aircraft performance. However, the magnitude of the Li-S resistance model is scaled to match the average Li-ion resistance model between 10 and 100% SOC, representing an assumed technology improvement.

The full charge is option used, meaning excessive battery capacity is available for shorter missions. Using this method allows for the necessary takeoff battery power. In practice, the same size battery could be swapped for quicker turnaround.

Energy density [Wh/L] is not directly specified, but rather an effective battery density of 2000 kg/m³ is used for all cases. The battery volume for all runs is near or below the wing box volume limit. Due to the high uncertainty in this parameter and available cargo hold space, volume considerations do not constrain the aircraft design and are not discussed further. Battery pack specific energy and power are swept in this work, as discussed later.

4.4. Structural materials and aerodynamics

Though the primary objective of this work is to evaluate propulsion benefits, it is reasonable to assume advanced structural materials and aerodynamics for both future conventional aircraft and AEA. Recent aircraft designs, such as the Airbus A350, Boeing 787, Bombardier CS300, and Irkut MC-2, use polymer composites rather than aluminum for the primary structure [171, 185, 186, 187]. Carbon fiber reinforced polymer (CFRP) is assumed, as it has low density and high strength [188]. Laminar flow wings are an active area of research, but require low magnitudes of wing sweep and are not implemented in this work [73, 171, 189, 190]. However, a 10% maximum wing lift coefficient improvement is assumed. A VAN with a 15% area increase during takeoff and initial climb is included for conventional aircraft in TASOPT, while the takeoff opening area is optimized for AEA in TASOPTe.

Chapter 5

Parametric aircraft sizing and performance

A set of AEA are generated and compared against baseline conventional aircraft. Parameter sweeps are utilized to see the impact of uncertain design parameters on aircraft performance.

5.1. Optimization metric

All aircraft in this work are optimized across a weighted set of design and/or off-design missions. The objective function target for minimization in previous TASOPT-based studies was the payload fuel energy intensity (PFEI) metric [123, 191, 192]. In this work, the optimization target is a similar, but dimensionless, energy/productivity (E/P) metric. This metric calculated as

$$E/P = \frac{E}{W_{\text{pay}} R g} , \quad (26)$$

where the amount of energy required for a given mission (E) is non-dimensionalized by the mission productivity, which is represented by the product of payload (W_{pay}), range (R), and the acceleration due to gravity (g). For conventional aircraft fuel energy based on the lower heating value of jet fuel is used, while for AEA battery energy is used.

5.2. Baseline aircraft

For comparison purposes, TASOPT was used to generate optimized conventional aircraft results. First, an aircraft based on the original A320 design, A320neo-OPT, was created. A representative design range of 2600 nmi was taken from an A320 payload-range diagram at the design payload of 180 PAX, and this aircraft embodies a current narrow-body aircraft [177].

However, the baseline aircraft for environmental performance comparisons with AEA use future gas turbine propulsion technology assumptions, including component polytropic efficiencies greater than 90% and lower weight engine model. The same structural and aerodynamic improvements applied to AEA are also applied here. The overall configuration is still an A320 with 180 PAX, but the design range is varied to agree with that of AEA under different technology and operation assumptions, which are discussed in the next section. An additional conventional aircraft, A320adv-OPT, that uses future technology assumptions, but the original design range of 2600 nmi, is assessed. All conventional aircraft were globally optimized with the optimization variables listed in Table 6 and had a reserve fuel requirement of 20%.

Table 6. Conventional and all-electric aircraft optimization variables.

Variable	Description	Conventional	All-Electric
$C_{L,CR}$	cruise lift coefficient	•	•
AR	aspect ratio	•	•
Λ	wing sweep angle	•	•
$(t/c)_o$	root airfoil thickness ratio	•	•
$(t/c)_s$	panel-break and tip airfoil thickness ratio	•	•
λ_s	outer-panel taper ratio	•	•
$r_{cl,s}$	local/root c_l ratio at panel-break	•	•
$r_{cl,t}$	local/root c_l ratio at tip	•	•
FPR _D	design fan pressure ratio	•	•
h_{CR}	start-of-cruise altitude	•	•
BPR _D	design bypass ratio	•	
$T_{t4,TO}$	turbine inlet temperature at takeoff	•	
$Tt_{4,CR}$	turbine inlet temperature in cruise	•	
$f_{pb,TO}$	takeoff battery peak power fraction		•

5.3. Parametric values

The aircraft configuration and technology assumptions previously discussed are independent design parameters that have been set to specified quantities. However, additional design parameters have not been selected, as their influence on the aircraft performance is largely unknown a priori. Thus, it is useful to determine the optimized aircraft sensitivity to these additional parameters through parameter sweeps [121].

Contemporary narrow-body aircraft use two ultrahigh bypass ratio fans. However, AEA may use more than two propulsors, as electric motor efficiency is approximately scale invariant. Preliminary results indicated decreased performance beyond six propulsors, so the propulsor count is evaluated between two and ten, inclusive.

Battery specific energy, at the pack level, is swept between 400 and 2000 Wh/kg in 400 Wh/kg increments. 400 Wh/kg may be achievable with Li-ion or Li-metal batteries, while 800 Wh/kg is representative of a mature Li-S battery and is used for the nominal design in this work. Values of 1200, 1600, and 2000 Wh/kg are unlikely based on current forecasts. However, an unforeseen development in battery research may emerge, such as the closed-system Li-air battery [193].

Current 200 Wh/kg Li-ion batteries are capable of achieving specific powers near 1200 W/kg [96]. Li-S manufacturer projections indicate that specific power will increase with specific energy in future batteries [120]. However, it is unlikely that specific power will scale linearly with specific energy, as power is limited by surface area, while energy is more closely related to volume. In this work, the specific power improvement scales with the square root of the specific energy improvement. For example, 800 Wh/kg batteries (factor of four improvement) are assumed to be capable of 2400 W/kg (factor of two improvement).

Depending primarily on the battery specific energy assumption, the AEA design range is varied in 100 nmi increments, starting with 200 nmi and ending with non-convergence. Shown in Figure 13 are U.S. and global stage lengths for both A320 and

narrow-body aircraft, sourced from 2015 OAG data [194]. An AEA capable of flying 1000 nmi could replace approximately 70% of missions that are currently completed with similar size conventional aircraft.

Figure 13. U.S. and global stage lengths for A320 and narrow-body aircraft. Data compiled from [194].

The aircraft is sized for the (varying) design range with 180 PAX. However, off-design missions are used for optimization, which determine the fleet E/P and the final, optimized design. These off-design missions have load factors of 83.3% (150 PAX), a slight increase from current Airbus and Boeing load factors of near 81% [3, 4]. The region of Figure 13 below 1000 nmi is approximately linear. Considering this, each aircraft has 2 equally-weighted off-design missions at the design range and midway between the design range and 100 nmi. Missions of 300 nmi or less use only 1 off-design mission at the design range. All AEA were globally optimized with the optimization variables listed in Table 6.

5.4. Nominal design characteristics

Through parameter sweeps of specific energy, design range, and propulsor count, 205 different AEA were designed and optimized in TASOPTe. Exemplary results with a battery pack specific energy of 800 Wh/kg are presented here to illustrate key AEA design characteristics.

Figures 14, 15, and 16 illustrate the impact of the design mission range and number of propulsors on W_{MTO} , mission energy, and E/P, respectively. Weight and mission energy penalties are increasingly severe as the design range increases, and beyond 600 nmi TASOPTe is unable to size an aircraft. E/P for an AEA with 800 Wh/kg batteries is lowest with a 300 nmi design range.

The best performing aircraft, in respect to mission energy and E/P, use four propulsors for each design range. A comparison of this design with the two and ten propulsor designs is shown in Figure 17. As the propulsors count increases, the individual propulsor inlet areas decrease, but the total inlet area remains approximately constant. Additional propulsors move the aircraft center of gravity aft, which in turn moves the wing aft to maintain pitch trim. This results in an increasing horizontal tail area, as the wing to horizontal tail distance (moment arm) is reduced. The key driver in the weight and performance discrepancy with propulsor count variation stems from the propulsion and electrical system assumptions. HTS motor specific power increases with maximum power, and more propulsors result in longer cable lengths. However, the two propulsor case leads to increased landing gear length and weight. Thus, the four propulsor design is a tradeoff between electrical and propulsion components and landing gear weight.

Figure 14. W_{MTO} variation with propulsor count and design range. 800 Wh/kg batteries are used here, but similar trends appear for other specific energies.

Figure 15. Mission energy variation with propulsor count and design range. 800 Wh/kg batteries are used here, but similar trends appear for other specific energies.

Figure 16. E/P variation with propulsor count and design range. 800 Wh/kg batteries are used here, but similar trends appear for other specific energies.

Figure 17. Aircraft planform view wireframe overlays with 2, 4, and 10 propulsors. This aircraft used 800 Wh/kg batteries and had a design range of 500 nmi. Note that the wing span was not selected, but rather optimized to the constraint limit of 36 m.

Figure 18. OpenVSP A320neo aircraft wireframe model. Winglets are not shown.

Figure 19. OpenVSP AEA-800 aircraft wireframe model. The fuselage size and shape are based on an Airbus A320neo, as shown in Figure 18. The best aircraft performance with 800 Wh/kg batteries and a 500 nmi design range occurred with the 4 propulsors.

Though AEA using 800 Wh/kg batteries are capable of a 600 nmi design range, the weight and performance penalties render this design unreasonable. The 600 nmi design has a W_{MTO} of 149.1 t, approximately twice that of an A320neo, which is illustrated in Figure 18. Rather, a design range of 500 nmi is used for further examination, which has a 39.6 t lower W_{MTO} for only a 100 nmi decrease in range. As shown previously, the best performance for this design range occurs with four propulsors. This result comes from a tradeoff between a variety of considerations, including fan efficiency, propulsor drag, landing gear length and weight, wing shape, tail area, and electrical and propulsion system component weights. An OpenVSP model of this design, AEA-800, is shown in Figure 19. The wing is 34% less swept, but has approximately the same span (36 m), aspect ratio (10.3), and surface area (125.6 m²). The horizontal tail is 14% smaller, the vertical tail is 13% larger, and the total propulsor inlet area is 39% larger. Also, the landing gear is shorter, but heavier due to a larger W_{MTO} . As discussed previously, aircraft with W_{MTO} greater than approximately 79 t typically use two four-wheel trucks rather than two dual-wheels for the main LG.

Shown in Table 7 is comparison of the nominal 800 Wh/kg AEA design with optimized A320 aircraft using conventional propulsion. An optimized A320neo configuration designed for the original design mission, A320neo-OPT, results in a design similar to an A320neo, as expected. Using advanced technology assumptions with the same overall configuration in the A320adv-OPT results in a 23% smaller W_{MTO} and 41% lower energy requirement for the same design mission. Taking this design and lowering the design range to 500 nmi results in the A320ref-800, which has 16% smaller W_{MTO} and 19% smaller wing area. The A320ref-800 is the reference aircraft for comparisons with the AEA-800, an AEA designed with 800 Wh/kg batteries. The AEA-800 has a 161% larger W_{MTO} and 65% larger wing area than the A320ref-800, a conventional aircraft with the same design mission of 500 nmi.

Table 7. Optimized A320 and AEA key parameters.

Parameter	Units	A320neo-OPT	A320adv-OPT	A320ref-800	AEA-800
Design PAX	-	180	180	180	180
Design Range	nmi	2600	2600	500	500
W_{MTO}	t	65.3	50.0	42.0	109.5
Mission Energy	MWh	142.1	84.3	18.2	28.8
Mission E/P	-	0.617	0.366	0.412	0.649
Wing Span	m	36.0	36.0	35.9	36.0
Wing Area	m ²	109.5	94.1	76.3	125.6
Wing Sweep	deg	23.7	23.1	25.2	13.9
Wing Aspect Ratio	-	11.8	13.8	16.9	10.3
Wing Taper Ratio	-	0.146	0.151	0.150	0.304
Cruise Altitude	m	10891	11986	10936	7829
Cruise Speed	kt	449	447	448	448
Cruise Mach	-	0.780	0.780	0.778	0.747
Cruise L/D	-	18.3	18.2	16.5	18.6
Cruise C_L	-	0.582	0.617	0.548	0.605
Propulsor Count	-	2	2	2	4
Design BPR	-	5.7	17.5	21.7	-
Design FPR	-	1.69	1.50	1.41	1.25
Fan Diameter	m	1.47	1.69	1.62	1.72
Propulsor Max. Thrust	kN	73.6	73.9	58.1	61.6

The cruise altitude for the AEA-800 is over 3000 m (28%) less than any of the conventional aircraft in Table 7, which is illustrated in Figure 20. Conventional aircraft also climb during cruise, while AEA with constant mass batteries remain at the same cruise altitude. Due to the additional aircraft weight and consequential lift required, AEA climb and descend at approximately 11% higher speeds than conventional aircraft performing the same mission. The descent angle for the missions in Figure 20 is specified at 3°, but the climb angle for AEA is 0.86° less steep on average than the conventional aircraft counterpart. Due to a combination of these flight trajectory features, the total mission time is 4% less for the AEA-800 compared to the A320ref-800.

Figure 20. Conventional aircraft and AEA mission profiles.

Shown in Figure 21 is a weight distribution for the optimized A320 and AEA-800 aircraft previously discussed. Due to the advanced technology assumptions, the fuselage, wing, and tails are over 15%, 50%, and 60% lighter, respectively, on the A30adv-OPT and A320ref-800 in comparison to the A320neo-OPT. These benefits are also observed in the AEA-800. However, the electrical and propulsion system for the AEA-800 is a factor of four larger than the A320-adv-800. This design also requires massive batteries (48.7 t), which weigh more than the entire conventional aircraft counterpart, the A320ref-800 (42.0 t). The battery fraction in the AEA-800 (44%) is significantly greater than the fuel fraction in any of the optimized A320 designs (5-22%), as shown in Figure 22.

Figure 21. Conventional aircraft and AEA physical weight breakdown.

Figure 22. Conventional aircraft and AEA fractional weight breakdown.

Figure 23. Effect of battery discharge model on battery efficiency. Both are 800 Wh/kg and 2400 W/kg batteries with the same average internal resistance. The evaluated design range for evaluation was 500 nmi, and 4 propulsors performed best for each battery chemistry. The mission points are start (ST), takeoff (TO), climb (B1-5), cruise (C1-2), and descent (D1-5).

The discharge performance of future battery technology is uncertain, but Figure 23 illustrates the key differences between two potential battery chemistries, Li-ion and Li-S. The efficiency trend of the Li-ion battery roughly corresponds to the battery power required. Takeoff requires the most power and has the lowest efficiency, while descent requires the least power and has the highest efficiency. In contrast, the lowest efficiency for the Li-S battery occurs during climb. This is due to the discharge model, shown in Figure 9, where the resistance is highest at approximately 78% SOC.

The battery efficiencies shown in Figure 23 are all greater than 90%, which agrees with values in other AEA work [117, 118]. However, further increasing the design range and/or W_{MTO} results in increased battery power requirements, and hence lower battery efficiencies. Thus, the battery modelling presented here captures not only energy storage limitations, but battery power restrictions as well.

5.5. Parametric evaluation results

In addition to 800 Wh/kg, aircraft were evaluated with specific energies between 400 and 2000 Wh/kg. The propulsor count was again swept between two and ten propulsors, while the design range interval varied with the specific energy assumption. Key results of these parameter sweeps are shown in Figures 24-26. As expected, increasing the design range increases W_{MTO} and mission energy requirements. The most efficient missions in respect to E/P occur at intermediate design ranges, as shown in Figure 26. The mission productivity increases with range, but battery weight penalties offset this benefit at the upper end of the design range interval.

Most optimized AEA use four propulsors for the reasons discussed previously. However, many designs with high specific energy assumptions use two propulsors for short design ranges. The aircraft for these short missions have lower W_{MTO} and consequentially require less thrust. The propulsor size is thus small enough where the motor specific power benefits with two large, high-power propulsors overshadow the landing gear size penalties. Also, slight kinks in the W_{MTO} trends are visible near 79 t due to the LG sizing method.

For comparison, the BHL Ce-Liner is another battery-powered, narrow-body AEA design. This aircraft was designed with 2000 Wh/kg batteries for a mission of 189 PAX, 900 nmi, and M0.75 cruise [87]. The BHL Ce-Liner has a W_{MTO} of 109.3 t and mission energy requirement of 35.2 MWh, compared to 72.1 t and 32.2 MWh for a 2000 Wh/kg, 900 nmi AEA in this work. Both aircraft use two propulsors and advanced technology assumptions. However, this work assumes improved structural materials (composites), while the BHL Ce-Liner uses a C-wing and aft-mounted propulsors.

For consideration of environmental performance, the ratio of AEA battery energy to conventional aircraft fuel energy for the same mission is plotted in Figure 27. Design missions of 500 nmi or less, before the onset of massive battery weight penalties, result in the best performance of AEA compared to conventional aircraft. However, significantly limiting the design range also limits the usability of AEA.

Figure 24. W_{MTO} variation with design range and battery specific energy. Bradley presented similar trends with approximately 50% greater range capabilities and determined that 1000 Wh/kg would be required for a 900 nmi mission [195]. However, in this work the electrical and propulsion system is modeled with higher-fidelity.

Figure 25. Mission energy variation with design range and battery specific energy.

Figure 26. E/P variation with design range and battery specific energy.

Figure 27. AEA to conventional aircraft energy ratio variation with design range and battery specific energy. Note that conventional aircraft use fuel energy based on the lower heating value of jet fuel and AEA use battery energy.

Chapter 6

Environmental assessment

AEA are often cited as an option for environmentally friendly aviation. However, this is dependent on the entire energy chain, not just in-flight emissions. Here the energy and environmental impacts of AEA are evaluated and compared to conventional aircraft. In evaluating the future environmental performance of aircraft, two scenarios are used. The business-as-usual (BAU) scenario assumes limited environmental measures, while the highly renewable energy (HRE) scenario assumes substantial environmental measures.

6.1. Conventional aircraft equivalent emissions

Mission fuel requirements for conventional aircraft are directly computed by TASOPT. The equivalent carbon dioxide emissions (CO_2e) are then determined using emission intensities. The standard CO_2 emissions index for Jet-A is $3148 \text{ g CO}_2/\text{kg}_{\text{fuel}}$ [196].

The current well-to-pump indirect equivalent emissions for Jet-A are $826.8 \text{ g CO}_2\text{e}/\text{kg}_{\text{fuel}}$ [197]. This value is assumed to reduce to 616.9 or 821.3 $\text{CO}_2\text{e}/\text{kg}_{\text{fuel}}$ by 2050, depending on future emission policy scenarios [197]. These values are paired with the HRE and BAU scenarios, respectively.

The current non- CO_2 direct equivalent emissions are estimated as $2518 \text{ CO}_2\text{e}/\text{kg}_{\text{fuel}}$ on a 100-year absolute global warming potential (AGWP_{100}) basis and $1259 \text{ CO}_2\text{e}/\text{kg}_{\text{fuel}}$ on a 3% discount rate net present value ($\text{NPV}_{3\%}$) basis [198]. The non- CO_2 direct equivalent emissions are assumed to grow at 1.4% per year and include emissions from NO_x , sulfates, soot, water, and contrails [198].

Analysis of conventional aircraft equivalent emissions scales the well-to-pump emissions linearly and the non- CO_2 emissions via the stated growth rate between 2015 and 2050 in correlation with the electricity generation assumptions discussed next.

6.2. Electric aircraft equivalent emissions

Mission battery energy requirements for AEA are directly computed by TASOPTe. However, multiple inefficiencies exist further upstream in the energy supply chain. The electricity transmission and distribution efficiency is approximately 93% [199]. The charging efficiency is assumed to be 95%, which is typical for Li-ion batteries [200]. The round-trip (energy) efficiency is the ratio of the available battery discharge energy to the input energy required to restore the initial battery SOC [201]. This value varies depending on the battery chemistry and SOC range used, but 85% is assumed in this work [132]. This is typical for Li-ion batteries and reasonable for future Li-S batteries [10, 18, 200, 202, 203]. The combination of these losses results in an effective 75% efficiency between the aircraft and electricity source.

Current U.S. electricity generation consists of approximately 17% renewable energy, with the largest contributors being hydropower (7.4%) and onshore wind (6.0%) sources. The remaining electricity is primarily from natural gas (31%), coal (31%), and nuclear (20%) sources. This results in a current U.S. emission intensity of approximately 500 g CO₂/kWh [199].

For analysis of AEA, two future electrical grid scenarios are assumed. The BAU scenario uses the U.S. Energy Information Administration Annual Energy Outlook 2017 predictions, as shown in Figure 28 [204]. Here, the renewable energy fraction grows rapidly until about 2023, then stabilizes, while coal is continually replaced with natural gas. The HRE scenario uses the NREL Renewable Electricity Futures Study predictions, as shown in Figure 28 [205]. The specific case used is the Incremental Technology Improvement with 80% renewable energy in 2050 (2014 update) [205]. Here, the renewable energy fraction grows linearly, while coal and natural gas fractions continually diminish. Knowing the generation mix, lifecycle equivalent CO₂ emissions for each electricity source can be determined using emission intensities, which are shown in Table 8. The combined equivalent CO₂ emissions for all sources is illustrated in Figure 29 for both scenarios.

Figure 28. Future U.S. electrical grid scenarios. Data compiled from [204, 205].

Table 8. Lifecycle emission intensities by generation source.

Electricity Generation Source	Emission Intensity [g CO ₂ e/kWh]	Reference
Wind-Offshore	11	[206]
Wind-Onshore	11	[206]
CSP	21	[207]
PV-Utility	45	[208]
PV-Rooftop	45	[208]
Geothermal	37	[209]
Biomass	40	[210]
Hydropower	7	[211]
Nuclear	12	[212]
Petroleum	840	[213]
Natural Gas-CC	487	[214]
Natural Gas-CT	670	[215]
Coal	980	[216]

Figure 29. Combined electricity generation equivalent CO₂ emissions by scenario.

Figure 30. Conventional and AEA energy conversion chain comparison. Efficiencies are calculated during cruise for the A320ref-800 and AEA-800.

6.3. Environmental performance results

An energy conversion chain comparison of the 800 Wh/kg AEA design (AEA-800) with a conventional aircraft design (A320ref-800) is shown in Figure 30. Both aircraft are optimized for a 500 nmi design range. An onboard efficiency of 43.1% is observed for the conventional aircraft during cruise. The AEA has a much greater onboard efficiency of 66.1% during cruise. However, if upstream losses are accounted for, the efficiency is only 49.6%. Additional losses are incurred during power generation, but this varies based on the generation source.

Based on the parameter sweep results in Figures 24-26, a design range was selected for each specific energy assumption for further analysis. The only converged solution with 400 Wh/kg was at 200 nmi. For the other specific energies, the second longest design range was chosen. Using the performance results for these AEA and the corresponding conventional aircraft, the ratio of equivalent CO₂ emissions are shown in Figures 31 and 32. In discussing these results, it is important to note that the generating breakdown difference between the BAU and HRE scenarios. Even if the same fraction of energy is from renewable sources, the emissions may be different due to the specific generation choices (e.g. coal vs. natural gas, solar vs. wind).

The non-CO₂ direct equivalent emissions are calculated on a AGWP₁₀₀ and NPV_{3%} basis in Figures 31 and 32, respectively. Under the BAU electrical grid scenario, AEA always result in higher equivalent CO₂ emissions than their conventional aircraft counterparts for the missions plotted in Figures 31 and 32. However, under the HRE electrical grid scenario, AEA using 800-2000 Wh/kg result in lower equivalent CO₂ emissions after approximately 2035 and 2043 using the AGWP₁₀₀ and NPV_{3%} assumptions, respectively. The electrical grid for these years uses 50% and 64% renewable energy. AEA using 400 Wh/kg batteries have a breakeven point in 2040 and 2046 using the AGWP₁₀₀ and NPV_{3%} assumptions, respectively. The electrical grid for these years uses 59% and 69% renewable energy.

Figure 31. AEA to conventional aircraft equivalent CO₂ emissions ratio, AWP₁₀₀ basis.

Figure 32. AEA to conventional aircraft equivalent CO₂ emissions ratio, NPV_{3%} basis.

The results in Figures 31 and 32 indicate that AEA result in higher equivalent CO₂ emissions under the HRE scenario until at least 2035, which requires 50% renewable energy. It may be desirable to design AEA for shorter ranges than they are capable of achieving in order to realize environmental benefits sooner. For this purpose, the design ranges are decreased for the 800-2000 Wh/kg cases, and the ratio of equivalent CO₂ emissions are plotted in Figures 33 and 34.

Under the BAU electrical grid scenario using a AWP₁₀₀ basis, AEA result in lower equivalent CO₂ emissions compared to their conventional aircraft counterparts in 2034 for the 800 Wh/kg design and approximately 2028 for the other designs. This corresponds to 26% and 24% renewable energy, respectively. Under the HRE electrical grid scenario, AEA using 800 Wh/kg have lower equivalent CO₂ emissions after about 2027 and 2034 using the AGWP₁₀₀ and NPV_{3%} assumptions, respectively. The electrical grid for these years uses 36% and 48% renewable energy. Aircraft with 1200-2000 Wh/kg batteries have a breakeven point in 2026 and 2031 using the AGWP₁₀₀ and NPV_{3%} basis, respectively. The electrical grid for these years uses 34% and 43% renewable energy.

Figure 33. AEA to conventional aircraft equivalent CO₂ emissions ratio at reduced design ranges, AWP₁₀₀ basis.

Figure 34. AEA to conventional aircraft equivalent CO₂ emissions ratio at reduced design ranges, NPV_{3%} basis.

Chapter 7

Challenges and areas of future research

In this work, AEA designs resembling an A320neo have been evaluated. This airframe was selected so the benefits of electric propulsion could be observed for a well-known transport aircraft configuration. However, other configurations may be more suitable for AEA and should be evaluated in future work. A variety of other topics related to AEA warrant further research and are discussed here.

7.1. Impact analyses

Presented in this work are equivalent emissions on a flight-by-flight basis. However, this does not include the lifecycle emissions associated with manufacturing. Depending on the battery chemistry, lifecycle emissions for battery manufacture may not be negligible.

Additionally, introduction of AEA is dependent on commercial considerations by aircraft manufacturers, airlines, and airports. There must be a financial incentive to partake in this high-risk venture. Early markets for AEA adoption need to be identified. The cost of AEA components, particularly batteries, is largely unknown, but likely will exceed that of conventional aircraft components. The operating cost change in converting to AEA is largely dependent on the ratio of electricity to jet fuel prices and battery replacement costs, but other financial incentives, such as carbon taxes, may incentive earlier adoption.

The effect on airport capacity and the aviation network, as well as the airport and electrical grid infrastructure should be considered as well. AEA may provide an opportunity for electrical grid load-leveling through night battery charging. Batteries could also be charged during peak solar and wind generation hours, which would limit curtailment of excess power. This would have implications for energy policy in terms of the electricity generating mix that is developed.

7.2. Electrical and propulsion system

Narrow-body AEA require electrical power that is at least an order of magnitude greater than previously seen on aircraft, which poses potential safety challenges. High voltages (e.g. 1 kV) for this system exceed the air breakdown voltage at high altitudes, so high voltage insulation requirements need further study [113, 149]. Methods to reduce the risk of power outages and electromagnetic interference should be examined as well.

Advanced propulsion system components are enabling technologies for AEA. These include very low FPR fans, lightweight motors, gearboxes with high gear ratios, variable area nozzles, and an efficient cooling system. HTS components, including motors, generators, converters, inverters, and rectifiers, cryocoolers, and cabling, need further weight and loss reduction before their implementation is reasonable [217]. Analysis of AEA with boundary layer ingestion (BLI) is also recommended for further study.

7.3. Batteries

Currently AEA are limited to light aircraft with limited passenger capacity, range, and speed due to rechargeable battery limitations, especially low specific energy. Substantial improvement in battery technology, including specific energy, specific power, and energy density, would be required for narrow-body AEA. Furthermore, the battery packing efficiency (ratio of cell to pack mass) should be improved for aviation purposes from current values of 65-75% for electric vehicles. To reduce the weight penalty of batteries, NASA is currently studying multifunctional structures with energy storage [218]. This novel design would allow a portion of the aircraft structure to also serve as a battery and is worth further study. Implementation requirements of mass-gaining batteries, such as air intake, pressurization, and maintenance access, are not yet fully understood.

Further analysis of AEA should include consideration of battery state of health. The available capacity of a battery decreases after repeated charge-discharge cycles (capacity fade) [219, 220]. This impacts the range and replacement requirements.

The reserve battery requirement in this work was set to 30% SOC (20% usable SOC), corresponding to approximately 30 minutes of flight. This should be examined more closely, with consideration of available power at low SOC for aborted landings, as well as deviations and go-around maneuvers.

The battery management system (BMS) for aircraft should be further developed, with consideration of multiple battery packs with various discharge rates. This analysis should include using multiple battery types with varying properties so the energy, power, and economic tradeoff can be observed. Considering the high aviation safety standards and well-publicized battery issues with MOE, such as the Boeing 787 battery fires, an understanding of how to safely manage battery discharge is crucial for AEA to become viable [155].

7.4. Operations

Airport infrastructure and operations would be impacted by battery charging requirements. Conventional aircraft typically turnaround in 30-45 minutes, which may be difficult to achieve with AEA battery charging or swapping. State of the art batteries, with respect to specific energy, have recommended charging times of around two hours, which is not reasonable for commercial aviation [119]. Initial study results suggest that the upper end of the current turnaround time interval could potentially be reached via battery swapping [16]. Either option would have implications for airport investments. Charging or swapping infrastructure would be required, and the number of gates needed for an equivalent fleet may increase with turnaround time being limited by charging or swapping rather than passenger movements and servicing.

Runway length currently constrains the AEA aircraft design. Short-haul flights are prevalent at short-runway airports, thus limiting the possible routes for AEA. Longer runways or wings with high lift capabilities would enable AEA implementation. Assisted

takeoff, such as the ElectroMagnetic Aircraft Launch System (EMALS) is another enabling takeoff technology [221].

AEA have the potential to use DEP for propulsive efficiency benefits. However, DEP may also allow steeper descent. The decent angle of an aircraft is limited by the amount of drag that can be created. Recent research has examined using an engine air-brake to increase drag during descent [222]. Drag could be increased for AEA by allowing some of the propulsors to windmill, which may recover some energy as well. In analyzing this idea, exploitation of the DEP noise reduction potential should be considered.

Chapter 8

Conclusion

The introduction of AEA into commercial aviation would lead to profound impacts on aircraft manufacturers, airlines, airports, and the transportation system as a whole. The concept of all-electric propulsion has expanded the aircraft design space, resulting in over 50 different AEA research projects over the past decade. The majority of these aircraft designs have targeted light aircraft, but numerous narrow-body AEA have also been evaluated. Two of these are commercial narrow-body projects currently in progress.

In this work, AEA were evaluated at design ranges of 200-1600 nmi with 2-10 propulsors and 400-2000 Wh/kg batteries. The performance of these AEA was compared to advanced conventionally powered aircraft. All aircraft were based on the A320neo configuration. Optimized AEA were found to use either two or four propulsors depending on the specific energy and design range assumptions. Most cases found the best performance with four propulsors. This result stems primarily from a tradeoff between landing gear weight and electrical and propulsion system weight. Significant aircraft weight and performance penalties limit the design range for each specific energy assumption.

Current battery technology makes AEA with 180 PAX likely infeasible. A factor of four increase in battery pack specific energy to 800 Wh/kg would enable flights of up to 500 nmi. However, a lower design range of 300 nmi would enable improved performance in respect to required energy per mission and equivalent CO₂ emissions. Despite the higher total energy use, narrow-body AEA have the potential for lower equivalent CO₂ emissions if the electrical grid transitions toward renewable energy. This is largely enabled by the complete elimination of all high-altitude emissions, which would remove associated non-CO₂ warming. Also, the absence of direct-emissions from ground operations would significantly improve air quality around airports.

Further benefits would likely be seen using a more advanced configuration, such as the “double bubble” concept seen in the MIT D8, which will be examined in future work. This type of design would also allow for additional battery storage that may be required for longer range AEA. An increased span constraint likely enables improved environmental performance. Finally, the use of DEP may enable further efficiency gains, which may be unique to electric aircraft configurations.

References

- [1] IPCC, *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)], Geneva, Switzerland, 2014, pp. 1-151.
- [2] International Energy Agency, *World Energy Statistics*, 2016.
- [3] Airbus, *Airbus Global Market Forecast - Growing Horizons 2017-2036*, 2017.
- [4] Boeing, *Boeing Current Market Outlook 2010 - 2029*, 2010.
- [5] Dorbian, C. S., Wolfe, P. J., and Waitz, I. A., "Estimating the Climate and Air Quality Benefits of Aviation Fuel and Emissions Reductions," *Atmospheric Environment*, Vol. 45, No. 16, 2011, pp. 2750–2759.
- [6] Yim, S. H. L., Lee, G. L., Lee, I. H., Allroggen, F., Ashok, A., Caiazzo, F., Eastham, S. D., Malina, R., and Barrett, S. R. H., "Global, Regional and Local Health Impacts of Civil Aviation Emissions," *Environmental Research Letters*, Vol. 10, No. 3, 2015, pp. 1–12.
- [7] Green, J. E., and Jupp, J. A., "CAEP/9-Agreed Certification Requirement for the Aeroplane CO₂ Emissions Standard: A Comment on ICAO Cir 337," *Aeronautical Journal*, Vol. 120, No. 1226, 2016, pp. 693–723.
- [8] Ashcraft, S. W., Padron, A. S., Pascioni, K. A., Stout, G. W., and Huff, D. L., *Review of Propulsion Technologies for N+3 Subsonic Vehicle Concepts*, Cleveland, OH, 2011.
- [9] Darecki, M., Edelstenne, C., Enders, T., Fernandez, E., Hartman, P., Herteman, J.-P., Kerkloh, M., King, I., Ky, P., Mathieu, M., Orsi, G., Schotman, G., Smith, C., and Wörner, J.-D., *Flightpath 2050 Europe's Vision for Aviation*, 2011.
- [10] Hepperle, M., "Electric Flight – Potential and Limitations," *AVT-209 Workshop on Energy Efficient Technologies and Concepts Operation*, Lisbon, Portugal, 2012, pp. 1–30.
- [11] McDonald, R. A., "Electric Propulsion Modeling for Conceptual Aircraft Design," 52nd AIAA Aerospace Sciences Meeting, 2014, pp. 1–19.
- [12] Schäfer, A. W., Evans, A. D., Reynolds, T. G., and Dray, L., "Costs of Mitigating CO₂ Emissions from Passenger Aircraft," *Nature Climate Change*, Vol. 6, No. 4, 2015, pp. 412–417.
- [13] Staples, M. D., Malina, R., and Barrett, S. R. H., "The Limits of Bioenergy for Mitigating Global Life-Cycle Greenhouse Gas Emissions from Fossil Fuels," *Nature Energy*, Vol. 2, No. 1, 2017, pp. 1–8.
- [14] Roboam, X., "New Trends and Challenges of Electrical Networks Embedded in 'More Electrical Aircraft,'" *2011 IEEE International Symposium on Industrial Electronics*, 2011, pp. 26–31.

- [15] Committee on Propulsion and Energy Systems to Reduce Commercial Aviation Carbon Emissions, *Commercial Aircraft Propulsion and Energy Systems Research - Reducing Global Carbon Emissions*, 1 ed., National Academies Press, Washington, D.C., 2016.
- [16] Bradley, M. K., and Droney, C. K., *Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development*, Huntington Beach, CA, 2012.
- [17] Pornet, C., and Isikveren, A. T., "Conceptual Design of Hybrid-Electric Transport Aircraft," *Progress in Aerospace Sciences*, Vol. 79, No. 1, 2015, pp. 114–135.
- [18] Friedrich, C., and Robertson, P. A., "Hybrid-Electric Propulsion for Automotive and Aviation Applications," *CEAS Aeronautical Journal*, Vol. 6, No. 2, 2015, pp. 279–290.
- [19] Jansen, R. H., Bowman, C., Jankovsky, A., Dyson, R. W., and Felder, J. L., "Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports," *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, Atlanta, GA, 2017, pp. 1–20.
- [20] Rolls-Royce, and Airbus Group, *E-Thrust - Electrical Distributed Propulsion System Concept for Lower Fuel Consumption, Fewer Emissions and Less Noise*, 2014.
- [21] Zunum Aero, 2018, Available: <http://zunum.aero/>.
- [22] Armstrong, M. J., Ross, C. A. H., Blackwelder, M. J., and Rajashekara, K., "Propulsion System Component Considerations for NASA N3-X Turboelectric Distributed Propulsion System," *SAE International Journal of Aerospace*, Vol. 5, No. 2, 2012, pp. 344–353.
- [23] Vascik, P., and Hansman, R. J., "Systems-Level Analysis of On Demand Mobility for Aviation," MIT, 2017.
- [24] A³, "Vahana The Next Technological Breakthrough in Urban Air Mobility.," 2017, Available: <https://www.airbus-sv.com/projects/1>.
- [25] ACS Aviation, "Produtos," 2017, Available: <https://www.acs-solutions.com.br/index.php/produtos>.
- [26] Airbus, *Airbus Group E-Fan Brochure*, Munich, Germany, 2014.
- [27] AirSpaceX, "Clean Electric," 2017, Available: <http://airspacex.com/>.
- [28] APEV, "The Pouchelec, The Electric Pouchel," 2017, Available: http://www.pouchel.com/english/index_eng.php?p=elec_eng.html.
- [29] Aurora Flight Sciences, "eVTOL The Future of On-Demand Air Transportation," 2017, Available: <http://www.aurora.aero/evtol/>.
- [30] Autonomous Flight, "The Future is Here.," 2017, Available: <http://autonomousflight.com/>.
- [31] Barnstorff, K., "The Puffin: A Passion for Personal Flight," 2010, Available: <https://www.nasa.gov/topics/technology/features/puffin.html>.

- [32] Bergqvist, P., "All-Electric Airplane Reaches 153 Knots," *Flying Magazine*, 2011, Available: <https://www.flyingmag.com/news/all-electric-airplane-reaches-153-knots>.
- [33] Beyond Aviation, "Archive of the Goals of the Beyond Aviation Project," 2017, Available: <http://www.beyond-aviation.com/index.html>.
- [34] Carter Aviation Technologies, 2017, Available: <http://www.cartercopters.com/>.
- [35] Carter, J., "Electric CarterCopter Air Taxi," 2017, Available: <http://evtol.news/wp-content/uploads/2017/06/Carter-Presentation-CAFE-Elec-AC-Symposium-w-video.pdf>.
- [36] Coppinger, R., "Prototype Flight Success Could See French All-Electric GA Product," *Flight Global*, 2008, Available: <https://www.flightglobal.com/news/articles/prototype-flight-success-could-see-french-all-electric-ga-product-220729/>.
- [37] DeloreanAerospace, 2017, Available: <http://www.deloreanaerospace.com/>.
- [38] Electric Visionary Aircrafts, 2017, Available: <http://eva.xyz/>.
- [39] ElectroVelocity, "The ElectraFlyer X - 100% Electric Flight," 2011, Available: <http://electrovelocity.com/2011/03/04/the-electraflyer-x-100-electric-flight/>.
- [40] Eviation, "Alice Commuter," 2017, Available: <http://www.eviation.co/alice/>.
- [41] Evektor, "Electric Powered Small Aircraft," 2017, Available: <https://www.evektor.cz/en/sportstar-epos>.
- [42] "Extra 330LE Electric Aircraft," *Aerospace Technology*, 2017, Available: <http://www.aerospace-technology.com/projects/extra-330le-electric-aircraft/>.
- [43] F. M., "Skylys Aircraft Presents the Air Speeder, an Amphibious eVTOL," *Aero Buzz.FR*, 2017, Available: <https://www.aerobuzz.fr/breves-aviation-generale/skylys-aircraft-presente-lair-speeder-un-evtol-amphibie/>.
- [44] Flight of the Century, "Long-ESA," 2017, Available: <http://www.flightofthecentury.com/long-esa/>.
- [45] Grady, M., "E-Flight Takes Center Stage At Aero," 2015, Available: <https://www.avweb.com/avwebflash/news/E-Flight-Takes-Center-Stage-At-Aero-223875-1.html>.
- [46] Grady, M., "EADS Unveils Electric, Aerobatic, Four-Engine Airplane," *AVweb*, 2010, Available: https://www.avweb.com/avwebflash/news/EADSUnveilsElectricAerobaticFourEngineAirplane_202805-1.html.
- [47] HopFlyt, 2017, Available: <https://hopflyt.com/>.
- [48] Horne, T., "Pipistrel Alpha Electro: The Trainer of the Future?," *AOPA*, 2015, Available: https://www.aopa.org/news-and-media/all-news/2015/october/pilot/f_pipistrel.

- [49] JAXA, "Demonstration of the Feasibility of Lift Fan Type VTOL Control System," 2017, Available: <http://www.aero.jaxa.jp/research/basic/propulsion/liftfan/>.
- [50] Kauh, E., "South America's First Electric Airplane Takes Flight," *AVweb*, 2017, Available: <https://www.avweb.com/avwebflash/news/South-Americas-First-Electric-Airplane-Takes-Flight-224337-1.html>.
- [51] Langelaan, J. W., Chakrabarty, A., Deng, A., Miles, K., Plevnik, V., Tomazic, J., Tomazic, T., and Veble, G., "Green Flight Challenge: Aircraft Design and Flight Planning for Extreme Fuel Efficiency," *Journal of Aircraft*, Vol. 50, No. 3, 2013, pp. 832–846.
- [52] LazairInfo.com, "eLazair," 2017, Available: <http://lazairinfo.com/electric-lazair/>.
- [53] Lee, D., "London-Paris Electric Flight 'In Decade'," *BBC News*, 2017, Available: <http://www.bbc.com/news/technology-39350058>.
- [54] Lillium GmbH, "Lilium Celebrates Successful Flight Tests of World's First Electric VTOL Jet," 2017, Available: <https://lilium.com/press-releases/lilium-celebrates-successful-flights-tests.pdf>.
- [55] M. R., "The Flight from Demoichelle to Bourget," *Aero Buzz.FR*, 2010, Available: <https://www.aerobuzz.fr/industrie/le-vol-de-la-demoichelle-au/>.
- [56] Mark, R., "DeLorean's DR-7 Prototype Could Fly in Late 2018," 2017, Available: <https://www.flyingmag.com/deloreans-dr-7-prototype-could-fly-in-late-2018#page-2>.
- [57] Moore, M., "The Joby S2 VTOL Concept Exploring the New Degrees of Design Freedom of Distributed Electric Propulsion," 2014, Available: <http://evtol.news/2014/11/01/the-joby-s2-vtol-concept-nov-1-2014/>.
- [58] Muoio, D., "NASA has an Ambitious \$43 Million Plan to Make Electric Planes a Reality," 2017, Available: <http://www.businessinsider.com/nasa-is-spending-43-million-on-electric-planes-2017-5/#nasa-is-first-building-a-small-entirely-electric-plane-called-the-x-57-it-plans-on-completing-the-plane-in-just-under-four-years-2>.
- [59] Noland, D., "Who's Killing the Electric Plane?," *Popular Mechanics*, 2009, Available: <http://www.popularmechanics.com/flight/a4465/4330186/>.
- [60] Panthera, "Technical Data," 2017, Available: <http://www.panthera-aircraft.com/technical-data>.
- [61] Pew, G., "German-Certified Light Electric Plane To Visit Osh," 2013, Available: <https://www.avweb.com/avwebflash/news/Germany-Certifies-Light-Electric-Plane-Airventure-yuneec-greenwing-espyder-220144-1.html>.
- [62] Phelps, M., "Yuneec's E430 Electric Airplane Has Up to 2.5 Hours' Endurance," *Flying Magazine*, 2009, Available: <https://www.flyingmag.com/news/yuneecs-e430-electric-airplane-has-25-hours-endurance>.
- [63] Pipistrel, "Alpha Electro (prototype name WATTsUP)," 2017, Available: <http://wattsup.pipistrel.si/aircraft/#techdata>.

- [64] Reynolds, R., "Electric MC30E Firefly Flies With New Motor," *EAA*, 2011, Available: https://web.archive.org/web/20111217064903/http://eaa.org/news/2011/2011-08-10_firefly.asp.
- [65] Ruixiang General Aircraft Manufacturing Corporation, Ltd., "Ruixiang Extended Range Two-Seater All-Electric Light-Sport Aircraft," 2017, Available: <http://rgac.biz/Ruixiang/Productshow/ERX1EA.php>.
- [66] Ruixiang General Aircraft Manufacturing Corporation, Ltd., "Ruixiang Two-Seater All-Electric Light-Sport Aircraft," 2017, Available: <http://rgac.biz/Ruixiang/Productshow/ERX1E.php>.
- [67] S2, 2017, Available: <http://www.jobyaviation.com/S2/>.
- [68] Seaplane International, "The First Electric-Powered Amphibia in the World," 2011, Available: <http://www.seaplaneinternational.com/2011/08/12/the-first-electric-powered-amphibia-in-the-world/>.
- [69] Siemens, "Aerobatic Airplane Extra 330LE," 2016, Available: <https://www.siemens.com/press/pool/de/events/2016/corporate/2016-12-innovation/inno2016-aerobatic-airplane-e.pdf>.
- [70] Sonex Aircraft, "e-Flight esa," 2017, Available: <http://www.sonexaircraft.com/research/e-flight.html>.
- [71] Steiner, H.-J., Vratny, P. C., Gologan, C., Wiczorek, K., Isikveren, A. T., and Hornung, M., "Optimum Number of Engines for Transport Aircraft Employing Electrically Powered Distributed Propulsion," *CEAS Aeronautical Journal*, Vol. 5, No. 2, 2014, pp. 157–170.
- [72] Stoll, A., "Faster, Quieter, Safer, and Cheaper Distributed Electric Propulsion and the Coming VTOL Revolution," 2017, Available: https://sites.nationalacademies.org/cs/groups/depssite/documents/webpage/deps_169312.pdf.
- [73] Stückl, S., van Toor, J., and Lobentanzer, H., "VoltAir - The All Electric Propulsion Concept Platform – A Vision For Atmospheric Friendly Flight," *28th Congress of the International Council of the Aeronautical Sciences*, Brisbane, Australia, 2012, pp. 1–11.
- [74] Swartz, K., "Charging Forward: New eVTOL Concepts Advance," *The Electric VTOL News*, 2017, Available: <http://evtol.news/2017/06/22/charging-forward-new-evtol-concepts-advance/>.
- [75] The Lilium Jet, 2017, Available: <https://lilium.com/>.
- [76] Vahana, 2017, Available: <https://vahana.aero/>.
- [77] Vegh, J. M., Alonso, J. J., Orra, T. H., and Ilario da Silva, C. R., "Flight Path and Wing Optimization of Lithium-Air Battery Powered Passenger Aircraft," *53rd AIAA Aerospace Sciences Meeting*, Kissimmee, FL, 2015, pp. 1–13.
- [78] Vegh, J. M., and Alonso, J. J., "Design and Optimization of Short-Range Aluminum-Air Powered Aircraft," *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016, pp. 1–15.

- [79] Vratny, P. C., *A Battery Powered Transport Aircraft*, AV Akademikverlag GmbH & Co. KG, Saarbrücken, Germany, 2012.
- [80] Yuneec-Flightstar e-Spyder, 2009, Available: <https://web.archive.org/web/20091107050125/http://www.flyespyder.com/>.
- [81] Zee, 2017, Available: <http://www.zee.aero/>.
- [82] “Zee Z-P1 Spotted Again,” *The Electric VTOL News*, 2017, Available: <http://evtol.news/2017/05/02/zee-z-p1-spotted-again/>.
- [83] Uber Elevate, “Fast-Forwarding to the Future of On-Demand, Urban Air Transportation,” 2017, Available: <https://www.uber.com/info/elevate/>.
- [84] Uber Elevate, *Fast-Forwarding to a Future of On-Demand Urban Air Transportation*, 2016.
- [85] Borer, N. K., Patterson, M. D., Viken, J. K., Moore, M. D., Clarke, S. C., Redifer, M. E., Christie, R. J., Stoll, A. M., Dubois, A., Bevirt, J., Gibson, A. R., Foster, T. J., and Osterkamp, P. G., “Design and Performance of the NASA SCEPTOR Distributed Electric Propulsion Flight Demonstrator,” *16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C., 2016, pp. 1–20.
- [86] Papathakis, K. V., Burkhardt, P. A., Ehmann, D. W., and Sessions, A. M., “Safety Considerations for Electric, Hybrid-Electric, and Turbo-Electric Distributed Propulsion Aircraft Testbeds,” *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, American Institute of Aeronautics and Astronautics, Atlanta, GA, 2017, pp. 1–12.
- [87] Hornung, M., Isikveren, A. T., Cole, M., and Sizmann, A., “Ce-Liner - Case Study for eMobility in Air Transportation,” *13th AIAA Aviation Technology, Integration, and Operations Conference*, Los Angeles, CA, 2013, pp. 1–11.
- [88] U.S. Department of Energy, “DOE Awards \$6 Million to First Crop of Battery500 Seedlings,” 2017, Available: <https://chargedevs.com/newswire/doe-awards-6-million-to-first-crop-of-battery500-seedlings/>.
- [89] BMW, “BMW Group Technology Workshops E-Mobility,” 2016, pp. 1–23.
- [90] USABC, *Advanced Battery Development*, 2013.
- [91] Chan, C. K., Peng, H., Liu, G., McIlwrath, K., Zhang, X. F., Huggins, R. A., and Cui, Y., “High-Performance Lithium Battery Anodes Using Silicon Nanowires,” *Nature Nanotechnology*, Vol. 3, No. 1, 2008, pp. 31–35.
- [92] Anderman, M., *Assessing the Future of Hybrid and Electric Vehicles: The xEV Industry Insider Report*, 2013.
- [93] Pillot, C., “The Rechargeable Battery Market and Main Trends 2014-2025,” 2016, pp. 1–98.

- [94] Romare, M., and Dahllöf, L., *The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries*, 2017.
- [95] Blomgren, G. E., "The Development and Future of Lithium Ion Batteries," *Journal of The Electrochemical Society*, Vol. 164, No. 1, 2017, pp. A5019–A5025.
- [96] Idaho National Laboratory Advanced Vehicles, "Library - Alphabetical," <https://avt.inl.gov/content/pubs-az> [retrieved 31 January 2018].
- [97] Kukkonen, S., "Current Trends in Battery Technology," 2014, pp. 1–26.
- [98] Nitta, N., Wu, F., Lee, J. T., and Yushin, G., "Li-ion Battery Materials: Present and Future," *Materials Today*, Vol. 18, No. 5, 2015, pp. 252–264.
- [99] Ji-hye, S., "Solid-State Battery for Samsung Galaxy Likely in Years," *The Korea Herald*, 2017, Available: <http://www.koreaherald.com/view.php?ud=20170630000615>.
- [100] Materials Research Laboratory, "Jennifer Rupp Wins International Electrochemistry Prize," *MIT News*, 2017, Available: <http://news.mit.edu/2017/mit-jennifer-rupp-wins-international-electrochemistry-prize-1222>.
- [101] Reisch, M., "Solid-State Batteries Inch Their Way Toward Commercialization," *Chemical & Engineering News*, Vol. 95, No. 46, 2017, pp. 19-21, Available: <https://cen.acs.org/articles/95/i46/Solid-state-batteries-inch-way.html>.
- [102] Fetcenko, M., "BASF - ANL Collaboration on NCM Cathode Materials BASF," 2014, pp. 1–13.
- [103] Schipper, F., Erickson, E. M., Erk, C., Shin, J.-Y., Chesneau, F. F., and Aurbach, D., "Review—Recent Advances and Remaining Challenges for Lithium Ion Battery Cathodes," *Journal of The Electrochemical Society*, Vol. 164, No. 1, 2017, pp. A6220–A6228.
- [104] Jayaprakash, N., Shen, J., Moganty, S. S., Corona, A., and Archer, L. A., "Porous Hollow Carbon@Sulfur Composites for High-Power Lithium-Sulfur Batteries," *Angewandte Chemie International Edition*, Vol. 50, No. 26, 2011, pp. 5904–5908.
- [105] Yin, Y.-X., Xin, S., Guo, Y.-G., and Wan, L.-J., "Lithium–Sulfur Batteries: Electrochemistry, Materials, and Prospects," *Angewandte Chemie International Edition*, Vol. 52, No. 50, 2013, pp. 13186–13200.
- [106] Balaish, M., Kraytsberg, A., and Ein-Eli, Y., "A Critical Review on Lithium–Air Battery Electrolytes," *Physical Chemistry Chemical Physics*, Vol. 16, No. 7, 2014, p. 2801.
- [107] Grande, L., Paillard, E., Hassoun, J., Park, J.-B., Lee, Y.-J., Sun, Y.-K., Passerini, S., and Scrosati, B., "The Lithium/Air Battery: Still an Emerging System or a Practical Reality?," *Advanced Materials*, Vol. 27, No. 5, 2015, pp. 784–800.
- [108] Kuhn, H., and Sizmann, A., "Fundamental Prerequisites for Electric Flying," *Deutscher Luft- und Raumfahrtkongress 2012*, Berlin, Germany, 2012, pp. 1–8.

- [109] SolidEnergy, *HermesTM High Energy Rechargeable Metal Cells for Space*, 2017.
- [110] Bruce, P. G., Freunberger, S. A., Hardwick, L. J., and Tarascon, J.-M., "Li-O₂ and Li-S Batteries with High Energy Storage," *Nature Materials*, Vol. 11, No. 2, 2011, pp. 19–29.
- [111] Yang, C.-P., Yin, Y.-X., and Guo, Y.-G., "Elemental Selenium for Electrochemical Energy Storage," *Journal of Physical Chemistry Letters*, Vol. 6, No. 2, 2015, pp. 256–266.
- [112] Christensen, J., Albertus, P., Sanchez-Carrera, R. S., Lohmann, T., Kozinsky, B., Liedtke, R., Ahmed, J., and Kojic, A., "A Critical Review of Li/Air Batteries," *Journal of The Electrochemical Society*, Vol. 159, No. 2, 2012, pp. R1–R30.
- [113] Dever, T. P., Duffy, K. P., Provenza, A. J., Loyselle, P. L., Choi, B. B., Morrison, C. R., and Lowe, A. M., *Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion*, Cleveland, OH, 2015.
- [114] Kushnir, D., "Lithium Ion Battery Recycling Technology 2015: Current State and Future Prospects. ESA REPORT # 2015:18," 2015, pp. 1–56.
- [115] Woodford, W. H., Ransil, R. A., and Chiang, Y.-M., *Advanced Batteries: 'Beyond Li-ion'*, 2012.
- [116] Xu, J., *Design Perspectives on Delivery Drones*, Santa Monica, CA, 2017.
- [117] Pornet, C., Gologan, C., Vratny, P. C., Seitz, A., Schmitz, O., Isikveren, A. T., and Hornung, M., "Methodology for Sizing and Performance Assessment of Hybrid Energy Aircraft," *Journal of Aircraft*, Vol. 52, No. 1, 2015, pp. 1–12.
- [118] Stückl, S., "Methods for the Design and Evaluation of Future Aircraft Concepts Utilizing Electric Propulsion Systems," Technische Universität München, Bauhaus Luftfahrt, 2015.
- [119] Panasonic, Panasonic Lithium Ion NCR18650B, 2012.
- [120] OXIS Energy Limited, *Ultra Light Lithium Sulfur Pouch Cell*, 2017.
- [121] Drela, M., *TASOPT 2.16 Transport Aircraft System OPTimization Technical Description*, Cambridge, MA, 2016.
- [122] Drela, M., "Design Drivers of Energy-Efficient Transport Aircraft," *SAE International Journal of Aerospace*, Vol. 4, No. 2, 2011, pp. 602–608.
- [123] Drela, M., *Simultaneous Optimization of the Airframe, Powerplant, and Operation of Transport Aircraft*, London, UK, 2010.
- [124] Greitzer, E. M., Bonnefoy, P. A., de la Rosa Blanco, E., Dorbian, C. S., Drela, M., Hall, D. K., Hansman, R. J., Hileman, J. I., Liebeck, R. H., Lovegren, J., Mody, P., Pertuze, J. A., Sato, S., Spakovszky, Z. S., Tan, C. S., Hollman, J. S., Duda, J. E., Fitzgerald, N., Houghton, J., Kerrebrock, J. L., Kiwada, G. F., Kordonowy, D., Parrish, J. C., Tylko, J., Wen, E. A., and Lord, W. K., *N+3 Aircraft Concept Designs and Trade Studies, Volume 2: Appendices - Design Methodologies for Aerodynamics, Structures, Weight, and Thermodynamic Cycles*, Cambridge, MA, 2010.

- [125] Dyson, R. W., *NASA Electric Aircraft Test Bed (NEAT) Development Plan - Design, Fabrication, Installation*, Cleveland, OH, 2016.
- [126] Berg, F., Palmer, J., Miller, P., Husband, M., and Dodds, G., "HTS Electrical System for a Distributed Propulsion Aircraft," *IEEE Transactions on Applied Superconductivity*, Vol. 25, No. 3, 2015, pp. 1–5.
- [127] Isikveren, A. T., Seitz, A., Vratny, P. C., Pornet, C., Plötner, K. O., and Hornung, M., "Conceptual Studies of Universally-Electric Systems Architectures Suitable for Transport Aircraft," *Deutscher Luft- und Raumfahrtkongress 2012*, Berlin, Germany, 2012, pp. 1–16.
- [128] Jones, C. E., Norman, P. J., Galloway, S. J., Burt, G. M., Armstrong, M. J., and Bollman, A. M., "A Pre-Design Sensitivity Analysis Tool for Consideration of Full- Electric Aircraft Propulsion Electrical Power System Architectures," *2015 International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicle*, Aachen, Germany, 2015, pp. 1–6.
- [129] Pornet, C., "Electric Drives for Propulsion System of Transport Aircraft," *New Applications of Electric Drives*, edited by Chomat, M., 2015, pp. 115–142.
- [130] Cao, W., Mecrow, B. C., Atkinson, G. J., Bennett, J. W., and Atkinson, D. J., "Overview of Electric Motor Technologies Used for More Electric Aircraft (MEA)," *IEEE Transactions on Industrial Electronics*, Vol. 59, No. 9, 2012, pp. 3523–3531.
- [131] Datta, A., and Johnson, W., "Requirements for a Hydrogen Powered All-Electric Manned Helicopter," *12th AIAA Aviation Technology, Integration, and Operations Conference*, Indianapolis, IN, 2012, pp. 1–28.
- [132] Larminie, J., and Lowry, J., *Electric Vehicle Technology Explained*, John Wiley & Sons, Ltd, Chichester, UK, 2003.
- [133] Schiferl, R., Flory, A., Livoti, W. C., and Umans, S. D., "High-Temperature Superconducting Synchronous Motors: Economic Issues for Industrial Applications," *IEEE Transactions on Industry Applications*, Vol. 44, No. 5, 2008, pp. 1376–1384.
- [134] Sinsay, J. D., Tracey, B., Alonso, J. J., Kontinos, D. A., Melton, J. E., and Grabbe, S., "Air Vehicle Design and Technology Considerations for an Electric VTOL Metro-Regional Public Transportation System," *12th AIAA Aviation Technology, Integration, and Operations Conference*, Indianapolis, IN, 2012, pp. 1–16.
- [135] Snyder, C. A., Berton, J. J., Brown, G. V., Dolce, J. L., Dravid, N. V., Eichenberg, D. J., Freeh, J. E., Gallo, C. A., Jones, S. M., Kundu, K. P., Marek, C. J., Millis, M. G., Murthy, P. L., Roach, T. M., Smith, T. D., Stefko, G. L., Sullivan, R. M., Tornabene, R. T., Geiselhart, K. A., and Kascak, A. F., *Propulsion Investigation for Zero and Near-Zero Emissions Aircraft*, Cleveland, OH, 2009.
- [136] Petermaier, K., "Electric Propulsion Components with High Power Densities for Aviation," 2015, pp. 1–16.
- [137] Clarke, S. C., "Aircraft Electric Propulsion Systems: Applied Research at NASA," 2015, pp. 1–37.

- [138] Xia, X., "Dynamic Power Distribution Management for All Electric Aircraft," Cranfield, 2011.
- [139] Shehab, E., and Palmer, J., "Modelling of Cryogenic Cooling System Design Concepts for Superconducting Aircraft Propulsion," *IET Electrical Systems in Transportation*, Vol. 6, No. 3, 2016, pp. 170–178.
- [140] Armstrong, M. J., "Identification of Emergent Off-Nominal Operational Requirements During Conceptual Architecting of the More Electric Aircraft," Georgia Tech, 2011.
- [141] McLoughlin, A., "More Electric – Ready for Take Off?," *13th European Conference on Power Electronics and Applications*, Barcelona, Spain, 2009, pp. 1–7.
- [142] Fite, E. B., *Fan Performance From Duct Rake Instrumentation on a 1.294 Pressure Ratio, 725 ft/sec Tip Speed Turbofan Simulator Using Vaned Passage Casing Treatment*, 2006.
- [143] Beltramo, M. N., Trapp, D. L., Kimoto, B. W., and Marsh, D. P., *Parametric Study of Transport Aircraft Systems, Cost and Weight*, 1977.
- [144] Camilleri, W., "An Assessment of High Overall Pressure Ratio Intercooled Engines for Civil Aviation," Cranfield, 2014.
- [145] Calkins, F. T., and Mabe, J. H., "Shape Memory Alloy Based Morphing Aerostructures," *Journal of Mechanical Design*, Vol. 132, No. 11, 2010, p. 111012.
- [146] Mabe, J., "Variable Area Jet Nozzle for Noise Reduction Using Shape Memory Alloy Actuators," *The Journal of the Acoustical Society of America*, Vol. 123, No. 5, 2008, pp. 5487–5492.
- [147] Giakoumakis, E., "Techno-Economic and Environmental Risk Assessment of a Turbo-Electric Distributed Propulsion System on a Blended Wing Body Aircraft," Cranfield, 2014.
- [148] Sagerser, D. A., Lieblein, S., and Krebs, R. P., *Empirical Expressions for Estimating Length and Weight of Axial-Flow Components of VTOL Powerplants*, 1971.
- [149] Bowman, C., Jansen, R., Brown, G. V., Duffy, K. P., and Trudell, J., "Key Performance Parameter Driven Technology Goals for Electric Machines and Power Systems," 2015, pp. 1–34.
- [150] Schiltgen, B. T., Gibson, A. R., Green, M. W., and Freeman, J., "More Electric Aircraft: 'Tube and Wing' Hybrid Electric Distributed Propulsion with Superconducting and Conventional Electric Machines," *SAE 2013 AeroTech Congress & Exhibition*, Montréal, Canada, 2013, pp. 1–13.
- [151] Vratny, P. C., Forsbach, P., Seitz, A., and Hornung, M., "Investigation of Universally Electric Propulsion Systems for Transport Aircraft," *29th Congress of the International Council of the Aeronautical Sciences*, St. Petersburg, Russia, 2014, pp. 1–13.
- [152] Brown, G. V., Kascak, A. F., Ebihara, B., Johnson, D., Choi, B. B., Siebert, M., and Buccieri, C., *NASA Glenn Research Center Program in High Power Density Motors for Aeropropulsion*, 2005.
- [153] Miyairi, Y., Perullo, C. A., and Mavris, D. N., "A Parametric Environment for Weight and Sizing Prediction of Motor/Generator for Hybrid Electric Propulsion," *51st AIAA/SAE/ASEE Joint Propulsion Conference*, Orlando, FL, 2015, pp. 1–19.

- [154] Antcliff, K. R., Guynn, M. D., Marien, T., Wells, D. P., Schneider, S. J., and Tong, M. T., "Mission Analysis and Aircraft Sizing of a Hybrid-Electric Regional Aircraft," *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016, pp. 1–18.
- [155] Olson, M. D., "A Conceptual Approach to Flight-Training Mission and Cost Analysis of an All-Electric Aircraft Equipped with Regenerative Energy Devices," *15th AIAA Aviation Technology, Integration, and Operations Conference*, Dallas, TX, 2015, pp. 1–31.
- [156] Patterson, M. D., German, B. J., and Moore, M. D., "Performance Analysis and Design of On-Demand Electric Aircraft Concepts," *12th AIAA Aviation Technology, Integration, and Operations Conference*, Indianapolis, IN, 2012, pp. 1–28.
- [157] Chen, M., and Rincón-Mora, G. A., "Accurate Electrical Battery Model Capable of Predicting Runtime and I–V Performance," *IEEE Transactions on Energy Conversion*, Vol. 21, No. 2, 2006, pp. 504–511.
- [158] Propp, K., Marinescu, M., Auger, D. J., O'Neill, L., Fotouhi, A., Somasundaram, K., Offer, G. J., Minton, G., Longo, S., Wild, M., and Knap, V., "Multi-Temperature State-Dependent Equivalent Circuit Discharge Model for Lithium-Sulfur Batteries," *Journal of Power Sources*, Vol. 328, No. 1, 2016, pp. 289–299.
- [159] Tremblay, O., "Experimental Validation of a Battery Dynamic Model for EV Applications," *24th International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium and Exhibition 2009, EVS 24*, 2009, pp. 930–939.
- [160] Zhang, T., Marinescu, M., O'Neill, L., Wild, M., and Offer, G., "Modeling the Voltage Loss Mechanisms in Lithium-Sulfur Cells: The Importance of Electrolyte Resistance and Precipitation Kinetics," *Physical Chemistry Chemical Physics*, Vol. 17, No. 35, 2015, pp. 22581–22586.
- [161] Doerffel, D., and Sharkh, S. A., "A Critical Review of Using the Peukert Equation for Determining the Remaining Capacity of Lead-Acid and Lithium-Ion Batteries," *Journal of Power Sources*, Vol. 155, No. 2, 2006, pp. 395–400.
- [162] USABC, *Appendix I Derivation of USABC Battery Peak Power Calculations*, 2017.
- [163] Bradley, M. K., Allen, T. J., and Droney, C. K., *Subsonic Ultra Green Aircraft Research: Phase II – Volume I – Truss Braced Wing Design Exploration*, Huntington Beach, CA, 2014.
- [164] Vratny, P. C., Gologan, C., Pornet, C., Isikveren, A. T., and Hornung, M., "Battery Pack Modeling Methods for Universally-Electric Aircraft," *4th CEAS Air & Space Conference*, Linköping, Sweden, 2013, pp. 525–535.
- [165] Bruner, S., "N+3 Phase I Final Review," 2010, pp. 1–172.
- [166] Chakraborty, I., Mavris, D. N., Emeneth, M., and Schneegans, A., "An Integrated Approach to Vehicle and Subsystem Sizing and Analysis for Novel Subsystem Architectures," *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, Vol. 0, No. 0, 2015, pp. 1–19.

- [167] Lukaczyk, T., Wendorff, A. D., Botero, E., MacDonald, T., Momose, T., Variyar, A., Vegh, J. M., Colonno, M. R., Economon, T. D., Alonso, J. J., Orra, T. H., and Ilario da Silva, C. R., "SUAVE: An Open-Source Environment for Multi-Fidelity Conceptual Vehicle Design," *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conference*, Dallas, TX, 2015, pp. 1–56.
- [168] Isikveren, A. T., "Quasi-Analytical Modelling and Optimisation Techniques for Transport Aircraft Design," KTH, Bauhaus Luftfahrt, 2002.
- [169] Liebeck, R. H., Page, M. A., Rawdon, B. K., Scott, P. W., and Wright, R. A., *Concepts for Advanced Subsonic Transports*, NASA CR 4624, 1994.
- [170] Linnell, R., *Weight Estimation Methods*, FKHV-1-RL790724:01, 1979.
- [171] Torenbeek, E., *Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes*, John Wiley & Sons, 2013.
- [172] Torenbeek, E., *Synthesis of Subsonic Airplane Design*, Delft University Press, 1982.
- [173] Raymer, D. P., *Aircraft Design: A Conceptual Approach*, 4th ed., AIAA Education Series, Reston, Virginia, 2006.
- [174] Seitz, A., "Advanced Methods for Propulsion System Integration in Aircraft Conceptual Design," Universität München, 2012.
- [175] Daggett, D. L., Brown, S. T., and Kawai, R. T., *Ultra-Efficient Engine Diameter Study*, 2003.
- [176] Guynn, M. D., Berton, J. J., Fisher, K. L., Haller, W. J., Tong, M. T., and Thurman, D. R., *Engine Concept Study for an Advanced Single-Aisle Transport*, 2009.
- [177] Airbus, *A320 Aircraft Characteristics Airport and Maintenance Planning*, 2017.
- [178] Drela, M., "Development of the D8 Transport Configuration," *29th AIAA Applied Aerodynamics Conference*, Honolulu, HI, 2011, pp. 1–14.
- [179] Boeing, *Boeing Commercial Aircraft - Design Groups/Codes (FAA & ICAO)*, 2014.
- [180] Brown, G. V., "Weights and Efficiencies of Electric Components of a Turboelectric Aircraft Propulsion System," *49th AIAA Aerospace Sciences Meeting*, Orlando, FL, 2011, pp. 1–18.
- [181] Pagonis, M., "Electrical Power Aspects of Distributed Propulsion Systems in Turbo-Electric Powered Aircraft," Cranfield, 2015.
- [182] Felder, J. L., Brown, G. V., and Dae Kim, H., "Turboelectric Distributed Propulsion in a Hybrid Wing Body Aircraft," *ISABE 2011*, Gothenburg, Sweden, 2015, pp. 1–20.
- [183] Isikveren, A. T., Pornet, C., Vratny, P. C., and Schmidt, M., "Optimization of Commercial Aircraft Using Battery-Based Voltaic-Joule/Brayton Propulsion," *Journal of Aircraft*, 2016, pp. 1–16.

- [184] Xi, H. X., Gong, W. Z., Zhang, Y., Bi, Y. F., Ding, H. K., Wen, H., Hou, B., and Xin, Y., "China's 33.5 m, 35 kV/2 kA HTS AC Power Cable's Operation in Power Grid," *Physica C: Superconductivity*, Vol. 445–448, No. 1, 2006, pp. 1054–1057.
- [185] Bombardier, *C Series*, 2015, Available: <http://commercialaircraft.bombardier.com/content/dam/Websites/bca/literature/cseries/Bombardier-Commercial-Aircraft-CSeries-Brochure-en.pdf.pdf>.
- [186] Fehrm, B., "United Aircraft's and COMAC's Eventful Year," *Leeham News and Comment*, 2018, Available: <https://leehamnews.com/2018/01/03/united-aircraft-comac-goes-flying/#more-25897>.
- [187] Kirner, R., Raffaelli, L., Rolt, A., Laskaridis, P., Doulgeris, G., and Singh, R., "An Assessment of Distributed Propulsion: Advanced Propulsion System Architectures for Conventional Aircraft Configuration," *Aerospace Science and Technology*, Vol. 50, No. 1, 2016, pp. 212–219.
- [188] Kling, U., Empl, D., Boegler, O., and Isikveren, A. T., "Future Aircraft Wing Structures Using Renewable Materials," *Deutscher Luft- und Raumfahrtkongress 2015*, 2015, pp. 1–8.
- [189] Abbas, A., de Vicente, J., and Valero, E., "Aerodynamic Technologies to Improve Aircraft Performance," *Aerospace Science and Technology*, Vol. 28, No. 1, 2013, pp. 100–132.
- [190] Duvelleroy, M. and Fendt, M., "Airbus' "BLADE" Laminar Flow Wing Demonstrator Makes First Flight," 2017, Available: http://www.airbus.com/newsroom/press-releases/en/2017/09/airbus_-_blade_-_laminar-flow-wing-demonstrator-makes-first-fligh.html.
- [191] Hall, D. K., "Analysis of Civil Aircraft Propulsors with Boundary Layer Ingestion," MIT, 2015.
- [192] Stratton, R. W., Min Wong, H., and Hileman, J. I., *Life Cycle Greenhouse Gas Emissions from Alternative Jet Fuels*, Cambridge, MA, 2010.
- [193] Lu, J., Jung Lee, Y., Luo, X., Chun Lau, K., Asadi, M., Wang, H.-H., Brombosz, S., Wen, J., Zhai, D., Chen, Z., Miller, D. J., Sub Jeong, Y., Park, J.-B., Zak Fang, Z., Kumar, B., Salehi-Khojin, A., Sun, Y.-K., Curtiss, L. A., and Amine, K., "A Lithium–Oxygen Battery Based on Lithium Superoxide," *Nature*, Vol. 529, No. 7586, 2016, pp. 377–382.
- [194] OAG, 2015, <https://www.oag.com/>.
- [195] Bradley, M. K., and Droney, C. K., *Subsonic Ultra Green Aircraft Research: Phase I Final Report*, Huntington Beach, CA, 2011.
- [196] Hileman, J. I., Donohoo, P. E., and Stratton, R. W., "Energy Content and Alternative Jet Fuel Viability," *Journal of Propulsion and Power*, Vol. 26, No. 6, 2010, pp. 1184–1196.
- [197] Rosen, C. V., "2017_Scenario Based Lifecycle Analysis of Greenhouse Gas Emissions from Petroleum-Derived Transportation Fuels in 2050," MIT, 2017.
- [198] Grobler, C., Allroggen, F., and Barrett, S. R. H., *Derived Climate Metrics Prepared as Part of ASCENT Project 21*, 2017.
- [199] U.S. Energy Information Administration, *November 2017 Monthly Energy Review*, 2017.

- [200] Capasso, C., and Veneri, O., ‘Experimental Analysis on the Performance of Lithium Based Batteries for Road Full Electric and Hybrid Vehicles,’ *Applied Energy*, Vol. 136, No. 1, 2014, pp. 921–930.
- [201] USABC, *Appendix F Glossary of Battery and Battery Testing Terminology for the USABC Battery Test Procedures*, 2017.
- [202] Gohardani, A. S., Millicam, N., and Dunn, R., ‘Green Aerospace Engineering: A Focus on the Technical and Economical Hurdles of Next Generation Lithium-Ion Batteries,’ *54th AIAA Aerospace Sciences Meeting*, San Diego, CA, 2016, pp. 1–19.
- [203] Manthiram, A., Chung, S.-H., and Zu, C., ‘Lithium–Sulfur Batteries: Progress and Prospects,’ *Advanced Materials*, Vol. 27, No. 12, 2015, pp. 1980–2006.
- [204] U.S. Energy Information Administration, *Annual Energy Outlook 2017 with Projections to 2050*, 2017.
- [205] Mai, T., Wiser, R., Sandor, D., Brinkman, G., Heath, G., Denholm, P., Hostick, D. J., Darghouth, N., Schlosser, A., and Strzepek, K., *Exploration of High-Penetration Renewable Electricity Futures. Vol. 1 of Renewable Electricity Futures Study*, Golden, CO, 2012.
- [206] Dolan, S. L., and Heath, G. A., ‘Life Cycle Greenhouse Gas Emissions of Utility-Scale Wind Power,’ *Journal of Industrial Ecology*, Vol. 16, No. S1, 2012, pp. S136–S154.
- [207] Burkhardt, J. J., Heath, G., and Cohen, E., ‘Life Cycle Greenhouse Gas Emissions of Trough and Tower Concentrating Solar Power Electricity Generation,’ *Journal of Industrial Ecology*, Vol. 16, No. S1, 2012, pp. S93–S109.
- [208] Hsu, D. D., O'Donoghue, P., Fthenakis, V., Heath, G. A., Kim, H. C., Sawyer, P., Choi, J.-K., and Turney, D. E., ‘Life Cycle Greenhouse Gas Emissions of Crystalline Silicon Photovoltaic Electricity Generation,’ *Journal of Industrial Ecology*, Vol. 16, No. S1, 2012, pp. S122–S135.
- [209] Eberle, A., Heath, G. A., Nicholson, S., and Carpenter, A., *Systematic Review of Life Cycle Greenhouse Gas Emissions from Geothermal Electricity*, Golden, CO, 2017.
- [210] O'Connor, D., *Literature Review and Sensitivity Analysis of Biopower Life-Cycle Assessments and Greenhouse Gas Emission*, Palo Alto, CA, 2013.
- [211] Kumar, A., Schei, T., Ahenkorah, A., Caceres Rodriguez, R., Devernay, J.-M., Freitas, M., Hall, D., Killingtveit, Å., and Liu, Z., *Hydropower. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2011.
- [212] Warner, E. S., and Heath, G. A., ‘Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation,’ *Journal of Industrial Ecology*, Vol. 16, No. S1, 2012, pp. S73–S92.

- [213] Moomaw, W., Burgherr, P., Heath, G., Lenzen, M., Nyboer, J., and Verbruggen, A., *Annex II: Methodology. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation* [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, Cambridge, United Kingdom and New York, NY, USA, 2011.
- [214] O'Donoughue, P. R., Heath, G. A., Dolan, S. L., and Vorum, M., "Life Cycle Greenhouse Gas Emissions of Electricity Generated from Conventionally Produced Natural Gas," *Journal of Industrial Ecology*, Vol. 18, No. 1, 2014, pp. 125–144.
- [215] Heath, G. A., O'Donoughue, P., Arent, D. J., and Bazilian, M., "Harmonization of Initial Estimates of Shale Gas Life Cycle Greenhouse Gas Emissions for Electric Power Generation," *Proceedings of the National Academy of Sciences*, Vol. 111, No. 31, 2014, pp. E3167–E3176.
- [216] Whitaker, M., Heath, G. A., O'Donoughue, P., and Vorum, M., "Life Cycle Greenhouse Gas Emissions of Coal-Fired Electricity Generation," *Journal of Industrial Ecology*, Vol. 16, No. S1, 2012, pp. S53–S72.
- [217] Brown, G. V., Felder, J., Kim, H. D., Chu, J., Tong, M., Trudell, J., Dever, T. P., Choi, B., and Morrison, C., "Efficient Flight-Weight Electric Systems," 2012, pp. 1–28.
- [218] Misra, A., "Summary of 2017 NASA Workshop on Assessment of Advanced Battery Technologies for Aerospace Applications," 2018, pp. 1–18.
- [219] Gogoana, R., "Internal Resistance Variances in Lithium-Ion Batteries and Implications in Manufacturing," MIT, 2012.
- [220] Wiaux, J. P., and Chanson, C., "The Lithium-Ion Battery Service Life Parameters," 2013, pp. 1–13.
- [221] Patterson, D., Monti, A., Brice, C., Dougal, R., Pettus, R., Srinivas, D., Dilipchandra, K., and Bertoncelli, T., "Design and Simulation of an Electromagnetic Aircraft Launch System," *Industry Applications Conference, 2002*, Pittsburgh, PA, 2002, pp. 1950–1957.
- [222] Shah, P. N., Pfeiffer, G., Davis, R., Hartley, T., and Spakovszky, Z. S., "Full-Scale Turbofan Demonstration of a Deployable Engine Air-Brake for Drag Management Applications," *Journal of Engineering for Gas Turbines and Power*, Vol. 139, No. 11, 2017, pp. 1–13.