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PERFORMANCE ANALYSIS OF REGIONAL ELECTRIC AIRCRAFT

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EXECUTIVE SUMMARY

The aviation industry is aiming to achieve net-zero operations by 2050. This will require switching from jet fuel to alternative energy sources. Jet fuel's high energy content, both per unit mass (specific energy) and per unit volume (energy density), makes this standard fuel difficult to replace. Improvements in battery technology have led the way in decarbonization of road transport, as energy-efficient electric drivetrains replace fossil-fueled internal combustion engines. Can aviation be similarly electrified?

This study explores the potential role of electric aircraft in decarbonizing aviation. Starting with a first-order analysis using the electric range equation, we identify two key parameters impacting the performance of electric aircraft: the specific energy (e_b) of the battery at the pack level and the empty mass fraction (EMF) of the aircraft. The e_b of a battery is the energy that can be stored per unit mass of the battery pack as measured in watt-hours per kilogram (Wh/kg). The EMF is the ratio of the aircraft's operating empty weight (OEW) without batteries to its maximum takeoff mass (MTOM).

We investigate the performance and emissions of three electric aircraft concepts—the 9Bolt, 19Bolt, and 90Bolt—across a range of values for e_b (250 to 500 Wh/kg) and EMF (0.6 to 0.4). The 9Bolt and 19Bolt aircraft would carry 9 and 19 passengers, respectively, and could replace fossil fuel commuter aircraft, which represent 0.03% of revenue passenger kilometers (RPK) and 4% of all departures. The 90Bolt is positioned to replace large turboprop aircraft, which represent 0.7% of global aviation's RPK and 9% of all departures.

We quantify the share of passenger aviation that can be replaced by electric aircraft using global airline route data from 2019. With current battery technology (e_b = 250 Wh/kg) the 9Bolt could fly 140 km missions after accounting for energy reserve requirements. With advanced battery technology (e_b = 500 Wh/kg), the larger 90Bolt could cover 280 km missions. The market of replaceable missions is sensitive to assumptions regarding the specific battery energy and EMF, as shown in **Figure ES 1**.

Using current battery technology, and assuming the central EMF case of a 15% reduction from current designs, the 9Bolt and 19 Bolt together could replace 9% of the commuter passenger market. With advanced battery technology, the three aircraft types could cover about two-thirds of the commuter passenger market (served by aircraft seating 19 or fewer passengers) and one-quarter of the turboprop market (turboprop-powered aircraft that seat 20 or more passengers). This amounts to replacing 0.21% of aviation RPKs. Coverage is sensitive to EMF assumptions, which vary between 24 and 89% for the 9Bolt and 19Bolt, and between 2 and 59% for the 90Bolt.

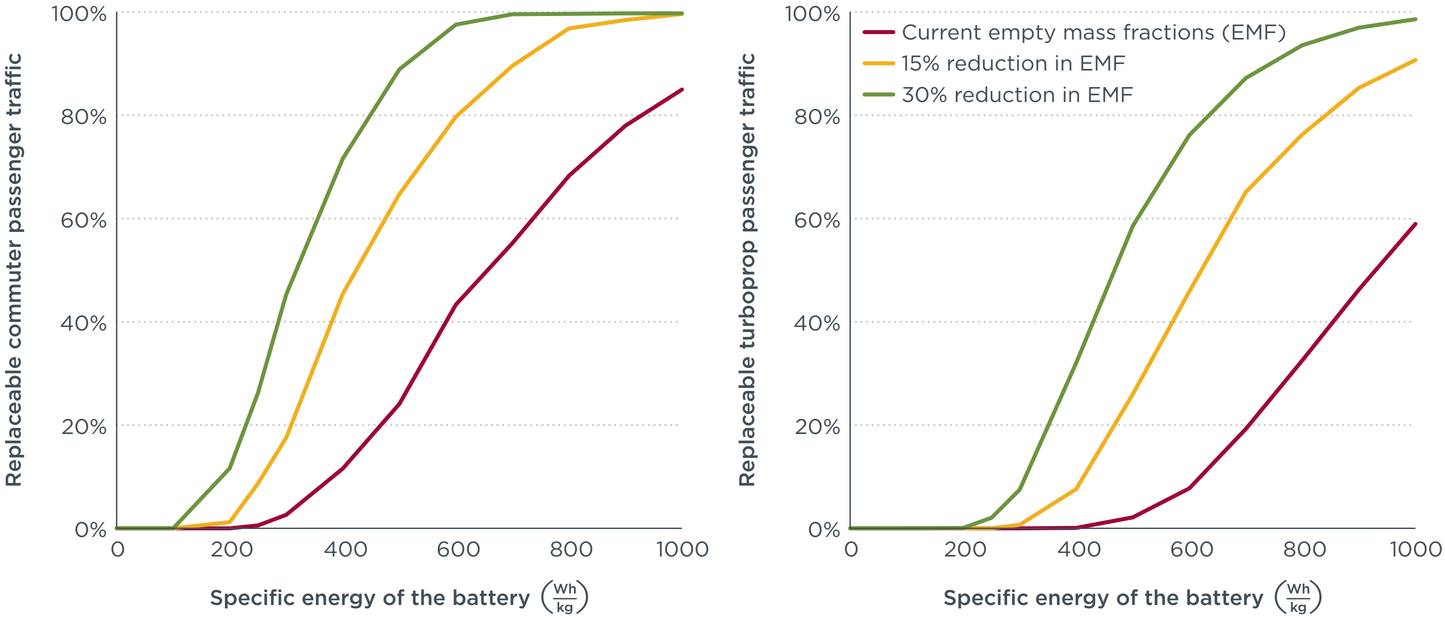

Figure ES 1. Replaceable commuter (left) and turboprop (right) aviation market by battery pack specific energy

While the share of the aviation market replaceable by electric aircraft is small, this new technology provides additional benefits that merit its use on suitable routes. The aircraft themselves would be 2.1 to 3.2 times more energy efficient in operation than their fossil-fueled counterparts. Compared to aircraft flown on e-kerosene, a sustainable alternative to fossil jet fuel, electric aircraft could be 4.5-6.9 times more energy efficient. And electric aircraft are zero-emission during operation and, thus, do not degrade air quality.

The greenhouse gas (GHG) emissions associated with the operation of electric aircraft are the well-to-wake (WTW) emissions from electricity generation and from battery replacement (which includes the manufacture of battery packs needed for regular battery replacement). Even in our most conservative scenario, where battery charging comes from a mix of grid electricity that corresponds to the currently stated policies of the US, electric aircraft would provide a 49%-57% reduction in carbon intensity per RPK when compared to fossil-fueled aircraft, as shown in **Figure ES 2**. This assumes batteries achieve an e_b of 300 Wh/kg in 2030 and 500 Wh/kg in 2050. In the best-case scenario, where batteries are charged using renewable energy, the reduction in carbon intensity is estimated to be 82%-88%.

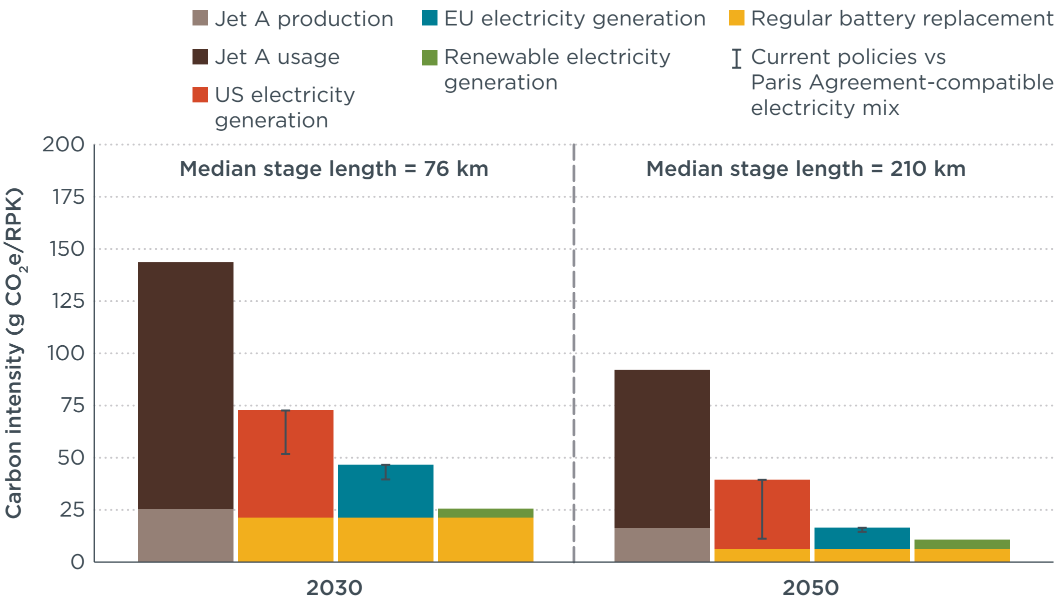

Figure ES 2. Well-to-wake GHG emissions of electric and fossil-fueled aircraft operations including battery replacement, 2030 and 2050

In summary, while electric aircraft will be limited to small and short-range passenger aircraft, their higher energy efficiency, lower carbon intensity, and zero-emission operations merit their adoption to their maximum potential. By 2050, assuming a pack-level specific energy of the battery of 500 Wh/kg, a 15% reduction in currently achievable EMF, and the use of electric aircraft on all possible routes, aviation's carbon emissions could be reduced by 3.7 million tonnes of CO_2e annually, representing 0.2% of expected emissions in 2050.

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ABBREVIATIONS

BMF	battery mass fraction, m_b/MTOM
C_L	coefficient of lift
CO_2	carbon dioxide
DoD	depth of discharge
e_b	specific energy of the battery at the pack level
EIS	entry into service
EMF	empty mass fraction, OEW/MTOM without batteries
g CO_2e	grams of CO_2 equivalent
GHG	greenhouse gas
ICAO	International Civil Aviation Organization
ICCT	International Council on Clean Transportation
L/D	lift-to-drag ratio
LH_2	liquid hydrogen
m_b	battery mass
MJ	megajoules
m_p	payload mass
MTOM	maximum takeoff mass
η_e	electrical efficiency
η_p	propulsive efficiency
η_{total}	total efficiency, product of electrical and propulsive efficiency
OEW	operating empty weight
PMF	payload mass fraction, m_p/MTOM
RPK	revenue passenger kilometer
R_{alt}	alternate distance
R_{max}	maximum range
R_{OC}	operational cruise range
SAF	sustainable aviation fuel
SoC	state of charge
v_{loiter}	loiter velocity
Wh	watt-hours
WTW	well-to-wake

INTRODUCTION

The decarbonization of the aviation industry is underway. Goals have been set, and pathways devised—including our own (Graver et al., 2022). While most attention is paid to sustainable aviation fuels (SAFs), a drop-in fuel that requires few, if any, alterations to aircraft or airport infrastructure, a subset of the industry is working on advanced concept aircraft. Airbus is prioritizing development of hydrogen aircraft with plans to enter a hydrogen model into service by 2035 (Airbus, 2020). The ICCT has conducted its own analysis of the technology and concluded that evolutionary liquid hydrogen (LH_2) designs could address about a third of the passenger aviation market starting in 2035 (Mukhopadhaya & Rutherford, 2022).

Other companies are working to electrify aviation, using both hybrid and fully electric aircraft. The designs in the works tend to be for smaller air taxi, commuter, and regional aircraft with limited flight ranges and small passenger market penetration.

Eviation, an Israeli start-up, was the first to divulge plans to produce a fully electric aircraft, Alice, in 2019 (Reuters Staff, 2019). The 9-seat passenger variant of the plane fits within the commuter market, which we define as routes operated with aircraft of 19 seats or fewer. Eviation's current public specifications for Alice list its maximum range at 440 nautical miles (815 km) with no payload or reserves, and facing no headwinds (*Aircraft – Eviation*, n.d.). The U.S. passenger commuter airline Cape Air has placed orders for the aircraft (Patel, 2019) and DHL has ordered the cargo variant, with both expecting delivery in 2024 (Reuters, 2021).

Unlike Eviation, **Tecnam** has been producing aircraft for decades. The Italian manufacturer announced that it was working on P-VOLT, a fully electric version of its 9-passenger P2012. Norwegian regional carrier Widerøe is looking to take delivery of the P-VOLT starting in 2026. According to a company press release, nearly three-quarters of the airline's routes are less than 275 km in length; the aircraft would serve airports in the North and West of Norway (Tecnam, 2021).

Sweden-based **Heart Aerospace** is working on a larger aircraft, the 19-seat ES-19. This aircraft has a target range of 400 km, which is expected to increase over time as battery technology improves (Heart Aerospace, n.d.). This project has received multiple orders, including from Finnair for 20 aircraft (Finnair, 2021) and from United Airlines, with its Mesa Airlines regional partner, for 100 aircraft (United Airlines, 2021). In its press release, United stated that the aircraft could operate on more than 100 regional routes out of most of its hubs. This includes routes to small airports the airline previously served but no longer does due to the high operating cost of fossil-fueled commuter aircraft. Heart Aerospace expects the ES-19 to enter service in 2026; it intends to develop larger aircraft once they are technologically and economically feasible (Heart Aerospace, n.d.)

U.S. start-up **Wright Electric** is working on still larger electric aircraft that could account for a larger passenger market share. The Wright Spirit would be a 100-seat retrofit of a British Aerospace (BAe) 146 aircraft that could operate on routes of one hour or less (Wright Electric, n.d.). This airplane size would likely compete with present-day 76-passenger turboprops (Graver et al., 2020).

Electric aircraft are being promoted by public policy. The Nordic countries—Denmark, Finland, Iceland, Norway, and Sweden—have prioritized fossil-fuel-free flight and electrification. The Nordic Council of Ministers created the Nordic Network for Electric Aviation (NEA) to bring together stakeholders in developing electric aircraft technology and infrastructure, both domestically and across the region (Nordic Innovation, n.d.). While the project is now closed, the countries and their airlines continue to make progress.

In her New Year's address, the Prime Minister of Denmark announced the government's intent for all domestic flights to be fossil-fuel-free by 2030, with flights in 2025 starting to operate on "green" fuel (that is, SAFs) (Surgenor, 2022).[1] In Sweden, net-zero targets have been set for domestic (2030) and international (2045) operations (Swedavia, 2022). To achieve these goals, Scandinavian Airlines, the flag carrier of Denmark, Norway, and Sweden, signaled its intention to consume the equivalent SAF volume needed for all domestic flights by 2030 (Scandinavian Airlines, 2022).

Denmark and Sweden's goals are being adopted by the other Nordic countries. Like Denmark and Sweden, Iceland has set a goal of sustainable domestic aviation by 2030 (Sigurdardottir, 2020). Flag carrier Icelandair is working with Heart Aerospace to evaluate the suitability of electric aircraft for domestic flights (Icelandair Group, 2021). Norway's airport operator, Avinor, is working toward a completely electric domestic aviation market by 2040 (Avinor & Luftfartstilsynet, 2020). Finland stated its intention to support electrification of aviation in its emissions reduction action plan to the International Civil Aviation Organization (ICAO), including analyzing the infrastructure needed at airports to support electric aircraft (Finnish Transport and Communications Agency, 2021).

Considering these announcements from aircraft manufacturers, airports, and governments, this work focuses on quantifying the performance of electric aircraft of varying passenger capacities and the market for them. Key contributions include: analyzing the impact of reserve requirements on operational range, comparing the energy efficiencies of electric and fossil-fueled aircraft, determining the addressable share of the passenger aviation market, and quantifying the GHG emissions of generating electricity for, and replacing, the batteries of electric aircraft.

In the larger realm of global passenger aviation, electric aircraft will play a minor role in decarbonization due to range limitations that confine their use to commuter routes. The Waypoint 2050 net-zero roadmap from the Air Transport Action Group (Air Transport Action Group, 2021), predicts that electricity used to power aircraft directly will account for 2% of aviation energy use in 2050. While aviation's electricity demand could reach 25 exajoules by 2050, most of it will be steered toward creation of drop-in SAFs and hydrogen (Graver et al., 2022). Whether in terms of energy demand, RPKs, or most any other metric, the profile of electric aircraft will be small through 2050.

However, the use of electric aircraft could help conserve limited supplies of the hydrogen and SAFs needed for longer missions. Hydrogen aircraft can decarbonize short- and medium-haul routes (Mukhopadhaya & Rutherford, 2022), while SAF is the only option for long-haul aircraft. Covering short missions with electric aircraft would reduce demand for SAF and hydrogen, thereby magnifying the contribution of electric aircraft to decarbonized aviation.

The rest of the paper is arranged as follows. The next section outlines the methods we used to assess electric aircraft. We then present the modeled electric aircraft, including the expected performance characteristics and their sensitivity to key technological parameters, the share of aviation markets that could be replaced, the passenger emissions that could be mitigated, and operational energy requirements. We close with some policy recommendations and thoughts on future work. Several appendices provide details on how key study parameters were calculated. We also include a case study of the Nordic markets that could be served by electric aircraft in Appendix D: A case study of domestic Nordic aviation.

1 SAF can have drastically varying well-to-wake greenhouse gas emissions depending on the feedstock used to create it (Pavlenko & Searle, 2021). Ensuring low emissions on a lifecycle basis is essential to ensure that the SAF being used is "green".

METHODOLOGY

This section details the analyses and underlying assumptions employed in this work. With a first-order performance analysis, we identify key technological parameters that determine the payload and range capabilities of electric aircraft. This is followed by a discussion of battery technology, the methods used to quantify the addressable aviation market, and the scope of the greenhouse gas (GHG) emissions considered for fossil-fueled and electric aircraft. Finally, the expected adoption rate of electric aircraft is discussed.

AIRCRAFT PERFORMANCE

This work does not model specific aircraft geometries, instead opting for a first-order analysis to determine the electric aircraft's range.[2] Appendix A: Electric range equation derives the electric range equation using a force balance on an aircraft at constant altitude and constant speed, characteristic of the cruise segment of flight. This is reproduced here as Equation (1).

$$R_{max} = \frac{1}{g} \times L/D \times \frac{m_b}{MTOM} \times e_b \times \eta_{total} \qquad \textbf{(1)}$$

R_{max} represents the maximum cruise range of the aircraft. It is dependent on the aircraft's lift-to-drag ratio (L/D), the mass of the battery (m_b), the maximum takeoff mass (MTOM) of the aircraft, the specific energy of the battery at the pack level (e_b), and the overall energy conversion efficiency of the aircraft (η_{total}). g represents the acceleration due to gravity and is constant. Equation (1) is a useful expression of cruise range as it is independent of the size, payload, and speed of the aircraft. It indicates a direct proportionality between an electric aircraft's maximum cruise range and its key characteristics.

However, safety regulations require aircraft to carry reserve fuel (in the electric case, reserve battery energy) to account for any unforeseen circumstances such as bad weather, failed landing approaches, or diversion from the planned flightpath. Current regulations do not specify different reserves for battery electric aircraft. Based on the regulation for conventionally fueled aircraft, we assumed the following reserves:

1. Battery charge sufficient to fly to an alternate airport 100 km away;
2. Battery charge sufficient to loiter over an airport for 30 minutes; and
3. 5% of the allocated mission battery charge as contingency.

To get the operational cruise range (R_{OC}) of the aircraft, the reserve requirements need to be converted to a distance measure and subtracted from R_{max}. The distance to the alternate airport (R_{alt} = 100 km) can be directly subtracted from R_{max}. The distance covered while loitering is the product of the loiter velocity (v_{loiter}) and the loiter time (t_{loiter}). The requirement of a contingency charge (SoC_{cont}), which is a fraction of the operational cruise distance, further reduces the range to be 1-SoC_{cont} times the planned operational cruise distance. This adds a few terms to Equation (1):

$$R_{OC} = (1 - SoC_{cont})(R_{max} - R_{alt} - v_{loiter}\, t_{loiter}) \qquad \textbf{(2)}$$

This operational cruise range analysis should be treated as defining the maximum potential of electric aircraft. The operational cruise range calculation subtracts the

2 The simplicity of electric propulsion enables a wide range of non-conventional design decisions, such as distributed propulsion and high aspect ratio wings, that can impact an aircraft's performance. The impacts of these decisions can be encompassed in the choice of aircraft performance parameters that are input into first-order analyses. This allows us to be agnostic to the specifics of aircraft design and perform more rapid analyses, as no aerodynamic calculations are needed.

reserve requirements from the maximum cruise range of the aircraft. It does not account for energy use during ground operations, takeoff, and climb, all of which would necessarily reduce the range of the aircraft. Including the energy use from these non-cruise operations results in a slightly lower "mission range". **Figure 1** uses a waterfall chart to show the relationship among the different range values used in this work.

The short range of electric aircraft makes it difficult to determine the cruising altitude that will be reached for a particular mission. This makes calculating the energy required for the non-cruise operations difficult. Consequently, when determining the routes replaceable by electric aircraft, the operational cruise range is used. However, when we calculate the energy requirements of replacing specific routes, this simplification is no longer needed and the energy consumption for non-cruise operations are accounted for.

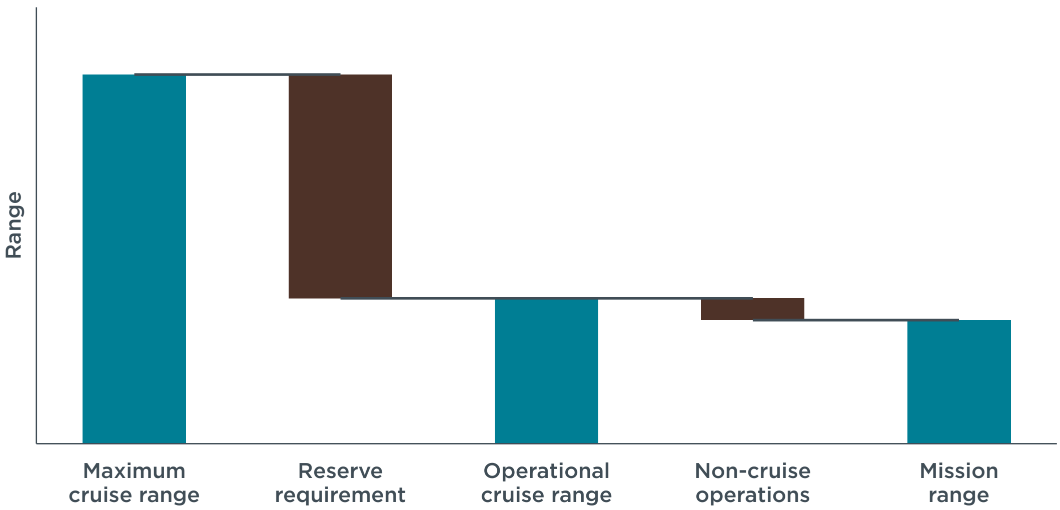

Figure 1. Schematic of range values used in this work

AIRCRAFT CHARACTERISTICS

This work models three sizes of electric aircraft: 9-, 19-, and 90-seat. Their performance is analyzed using Equations (1) and (2). This requires defining certain aircraft characteristics.

Lift-to-drag ratio (L/D) represents the aircraft's aerodynamic efficiency; it is affected by the aircraft design. Higher aspect-ratio wings, distributed propulsion, boundary layer ingestion, and natural laminar flow wings are all potential pathways to increasing L/D (de Vries, 2022; Dietl et al., 2018; Troeltsch et al., 2020). The L/D ratio varies by aircraft, but typically lies between 12 and 20 during cruise (Raffi Babikian, 2001). This study assumes a L/D ratio of 16 for the electric aircraft.

Battery mass fraction (BMF = $\frac{m_b}{MTOM}$) is a proxy for the aircraft's structural efficiency.[3] The *MTOM* of an electric aircraft is a sum of its operating empty weight (OEW), payload mass (m_p) and battery mass (m_b). Equation (3) expresses this relationship as fractions of the MTOM,

$$\frac{OEW}{MTOM} + \frac{m_p}{MTOM} + \frac{m_b}{MTOM} = 1 \qquad \textbf{(3)}$$

3 A higher battery mass fraction indicates a larger percentage of the takeoff mass is the battery and a lower percentage of the takeoff mass is available for the aircraft's structure and payload.

where the empty mass fraction (EMF = $\frac{OEW}{MTOM}$) is the direct measure of the structural efficiency of the aircraft. A lower EMF value at the same MTOM indicates a lighter aircraft structure. For a given MTOM, the payload mass fraction (PMF = $m_p/MTOM = \frac{m_p}{MTOM}$) depends on the number of passengers being carried. Consequently, the battery mass fraction can be expressed as a function of the empty and payload mass fractions:

$$BMF = 1 - EMF - PMF \tag{4}$$

Total efficiency η_{total} represents how efficiently the electric drivetrain can convert battery energy into propulsive power. η_{total} is determined by multiplying the propulsive efficiency of the propeller (η_p) and the electric efficiency (η_e). Typical values for η_p lie between 0.8 and 0.9 (Gur, 2014). η_e encapsulates all energy losses in the electric system from the battery to the shaft of the electric motor, and can be expected to lie around 0.9 (Raymer, 2018). Typical values for η_{total} range from 0.7 to 0.8.

Table 1 lists the values of all the parameters used for the aircraft analysis. In previous ICCT analyses, we assign passengers and their baggage a mass of 100 kg, per ICAO recommendations (International Civil Aviation Organization, n.d.) However, because we are analyzing commuter and regional aircraft, we assume lighter baggage than for a narrow- or widebody aircraft.

Table 1. Parameters used for the analysis of electric aircraft

Mass per passenger with baggage (kg)	95
Lift-to-drag, *L/D*	16
Propulsive efficiency, η_p	0.85
Electric efficiency, η_e	0.90
Total efficiency, $\eta_{total} = \eta_e \eta_p$	0.765
Alternate airport distance, R_{alt} (km)	100
Loiter time, t_{loiter} (min)	30

BATTERY CHARACTERISTICS

Electric aircraft operations set stringent requirements on batteries. The batteries need to be light, compact, quickly rechargeable, and able to provide the high power required for the takeoff and climb segments. They will need to be housed inside the airplane with sufficient cooling measures to prevent overheating (Irfan, 2014).

Rechargeable lithium-ion batteries are the dominant battery chemistry in today's commercial batteries. They are ubiquitous, powering everything from phones to electric cars. This is due to their high specific energies, measured in watt-hours per kilogram (Wh/kg), and high energy densities, measured in watt-hours per liter (Wh/L). Since their introduction in 1991, the specific energy and energy density of lithium-ion batteries at the cell level have more than tripled, with specific energy increasing from 80 Wh/kg to 256 Wh/kg and energy density increasing from 200 Wh/L to 697 Wh/L by 2015 (Placke et al., 2017).[4] By comparison, Jet A has a specific energy nearly 50 times higher (12,000 Wh/kg) and an energy density that is about 14 times higher (9,690 Wh/L).

A promising battery technology that is still in the research and development phase is all-solid-state batteries. These provide safety advantages as they are not flammable and are stable at high temperatures (Kim et al., 2015). A recent review benchmarking

4 "Cell-level" metrics include only the weight of the anode, cathode, electrolyte, and cell housing. These metrics are higher than "pack-level" metrics which include the weight of all ancillary parts, such as wires, insulation, and structural material that are required to store the battery but do not contribute to its energy storage capacity.

solid-state lithium battery research showed achievement of cell-level specific energy of up to 288 Wh/kg (Randau et al., 2020).

A completely different cell chemistry under research is aluminum-air. This chemistry is being considered by Wright Electric to power their 100-seat electric aircraft (Wright Electric, n.d.). These batteries promise high specific energies but are non-rechargeable and face many technical challenges before becoming commercially viable (Liu et al., 2017).

Commercially produced high energy density lithium-ion batteries—those that use lithium nickel manganese cobalt oxide (NMC811) or lithium nickel cobalt aluminum oxide (NCA) as the cathode, can achieve e_b of up to 250 Wh/kg at the pack level (Argonne National Laboratory, 2020). Placke et al. suggest that further optimizations to current lithium-ion batteries could achieve a e_b of 400 Wh/kg at the cell level. They also suggest that lithium-based solid-state batteries could theoretically achieve a cell-level e_b of 479 Wh/kg (Placke et al., 2017).

This study expressly uses the specific energy of the battery at the pack level (e_b). It explores battery specific energy values of 250-500 Wh/kg. Achieving e_b= 500 Wh/kg at the pack level by the year 2050 will require significant technical advancements in lithium-ion battery technology and may require development of a different battery chemistry. While there is no geometric modeling of aircraft in this study, basic estimates of battery volume are also provided. **Table 2** lists the different values for battery specific energy and volumetric energy density at the pack level, for various analysis years.[5]

Table 2. Pack-level battery specific energy and volumetric energy densities for different time frames

Year	Specific energy, e_b (Wh/kg)	Volumetric energy density, v_b (Wh/L)
Current	250	500
2030	300	630
2050	500	1100

Lithium-ion batteries degrade faster when held at very high (100%) or very low (0%) state of charge (SoC). They are often fitted with battery management systems that allow them to operate at only 95% of their total capacity (Bieker et al., 2022). For this reason, only 95% of the full battery energy storage is used in the simulations for this study. We also assume that 15% additional electricity is required to charge the battery (Bieker, 2021). This is to account for the energy lost during the charging process; for example, due to the heat generated in the battery.

MARKET COVERAGE

The electric aircraft designs in this work are focused on servicing routes in the commuter and turboprop sections of the aviation market. Commuter routes are serviced by aircraft that have fewer than 20 seats available per flight. Turboprop routes are serviced by turboprop aircraft and carry 20 or more passengers. For this analysis we depend on 2019 airline data from ICCT's Global Aviation Carbon Assessment (GACA) model (Graver et al., 2020). This database provides pertinent information on each route flown in 2019 including annual values for number of flights, passengers conveyed, distance traveled, RPK, and fuel burn.

Table 3 situates the commuter and turboprop routes in the context of the global aviation market. While commuter and turboprop routes account for only 0.03%

5 The volumetric energy density is assumed to have a linear relationship with the specific energy of the battery (Meeus, 2018).

and 0.74% of annual RPK totals, respectively, they account for a larger share of CO_2 emissions (0.16% and 1.2%) and departures (4.0% and 9.3%). Median stage length is an indicator for this trend. Shorter flights enable more departures in a day and emit more CO_2 per RPK.[6] The dataset does not include private or general aviation flights, so it underrepresents the low passenger capacity commuter market.

Table 3. Commuter and turboprop share of the global passenger aviation market

	Median stage length (km)	Percentage of global aviation values (%)		
		RPK	CO_2 emissions	Departures
Commuter routes	160	0.03	0.17	4.0
Turboprop routes	386	0.74	1.2	9.3

Market coverage is calculated using the operational cruise range. This will be longer than the mission range of the aircraft which needs to include the energy used during non-cruise operations such as ground operations, takeoff, climb, and descent. Therefore, the resulting market coverage values should be considered as upper bounds for the aircraft modeled here.

This analysis of the addressable market does not consider the possibility that electric aircraft will enable new routes due to lower operating costs (Shahwan, 2021). This is difficult to account for because the carbon mitigation of those new flights would depend on factors outside of the aviation sector. For example, commuter aircraft could be used to transfer passengers from smaller airports to large transit hubs, in many cases replacing road trips. This would not reduce the aviation sector's emissions, but rather abate emissions from road transport. For this reason, the addressable market analysis and emission mitigation analysis in this paper are based on historical data from established routes, rather than on modeled data for new routes.

EMISSION CALCULATIONS

This study compares the annual well-to-wake (WTW) greenhouse gas (GHG) emissions of jet fuel usage in fossil-fueled aircraft to the WTW GHG emissions associated with the electricity production and frequent battery replacement (which includes battery manufacture) required to power electric aircraft in a given year. The analysis does not compare the life-cycle emissions of electric vs fossil-fueled aircraft, as they do not refer to the vehicle lifetime, which would include vehicle production and maintenance emissions, and would consider a continually improving electricity mix being used to power the electric aircraft. The emission calculations are based on a year's worth of operations and only the emissions from the routes replaceable by electric aircraft are considered.

Jet fuel

Fossil-fueled aircraft are assumed to use Jet A as fuel. The GACA database provides the annual fuel burn (in kilograms) associated with each route. The annual fuel burn is multiplied by the specific energy of Jet A (43 MJ/kg) to get the annual energy consumption for that route. This is multiplied by the carbon intensity of Jet A to get annual emissions. We use a carbon intensity of 89 g CO_2 equivalent per megajoule of energy (g CO_2e/MJ) on a WTW basis (International Civil Aviation Organization, 2018) for Jet A. This value of 89 g CO_2e/MJ for Jet A includes 73 g CO_2e/MJ of combustion emissions and 16 g CO_2e/MJ of upstream (production) emissions.

6 Shorter flights mean that the takeoff and climb segments of the mission, which are the most energy intensive, are a larger fraction of the full mission duration. This increases the energy consumption and carbon emissions per kilometer traveled.

Emissions from operating the replaceable routes for the entire year are divided by the annual RPK of those routes to give the normalized GHG emissions, expressed in g CO_2e/RPK, for the annual operation of fossil-fueled aircraft. When projecting emissions into the future, we assume a 0.5% annual reduction in fuel burn (Graver & Rutherford, 2018).

Electricity consumption

Concerted efforts to decarbonize electricity grids are yielding continuous reductions in carbon intensity of electricity at the plug. However, projections of future energy production are highly uncertain, in large part due to the changing policy and incentive landscape (Teske, 2020). To account for this uncertainty, the study's analysis is grounded in two divergent scenarios put forward by the International Energy Agency (IEA) in its World Energy Outlook. The Stated Policies Scenario (STEPS) represents projections based on current policy statements, while the Sustainable Development Scenario represents a pathway to meeting the Paris Agreement targets without compromising on energy availability (International Energy Agency, 2020).

Table 4 lists the life-cycle carbon intensities of electricity consumption in the United States (US) and European Union (EU) that are used in this study. These values are based on projections of the electricity generation mix from the IEA, coupled with the Intergovernmental Panel on Climate Change (IPCC)'s life-cycle GHG emission factors for different electricity production methods, and adjusted by the expected losses in transmission and distribution (Intergovernmental Panel on Climate Change, 2011; International Energy Agency, 2021). Details of the calculations can be found in (Bieker, 2021). The carbon intensity for renewables assumes a 50/50 split between solar and wind power generation.

Table 4. Life-cycle carbon intensity of electricity consumption

	Life-cycle carbon intensity of electricity consumption (g CO_2e/kWh)				
	US		EU		
	STEPS	SDS	STEPS	SDS	Renewables
2030	339	201	167	121	29
2040	272	84	115	86	
2050	204	31	63	51	

These carbon intensities are multiplied by the energy required to operate the replaceable routes for a year using electric aircraft. In the operational cruise range calculations, the taxi, takeoff, climb, descent, and landing segments were ignored due to the large variation in their length for short range flights. However, because specific routes are being considered for this analysis, we can consider the differing energy use when calculating the total energy consumption of operating electric aircraft.

Simulating a full mission requires intensive modeling. Instead of simulating each replaceable route to calculate the energy usage, we calculate a mission-to-cruise (MTC) ratio that varies by aircraft class and stage length. The MTC is the ratio of mission energy to cruise energy as calculated using the modified electric range equation. MTC is used as a multiplier on the cruise energy usage to get the expected energy consumption for the entire mission.

We simulate full representative missions, including the takeoff, climb, cruise, descent, and landing segments, using SUAVE across varying e_b values (Lukaczyk et al., 2015). The ratios are linearly interpolated for distances within the range of operational cruise ranges. The MTC ratios for missions simulated in this study lie between 1.05 and 1.45. Running fossil-fueled aircraft through identical missions yielded similar MTC ratios.[7]

As mentioned earlier in the Battery characteristics section, we assume 15% energy loss during the charging process. To account for this, the energy consumption is further multiplied by a factor of 1.15 to calculate the electricity consumption to charge the electric aircraft. This final electricity consumption value is multiplied by the carbon intensity factors in **Table 4** to get the GHG emissions associated with electricity consumption of electric aircraft.

Battery production

GHG emissions of the battery production process are based on the latest data on battery production and battery chemistry. This study uses a value of 60 kg CO_2e/kWh for battery production emissions for 2021. This is assumed to fall by 20% every 10 years due to improvements in the manufacturing process and an increasing share of renewable energy usage (Bieker, 2021). The resulting values for 2030 and 2050 are 48 kg CO_2e/kWh and 31 kg CO_2e/kWh, respectively.

The frequency of battery replacement in electric aircraft is difficult to predict. Most battery aging research has focused on passenger cars (Guo et al., 2021).[8] Battery usage in an electric aircraft will differ from that in electric cars. Aircraft batteries will go through multiple duty cycles per day, mission reserve requirements will limit the depth of discharge (DoD) to less than 70%,[9] and the high power demand of takeoff will result in high discharge rates. Low DoD and high discharge rates are competing factors in battery aging. Low DoD is better for battery health, while high discharge rates age the battery more rapidly.

In the absence of specific battery age modeling, **this study assumes a battery life span of 3,000 duty cycles (Harlow et al., 2019)**. This roughly equates to an aircraft performing 8 missions daily for a year, or 4 missions daily for 2 years. Once the lifespan is reached, the battery would need to be replaced.

The 3000 duty cycles is about 6 times the certification limit for the batteries on the Pipistrel Velis Electro, which is the only currently certified electric aircraft. Those batteries are certified for 500 hours of operation, or about 600 life cycles based on a 50-minute flight (*Velis Electro EASA TC – Pipistrel Aircraft*, n.d.). The longer battery life assumed in this study is justified based on Pipistrel Aircraft's expectation that their certification limit will be raised after testing and Heart Aerospace's belief that its battery will perform for 3,000 duty cycles (*FAQ | Heart Aerospace*, n.d.). Additionally, previous ICCT research into heavy-duty vehicles with similarly large batteries (greater than 500 kWh), suggests that 2,500-3,000 duty cycles might be expected before the battery loses 20% of maximum charge (Basma et al., 2021).

We quantify the number of batteries used in a year to calculate the annual emissions associated with battery production for electric aircraft. For each route, the number of flights flown in a year is divided by the 3,000 duty-cycle lifespan to determine the number of battery replacements required. Most routes have an annual frequency of fewer than 3,000 duty cycles. In this case a fractional amount of the battery's production emissions is allocated to the annual emissions. For example, if a route is

7 The MTC ratio is sensitive to assumptions of cruise altitude, which are expected to be low (2000 to 4000 meters of altitude) for electric aircraft because of the short stage length. The MTC ratios for fossil-fueled aircraft were slightly lower (better) than their electric counterparts due to the lower weight of the aircraft and the fact that the aircraft gets lighter as it burns fossil jet fuel.

8 Battery lifespan depends on a multitude of factors including operating temperature, depth of discharge, number of duty cycles, and charging and discharging schedules.

9 This is a result of the electric aircraft modeled in this study. See **Table 6** in the Operational Cruise Range Simulations section.

flown 600 times in a year, then one-fifth of the emissions of producing that battery are added to the annual emissions.

The emissions of all the electric aircraft routes (from electricity consumption and battery manufacturing) are summed and divided by the total RPK serviced by all the electric aircraft to get a single annual GHG emissions value for the electric aircraft in g CO_2e/RPK.

AIRCRAFT ADOPTION

Most manufacturers expect to deliver their first aircraft in 2026 (*FAQ | Heart Aerospace*, n.d.; Tecnam, 2021; Wright Electric, n.d.). The expected lower operating cost and climate benefits, coupled with the advancing age of today's commuter aircraft fleet would likely result in rapid adoption of electric aircraft on suitable routes. The relatively small addressable market means that aircraft adoption will be limited by the number of replaceable routes, rather than by aircraft deliveries. For this reason, we analyze the impact of electric aircraft at their maximum deployment, that is, they service all replaceable routes in 2030 and 2050.

RESULTS

GENERALIZED ELECTRIC AIRCRAFT

The electric range equation, Equation (1), provides a convenient, payload-agnostic expression of the electric aircraft's maximum cruise range (without reserves). **Figure 2** presents the sensitivity of this range to the pack-level specific energy of the battery e_b and the battery mass fraction (BMF). The grey area represents realistic values for these parameters: 250–500 Wh/kg for e_b and 0.3–0.5 for BMF. A lift-over-drag ratio of 15 and an overall efficiency of 0.765 are assumed in this range calculation.

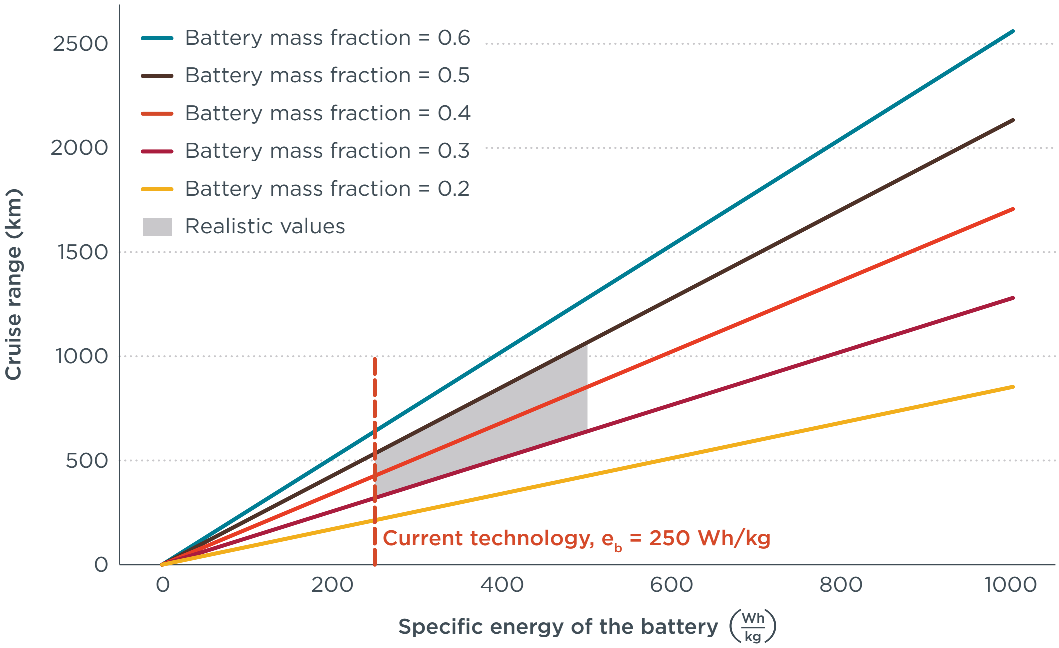

Figure 2. Sensitivity of the maximum cruise range of electric aircraft (without reserves) to its battery mass fraction and the specific energy of the battery at the pack level

This analysis suggests that current battery technology (e_b = 250 Wh/kg), with the central BMF case (0.4), would give aircraft a maximum cruise range of ~430 km (270 miles) while not accounting for reserve requirements.

This low-fidelity approximation of maximum cruise range reveals the independent relationship between aircraft range and MTOM. In contrast to conventional aircraft, larger electric aircraft do not imply greater range. Rather, increasing the BMF of the aircraft increases the aircraft's ranges. As shown in Equation (4), the achievable BMF is a function of the EMF and PMF. The EMF depends on the structural efficiency of the aircraft. Lighter structural components would result in a lower EMF. This directly increases the BMF of the aircraft for a constant payload and MTOM. The PMF can be decreased by increasing the MTOM of the aircraft (heavier aircraft) for the same payload mass. However, this decreases the transport efficiency of the aircraft by having a larger, heavier aircraft to carry the same payload.

AIRCRAFT DESIGN

For specific aircraft analyses, this work explores three designs with different passenger capacities. The three have 9, 19, and 90 seats and are called the 9Bolt, 19Bolt, and 90Bolt, respectively.

Table 5 lists the values of all the parameters used to define the aircraft and their performance. The MTOM of the 9Bolt and 19Bolt are chosen to be less than 8,618 kg (19,000 lbs) so that they can be certified under the CS-23/Part 23 category (European

Aviation Safety Agency (EASA), 2003; Federal Aviation Administration (FAA), 2016). The MTOM for the 90Bolt is chosen to be 37,500 kg, roughly the maximum landing mass of the BAe 146-300/Avro 146RJ[10] (European Aviation Safety Agency (EASA), 2010). The weight breakdown is shown in **Figure 3**.

Table 5. Characteristics of the modeled electric aircraft

	9Bolt	19Bolt	90Bolt
Passengers	9	19	90
MTOM (kg)	7,500	8,618	37,500
Loiter velocity, v_{loiter} (m/s)	70	70	98
Empty mass fraction, EMF	0.54	0.53	0.50
Payload mass fraction, PMF	0.11	0.21	0.23
Battery mass fraction, BMF = 1-EMF-PMF	0.35	0.26	0.27

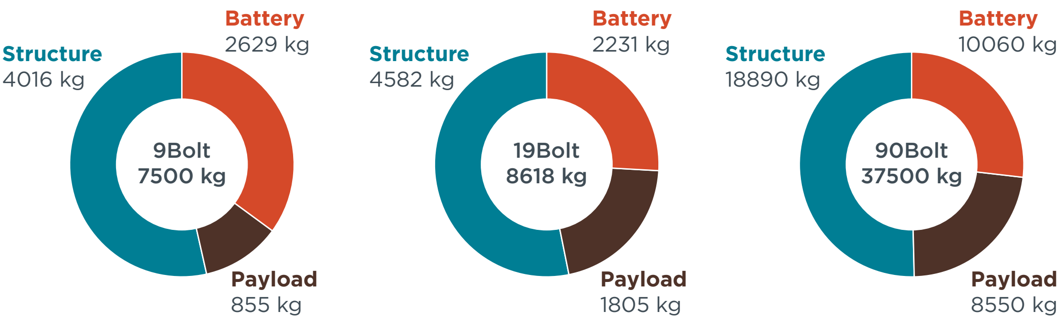

Figure 3. Weight breakdown for each electric aircraft

Empty mass fractions (EMF = $\frac{OEW}{MTOM}$) for existing aircraft are shown in **Figure 4**. Aircraft with higher MTOM generally have lower empty mass fractions. There are two clusters of points for aircraft carrying fewer than 20 passengers (blue and brown dots). The low MTOM cluster (< 10^4 kg) represents typical commuter aircraft that use turboprop or piston engines, while the low EMF cluster (blue and brown dots near the 90Bolt) represents business jets.

The figure also shows the range of empty mass fractions of the electric aircraft modeled in this paper as green dots with error bars. The determination of the electric aircraft's EMF and its range for the sensitivity analysis is explained in Appendix B: Empty mass fraction calculation. For all analyses, unless otherwise noted, the central case of the EMF (15% reduction from current aircraft) is used.

10 This aircraft was the testbed planned for the now abandoned E-Fan X collaboration between Airbus and Siemens (David Kaminski-Morrow, 2020).

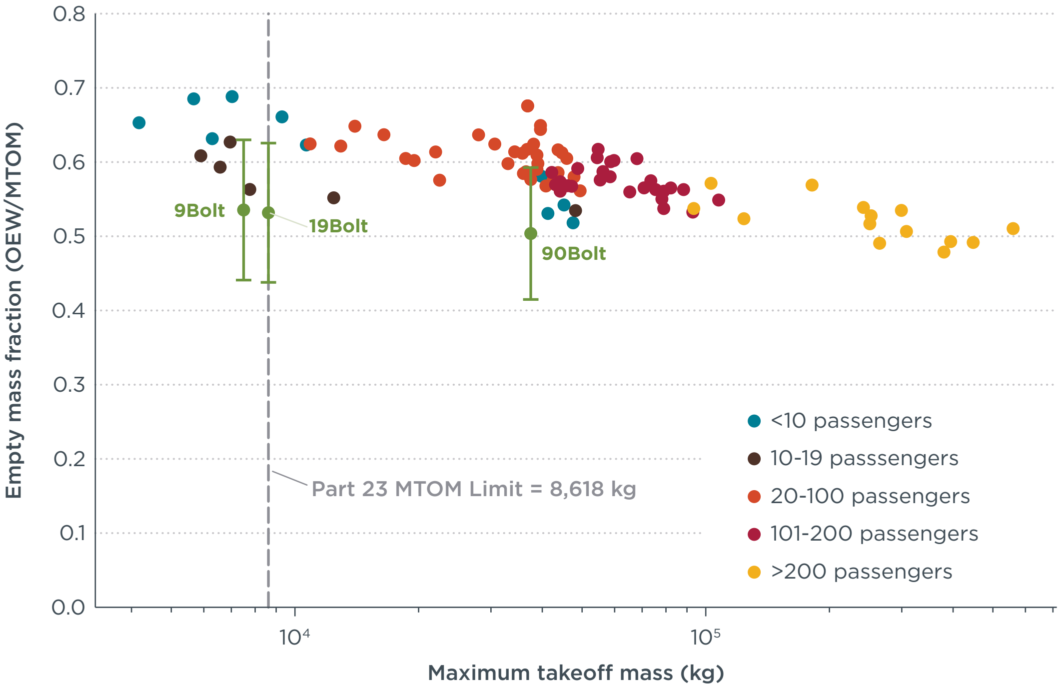

Figure 4. Empty mass fractions of current aircraft and modeled electric aircraft

One consequence of the 8,618 kg limit on the MTOM of the 19Bolt is that it results in the lowest BMF of the aircraft modeled. As seen in **Figure 2**, the BMF is a key factor in determining the aircraft's range. Certifying the aircraft under the CS-23/Part 23 category by limiting its MTOM would allow the 19Bolt to operate in airports with shorter runways, but the downside is a reduction in range.

The loiter velocity can also have a significant impact on the range of an electric aircraft, as explained in Equation (2). The values for this presented in **Table 5** are higher than comparable existing aircraft because the electric aircraft do not shed any fuel weight over the course of the mission and must loiter with its original takeoff mass. The calculation of the loiter velocity is explained in Appendix C: Loiter velocity calculation.

OPERATIONAL CRUISE RANGE SIMULATIONS

With the aircraft parameters defined, Equation (2) is used to determine the operational cruise range of the three electric aircraft. Operational cruise range refers to the maximum distance the aircraft could cruise, while having the mandated reserve energy in the batteries at the end of the mission. This is shorter than the maximum cruise range of the aircraft, which doesn't include the energy reserve requirements.

The sensitivity of the operational cruise range to the battery specific energy (e_b) is shown in **Figure 5**. This uses the central case of a 15% reduction in EMF from current aircraft. The 9Bolt has the longest range and has a steeper increase in range with increasing e_b. The steeper sensitivity is due to the higher BMF of the 9Bolt. The 19Bolt has a slightly lower BMF than the 90Bolt. However, it also has a lower loiter velocity. Consequently, the 19Bolt has a slightly longer operational cruise range, but that advantage decreases with an increase in e_b.

Table 6 provides details for operational cruise range simulations with e_b = 250 Wh/kg and 500 Wh/kg.

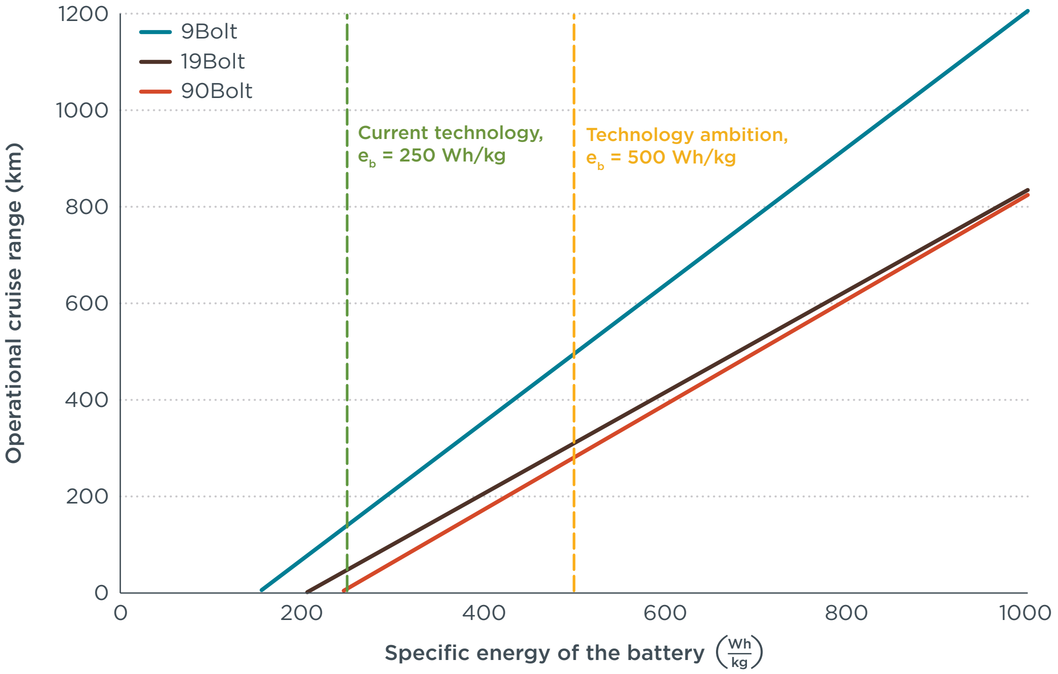

Figure 5. Operational cruise range sensitivity to battery pack level specific energy

Table 6. Electric aircraft performance characteristics at maximum operational cruise range

		9Bolt	19Bolt	90Bolt
Current technology e_b = 250 Wh/kg	**Operational cruise range (km)**	140	48	9
	Efficiency (MJ/RPK)	0.72	0.39	0.35
	Reserve battery charge	0.62	0.83	0.97
	Battery capacity (kWh)	657	557	2515
Technology ambition e_b = 500 Wh/kg	**Operational cruise range (km)**	495	310	281
	Efficiency (MJ/RPK)	0.73	0.39	0.36
	Reserve battery charge	0.31	0.42	0.50
	Battery capacity (kWh)	1,314	1,115	5,030

Operational cruise ranges: The operational cruise ranges with current battery technology are short, with the 90Bolt being able to fly only 9 km. With higher e_b, the ranges get longer and the reserve requirements account for a smaller proportion of the battery energy.

Battery capacities: Electric aircraft require large battery capacities. The smallest battery capacity, 557 kWh for the 19Bolt at e_b = 250 Wh/kg, is more than 7 times larger than the 78 kWh battery estimated to be in the most popular passenger electric car, the Tesla Model Y (U.S. Department of Energy, n.d.).[11] This study does not model the aircraft geometry and, thus, cannot make determinations on the impact of battery volume. However, based on the assumed volumetric energy density presented in **Table 2**, the 9Bolt and 19Bolt would have batteries that are approximately the size of 13 to 15 large suitcases while the 90Bolt's batteries would be closer to 60 to 65 large suitcases.[12]

Cruise energy efficiency: Electric aircraft are expected to be more efficient than their fossil-fueled counterparts due to the higher efficiency of the electric motors coupled with batteries. The electric range equation assumes steady and level flight, simulating

11 The Tesla Model Y has an estimated range of about 450 km, which is higher than the electric aircraft modeled here.

12 A large suitcase is defined as having 100-117 liters of carrying capacity (Varga, 2022).

cruise conditions. Consequently, we compare only the cruise energy efficiency of electric and fossil-fueled aircraft. **Figure 6** presents this comparison for each aircraft. The 9Bolt is 3.2 times as efficient, the 19Bolt is 2.6 times as efficient, and the 90Bolt is 2.1 times as efficient as fossil-fueled aircraft of similar passenger capacity.[13] This efficiency improvement will be still higher compared with liquid hydrogen combustion aircraft, which are expected to be slightly less energy efficient than aircraft burning hydrocarbons. (Mukhopadhaya & Rutherford, 2022). This comparison includes the 15% additional energy required to charge electric aircraft due to charging losses.

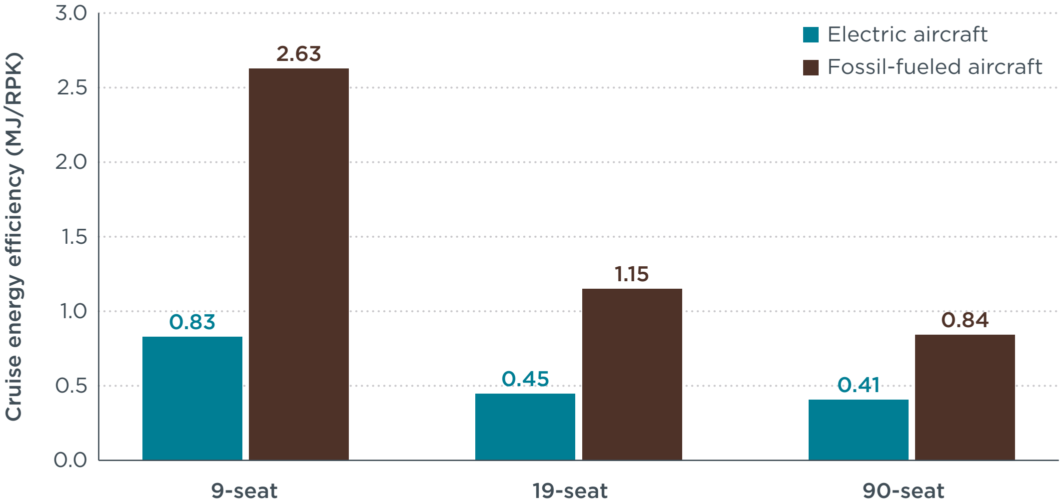

Figure 6. Cruise energy efficiency of electric and fossil-fueled aircraft

Reserve requirements: The large reserve battery requirements merit a closer look. **Figure 7** illustrates the impact on range of various components of mandatory reserves—allowances for contingencies, diversion to an alternate airport, and loitering. While the 9Bolt could theoretically carry 9 passengers 355 km, its mission range is limited to 140 km. The reserve requirements account for 215 km worth of range, or 62% of the battery energy. For the 90Bolt, only 3% of the battery can be used in the mission; 97% of the battery is required for reserves.

Reserves are necessary for the safe operation of the aircraft and are not optional. They highlight the improvements in battery technology needed for electric aircraft to become operationally viable. With higher battery specific energy, as for example in the technology ambition case, the reserves require a smaller percentage of the total battery energy, resulting in longer mission ranges.

13 For the cruise efficiency calculations, the 9Bolt is compared to the Beech King Air 200, the 19Bolt is compared to the British Aerospace Jetstream 41, and the 90Bolt is compared to the De Havilland Canada Dash 8-Q400 (Piano 5).

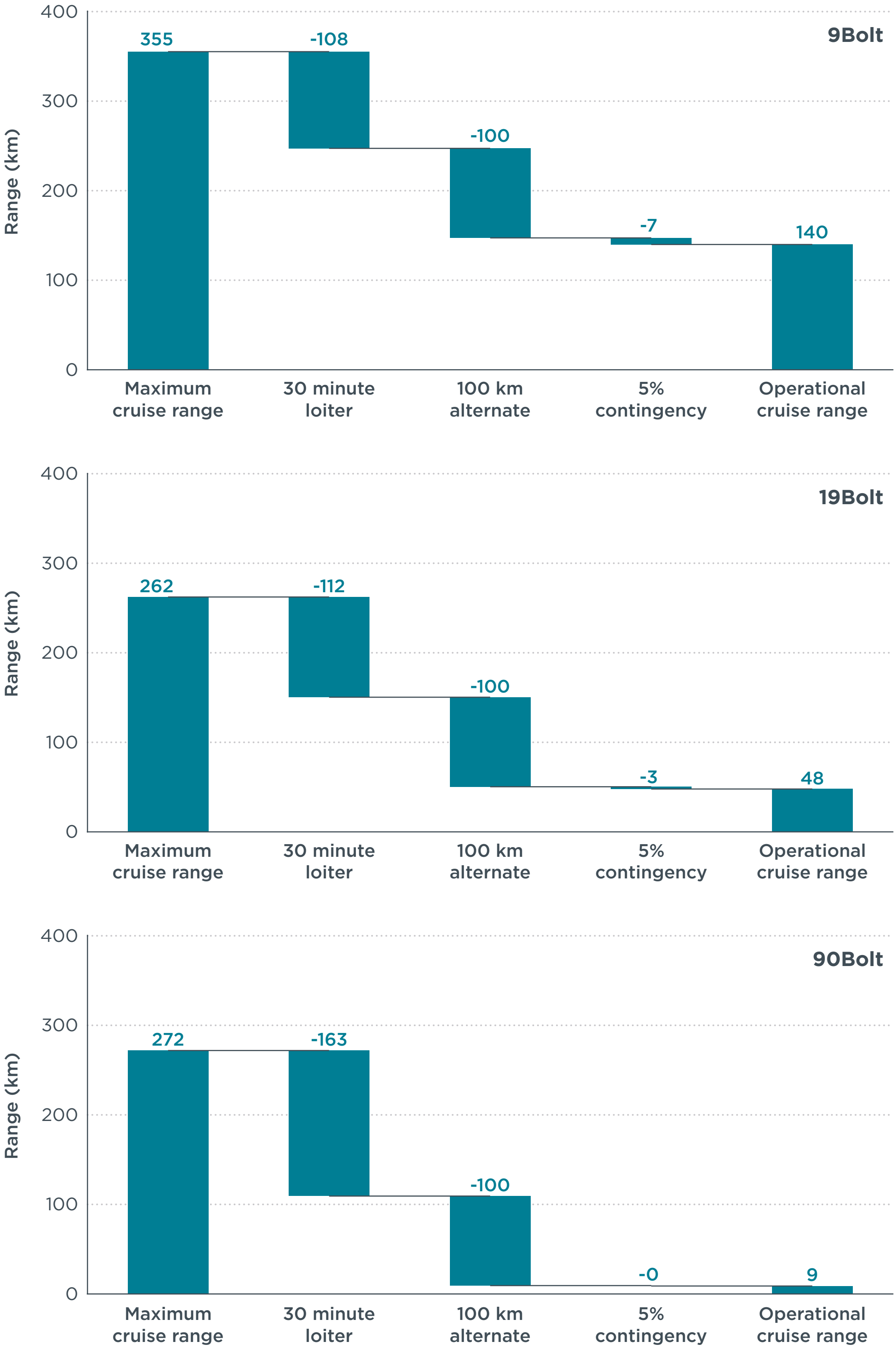

Figure 7. Waterfall plots for the range of the electric aircraft, e_b = 250 Wh/kg

ADDRESSABLE MARKET

Comparing the payload-range capability of these electric aircraft to routes flown in 2019 quantifies the passenger aviation market that could be replaced by these electric aircraft. This requires the use of payload-range diagrams. These diagrams illustrate the trade-off between the number of passengers aboard an aircraft and the range it can fly with that payload. As an extreme example, an aircraft that is completely empty can fly further than one that is completely full.

Figure 8 represents the capability of the electric aircraft to replace commuter (9Bolt and 19Bolt, left panel) and turboprop (90Bolt, right panel) routes. The routes are plotted as individual dots where the x-value represents the distance of the route, and the y-value represents the number of seats available on the aircraft that flew the route. Note that the y-axis values are different for the two adjacent plots. The 90Bolt (right plot) has a higher passenger capacity. The green dots represent routes that lie within the payload-range capability of the electric aircraft with current batteries (e_b = 250 Wh/kg), yellow dots are routes that can be serviced with batteries whose e_b = 500 Wh/kg, and red routes would require even higher e_b.

The payload-range capability of the aircraft with e_b = 250 Wh/kg is represented by solid lines while dotted lines represent capability enabled by batteries achieving e_b = 500 Wh/kg at the pack level. The dotted lines extend further to the right than the solid ones, indicating the longer range enabled by higher e_b values. This significantly increases the routes within the capability of the aircraft.

The range value here refers to the operational cruise range as defined in the Aircraft performance section. It does not account for the increased energy consumption during the takeoff and climb segments, or the reduced energy consumption during the descent and landing segments. This would necessarily reduce the range of the aircraft, so these calculations should be considered optimistic.

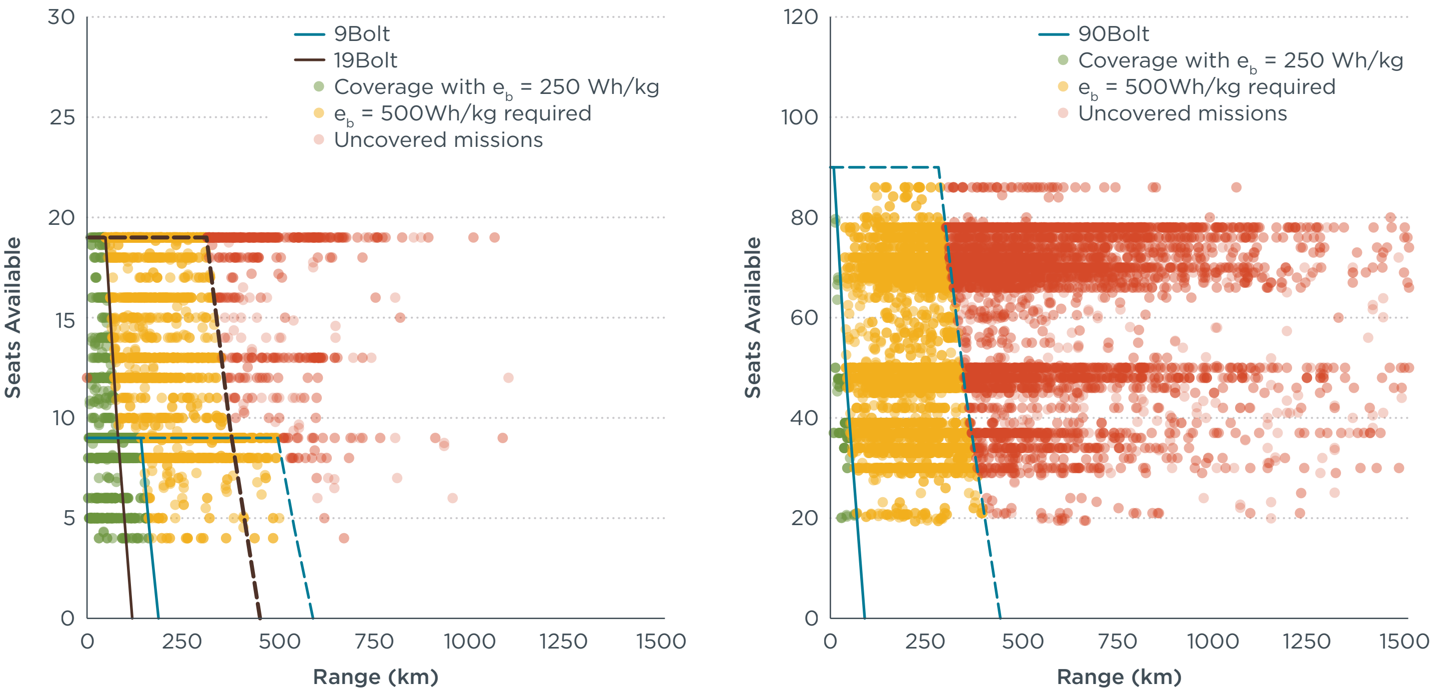

Figure 8. Commuter and turboprop missions that can be serviced by electric aircraft

This relationship between pack-level battery specific energy and the RPK coverage of the commuter and turboprop segments of the aviation market is shown in greater detail in **Figure 9**. Increasing e_b rapidly increases the RPK coverage of the electric aircraft, particularly at lower e_b values. Near-complete replacement of commuter routes and >90% coverage of turboprop is possible if batteries can achieve e_b = 1000 Wh/kg. However, with current battery technology, the 9Bolt and 19Bolt can replace only around 9% of the commuter market while the 90Bolt's serviceable market would be negligible. Improving battery technology has a clear, positive impact on market coverage. With e_b = 500 Wh/kg, commuter RPK coverage would be 65% and turboprop RPK coverage would be 26%. This amounts to 0.21% of the entire passenger aviation market.

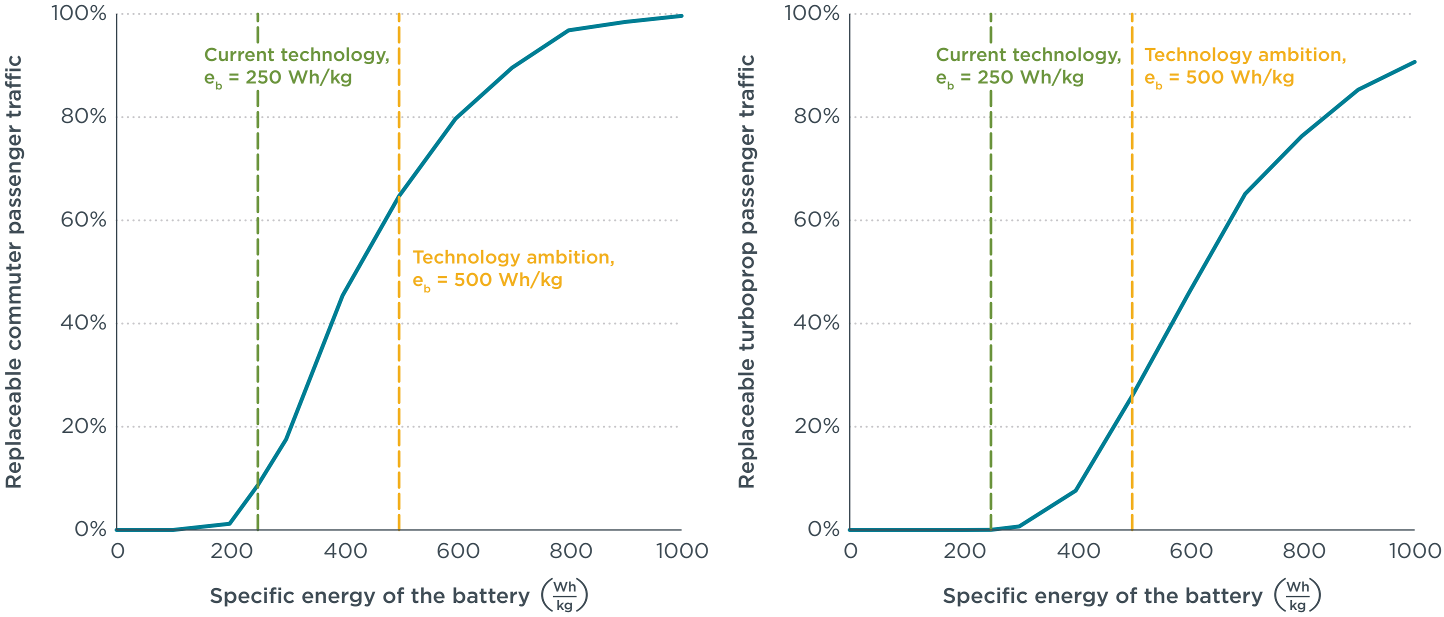

Figure 9. Sensitivity of market coverage to the specific battery energy at the pack level

The replaceable routes are short. While they account for a small percentage of the aviation market in terms of RPK, they represent a larger fraction of departures, which could have important consequences for health. Electric aircraft could account for 1.6–8.4% of global departures depending on battery technology achieving e_b = 250 Wh/kg or e_b = 500 Wh/kg at the pack level. Landing and takeoff operations of fossil-fueled aircraft affect local and regional air quality, primarily due to fine particulate matter emissions. These operations account for 25% of the 16,000 premature deaths attributable to global aviation operations (Yim et al., 2015). Electric aircraft produce no such emissions and would protect airport air quality.

The commitment of Nordic countries to fossil-free flight provides an opportunity to explore the potential of electric aircraft in the context of specific airports. Government-subsidized routes in these countries, known as Public Service Obligation (PSO) or Essential Air Service (EAS) in the US, provide a strong rationale for electrification. The potentially lower operational cost of electric aircraft (Shahwan, 2021) is an opportunity to reduce dependence on government subsidies.

Widerøe, the launch partner for the Tecnam P-Volt (Tecnam, 2021), operates PSO routes in Norway with the largest number originating in Bodø (BOO) (Widerøe, n.d.). **Figure 10** shows the operational cruise ranges of the 9Bolt centered around BOO. The smaller oval represents the 140 km operational cruise range of the 9Bolt with current battery technology (e_b = 250 Wh/kg). The larger oval represents the 495 km operational cruise range when e_b = 500 Wh/kg. All four airports within the small oval—Leknes (LKN), Mo i Rana (MQN), Røst (RET), and Svolvær (SVJ)—are PSO routes serviced by Widerøe. All the PSO routes from Bodø (6 more) lie within the larger oval. Appendix D: A case study of domestic Nordic aviation presents such figures for more airports across the Nordic Countries.

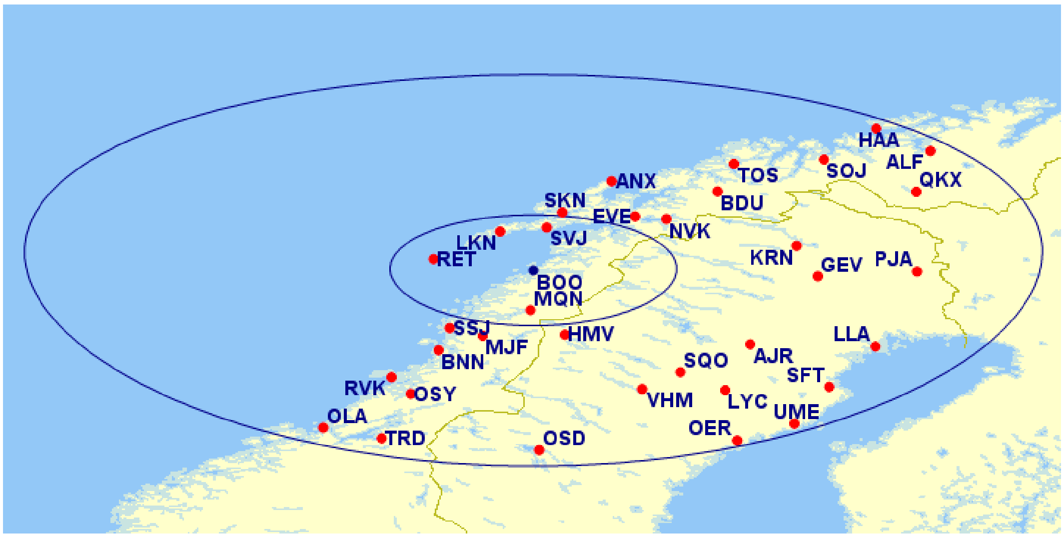

Figure 10. Possible airports served from Bodø Airport (BOO) in Norway based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

PERFORMANCE SENSITIVITY TO EMPTY MASS FRACTION

To investigate the sensitivity of aircraft performance to the EMF, this section presents aircraft performance results for two additional scenarios: no reduction in EMF, and a 30% reduction in EMF.

Using Equation (2), the operational cruise range for these aircraft can be calculated as a function of the EMF and the battery specific energy (e_b). This is shown in **Figure 11**, where the solid line represents the central 15% reduction in EMF case and the shaded region represents the range with higher or lower EMF values. The upper extreme of the shaded regions corresponds to the 30% reduction in EMF case, while the lower extreme of the shaded regions depicts the operational cruise ranges when no reduction in EMF is assumed. Reducing EMF can significantly improve the operational cruise ranges of the aircraft. A 30% reduction in EMF from those achieved by current aircraft increases the operational cruise ranges of these electric aircraft by 170–180 km when e_b=250 Wh/kg, and by 360–380 km when e_b = 500 Wh/kg.

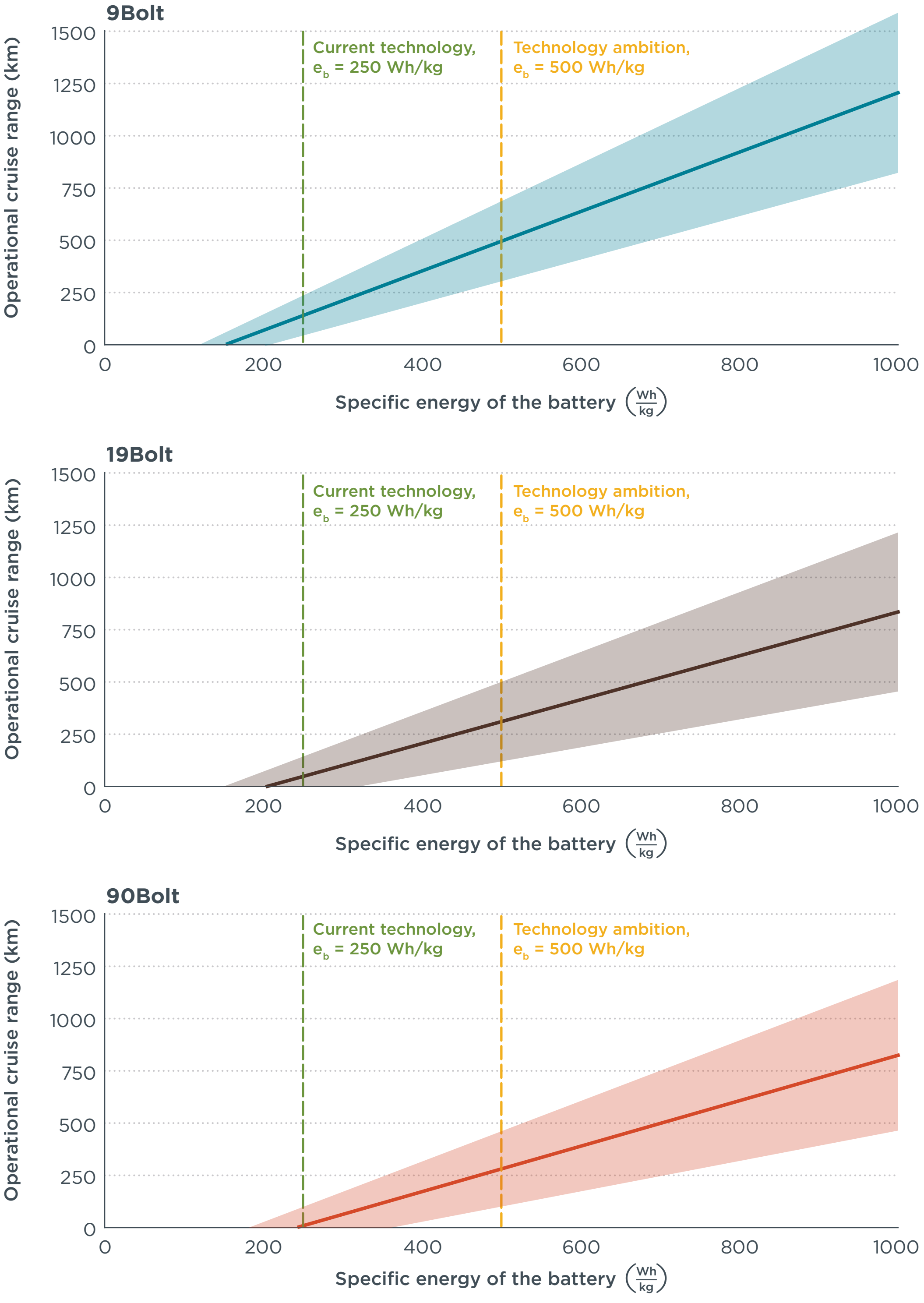

Figure 11. Operational cruise range by empty mass fraction and battery pack-level specific energy

This improvement in range directly translates to an increase in the addressable market for these aircraft. Performing the same payload-range analysis shown in the Addressable market section, the sensitivity of commuter (left) and turboprop (right) market coverage to the EMF and e_b is shown in **Figure 12**. The yellow line represents the middle case of 15% reduction in EMF which is used for most of this study. The red line shows the worst-case scenario where there is no reduction in EMF, while the green line is the optimistic scenario of a 30% reduction in EMF.

As before, increasing the pack-level specific energy of the battery increases the market coverage across all cases. In the optimistic scenario of a 30% reduction in

EMF, replacing the entire commuter market would require specific energies of the battery at the pack level to reach 700 Wh/kg; replacing the entire turboprop market would require specific energies of greater than 1000 Wh/kg. With the lithium-based technologies being developed today, including solid-state batteries, these specific energies will most likely not be achievable on a pack level.[14] Looking specifically at the e_b = 500 Wh/kg case, a 30% reduction in EMF (red line to green line) would increase the commuter market coverage from 24% to 88%, more than tripling the RPK coverage. In the same situation, the turboprop market coverage increases from 2% to 59%.

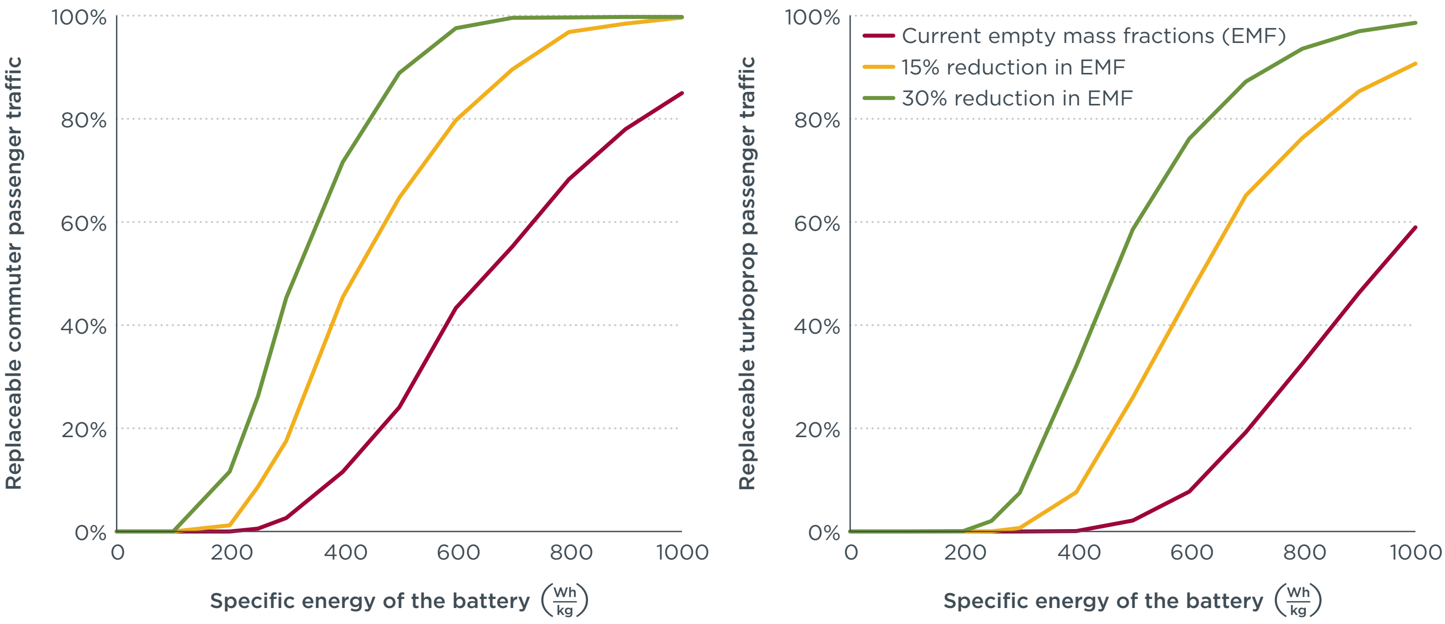

Figure 12. Sensitivity of the addressable market to the EMF and by the battery pack specific energy

Reducing the operating empty weight of the aircraft is a powerful way to improve the performance of electric aircraft without relying on improvements in battery technology. This could be done through extensive use of composites in the structure of the aircraft. Since commuter and turboprop aircraft development has been sidelined with the advent of jet aircraft (Read, 2019), there is room for improvement through the adoption of current state-of-the-art aircraft design practices. For the remainder of this work, we go back to the central case of assuming a 15% reduction in EMF compared to currently certified aircraft.

CO_2 MITIGATION POTENTIAL

Having quantified the addressable market and the relative efficiency of electric aircraft, the CO_2 mitigation potential of the electric aircraft can be calculated. Multiple daily missions and the very high discharge rates at takeoff will require regular battery replacement. Depending on the frequency of flights, electric aircraft could require battery changes every couple of years. Therefore, in quantifying the CO_2 mitigation enabled by electric aircraft, it is of paramount importance to include the carbon intensity of battery production along with the carbon intensity of electricity production.

Figure 13 compares the projected well-to-wake GHG emissions including battery replacement of fossil-fueled and electric aircraft with various electricity generation

14 See discussion in the Battery characteristics section.

scenarios.[15] As noted, these are not the life-cycle emissions of electric and fossil fuel aircraft, as they do not refer to the vehicle lifetime, which would include vehicle production and maintenance emissions, and would consider a continually improving electricity mix. The values refer only to the operation of an aircraft in a given year. In principle, GHG emissions from operating an electric aircraft should decline over time as renewable power sources come to dominate the future grid.

The brown bars represent fossil-fueled aircraft, divided by shading into the fuel production emissions and fuel usage emissions. The yellow bar represents the carbon intensity of the battery manufacturing process. The red and blue bars represent the carbon intensity of generating the electricity to power the electric aircraft using currently stated policies in the US and EU. The green bar represents the best-case scenario where all the electricity is generated using renewable energy. The error bars represent the difference between the carbon intensity of grid electricity under currently stated policies (STEPS) and under a Paris Agreement-compatible grid mix (SDS).

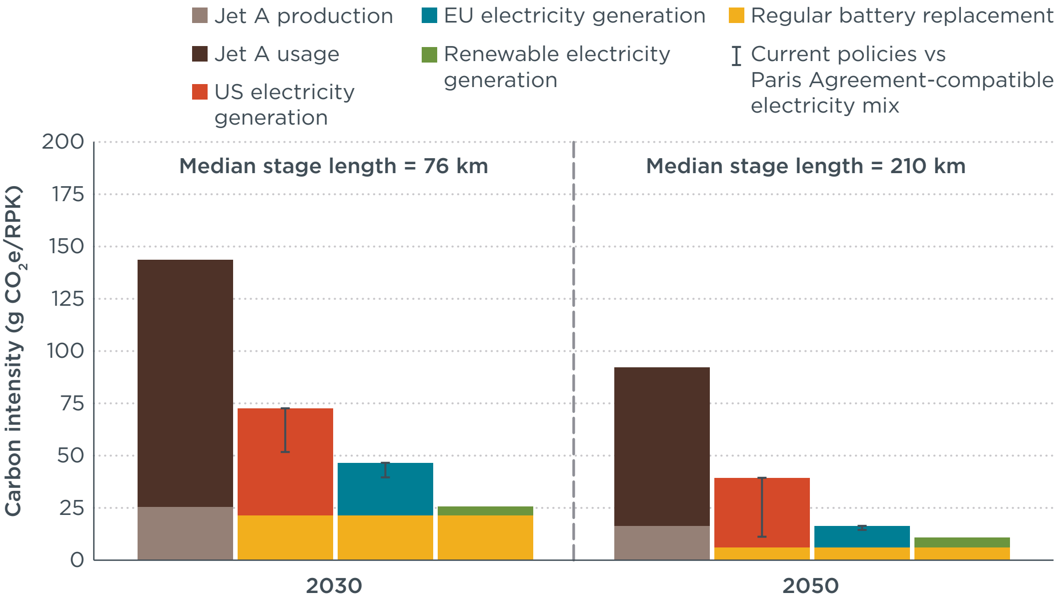

Figure 13. Well-to-wake GHG emissions of electric and fossil-fueled aircraft operations including battery replacement, 2030 and 2050

In 2030, the operation of electric aircraft could provide a 49%–82% reduction in carbon intensity when compared to fossil-fueled alternatives. This increases to a 57%–88% reduction by 2050. The range is bounded by the US STEPS electricity generation and the renewable electricity generation scenarios. The error bars representing the difference in the STEPS and SDS scenarios are larger for the US than for the EU. This indicates the gap between current US policies for grid decarbonization and what is needed to meet the Paris Agreement. In fact, the SDS scenario for the US has a grid carbon intensity lower than the SDS scenario for the EU, indicating the larger potential for renewable energy in the US.

The general trend over time across all fuel situations is a reduction in the carbon intensity of the flights. The increase in the battery e_b increases the length of the missions that can be serviced by electric aircraft. In 2030, the median stage length of the aircraft is 76 km, and it increases to 210 km by 2050. Longer flights are more

15 A 0.5% annual reduction in the fuel burn of fossil-fueled turboprop aircraft is assumed. No fuel efficiency improvements are assumed for the fossil-fueled commuter class aircraft. Because sustainable aviation fuel deployment remains minimal (0.05% of 2020 total aviation fuel use) and difficult to project, for this exercise we assume that future commercial planes continue to operate on Jet A. Additionally, no improvement in propulsive efficiency of electric aircraft is assumed, due to the relative maturity of electric powertrains.

efficient on a per-RPK basis, as the energy-intensive takeoff and climb segments are a smaller proportion of the flight time. This trend is shown in **Figure 14** where both the fossil-fueled and electric aircraft become more efficient as the median stage length of the replaced routes increases.

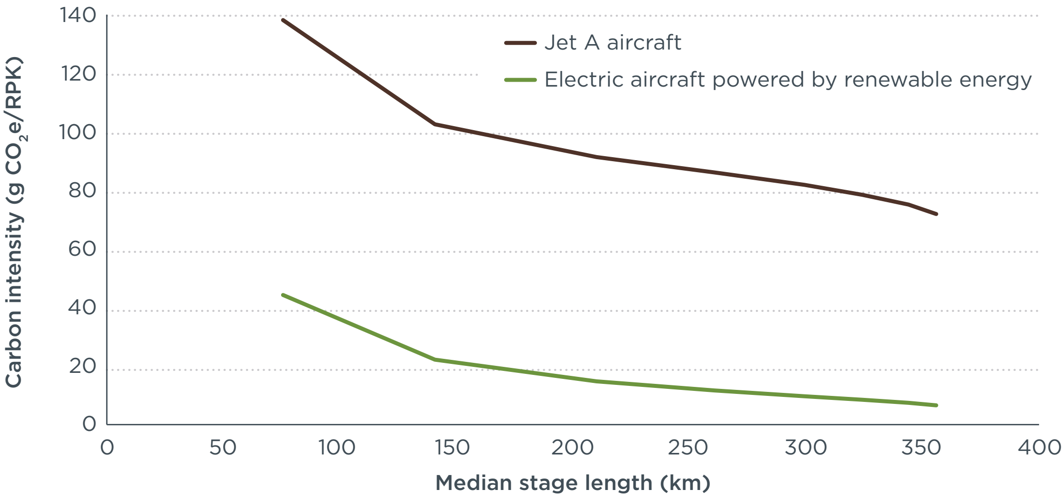

Figure 14. Well-to-wake GHG emissions of electric and fossil-fueled aircraft operations including battery replacement as a function of stage length

In the best-case scenario—where fueling is provided by renewable energy—electric aircraft would reduce carbon intensity by 82%–88%, depending on the median stage length. In this scenario, the battery production process would account for 57%–83% of the carbon intensity of electric aircraft. In the worst-case scenario, in which charging comes from the US STEPS grid mix, electric aircraft would provide a 49%–57% reduction in carbon intensity depending on year. When deployed to their maximum potential,[16] these aircraft could reduce aircraft emissions annually by 3.7 million tonnes (Mt) of CO_2e in 2050. This would be 0.2% of passenger aviation's projected annual emissions of 1,840 Mt of CO_2e in 2050.[17]

ENERGY REQUIREMENT

The electric aircraft modeled in this work would consume 0.2 terawatt-hours (TWh) globally in 2030, growing to 7.4 TWh in 2050. This is the energy equivalent of 15,000 to 620,000 tonnes of kerosene. However, electric aircraft are more energy-efficient, with the 90Bolt requiring about half the energy per RPK of a fossil-fueled aircraft.[18] Accounting for this higher efficiency, electric aircraft could save 32,000 tonnes of kerosene in 2030 and as much as 1.3 million tonnes in 2050.

In a deeply decarbonized future where fossil jet fuel is entirely phased out and replaced by e-kerosene produced using renewable energy, the energy efficiency advantage of electric aircraft would grow further. The energy conversion efficiency of e-kerosene production using direct air capture is 46% (Brynolf et al., 2018). This means that for every unit of energy input into the production process, only 0.46 units of energy output can be expected from e-kerosene. This compounds the benefit of using higher efficiency electric aircraft on suitable routes. Depending on the size

16 Maximum potential refers to all replaceable routes being serviced by electric aircraft with the central 15% reduction in EMF, and the flights being fueled by renewable energy. This is to be expected given internal turnover modeling.

17 Emission projections assume a 3% cumulative average growth rate of passenger traffic and a continuation of historical trends in aircraft efficiency improvements (Graver et al, 2022).

18 Based on cruise efficiency.

of the aircraft, **electric aircraft could use 4.5 to 6.9 times less electricity than an aircraft running on e-kerosene.**

NON-CO_2 IMPACTS

The impacts of aviation emissions are not limited to the warming effect of CO_2 emissions. Particulate matter (PM) emissions have a detrimental effect on health. It is estimated that global aviation operations cause 16,000 premature deaths largely due to secondary PM emissions linked to nitrogen oxides (Yim et al., 2015). Contrail cirrus formation in the aircraft wake and NO_x emissions from the combustion process can compound the warming impact of aviation. Recent studies put the effective radiative forcing of such non-CO_2 emissions at twice that of CO_2 emissions alone (European Union Aviation Safety Agency, 2020).[19]

Battery electric aircraft are truly zero-emission during operation. They do not emit CO_2, nor do they produce any NO_x, water vapor, or particulate matter. This eliminates the non-CO_2 warming impacts and the degradation of air quality. The reduction in air pollution is a significant improvement that can directly reduce the number of premature deaths associated with aviation air pollution. However, in terms of the global warming impacts of non-CO_2 emissions, the types of missions being replaced by electric aircraft (commuter and turboprop missions) operate at lower altitudes where the contrail cirrus formation is unlikely. Consequently, electric aircraft are unlikely to significantly reduce the non-CO_2 warming impacts of aviation.

19 While uncertainties in these estimates are large, the 95% confidence interval for the warming effect of non-CO_2 emissions spans roughly 0.5- to 3.5-times that of CO_2 alone. In other words, at best, aviation's warming impact from non-CO_2 emissions could be 1.5-times that of CO_2 alone; at worst, the warming impact could be 4.5-times that of CO_2 alone.

CONCLUSIONS

We assessed the performance characteristics, operational potential, and CO_2 mitigation potential associated with evolutionary electric-powered aircraft that could enter service by 2030. We modeled three aircraft—the 9Bolt, 19Bolt, and 90Bolt—which can carry 9, 19, and 90 passengers, respectively. This led to the following high-level conclusions.

Electric aircraft can provide a 49% to 88% reduction in CO_2e emissions relative to fossil-fueled reference aircraft. This includes the carbon intensity of the battery production process, which can account for up 80% of GHG emissions from the operation of electric aircraft. Decarbonization of the electric grid and better batteries with higher specific energy reduce the carbon intensity of electric aircraft. By 2050, electric aircraft could mitigate 3.7 Mt of CO_2e annually. This would represent 0.2% of the projected emissions from passenger aviation in 2050.

Electric aircraft can be 2.1 to 3.2 times more energy efficient during cruise. Electric motors convert electricity into propulsive force more efficiently than combusting fossil fuels in an aircraft engine. This difference is pronounced in commuter aircraft that are typically powered by piston engines rather than the turbines that power turboprop aircraft. It is still more pronounced regarding aircraft powered by e-fuels (kerosene or aviation gasoline), which are likely fuel sources in a deeply decarbonized future. In that case, electric aircraft could use 4.5–6.9 times less energy than those running on e-fuels.

Continued improvements in battery technology are needed to make electric aviation feasible. Current battery technology, with a pack-level battery specific energy of 250 Wh/kg, would allow missions of a maximum of 140 km carrying 9 passengers, after accounting for reserves. Nearly doubling the battery specific energy to 500 Wh/kg would increase the mitigation potential of electric aircraft and enable missions of up to 280 km carrying 90 passengers.

Reducing the empty mass fraction of the aircraft could significantly increase aircraft range and expand its addressable market. Reducing the operating empty weight without reducing the maximum takeoff mass allows electric aircraft to carry more batteries. The resulting increase in range improves the market coverage provided by electric aircraft. A 30% reduction in EMF from current aircraft technology would nearly quadruple the market coverage of commuter aircraft and improve the market coverage of turboprop aircraft by a factor of 15.

Overall, the warming mitigation potential of electric aircraft is small due to the limited payload and range capacity. However, being zero-emission during operation and being more energy efficient are key benefits over fossil-fueled aircraft. For this reason, the development of electric aircraft and the required infrastructure is warranted for regions with many short flights. The following policies could help:

Include electricity in the sustainable aviation fuel (SAF) definition for policies like ReFuelEU. The SAF mandates in ReFuelEU, starting at 2% of supply in 2025 and increasing to 63% in 2050, are the most significant climate regulation of the aviation sector to date. Electricity is a near-term renewable fuel of non-biological origin (RFONBO) and as such, should be included in the formal definition of SAF to incentivize the development of electric aircraft and the related infrastructure (Malins, 2020).

Electrify short, government-subsidized routes. These routes are known as Essential Air Service (EAS) in the US and Public Service Obligation (PSO) in the EU. They require government subsidies to ensure the airline operations are profitable while keeping fares reasonable for the small communities they serve. For example, the Widerøe has many Norwegian PSO routes that are short hops of under 100 km (Widerøe, n.d.).These are serviceable by aircraft using current battery technology. Electrification of these routes would provide a blueprint for the electrification of longer and larger flights when battery technology improves.

This study focused on the existing passenger routes that can be replaced by electric aircraft. The lower cost of operation of electric aircraft could make new or previously abandoned routes economically feasible. They could enable “feeder” routes from smaller regional airports to airline hubs. A quantification of these new routes, the modes of transport that they would replace, and the resulting environmental impact need to be assessed. In a similar vein, the environmental impact of electricity-powered urban air mobility, championed by companies such as Joby Aviation, Wisk Aero, and Volocopter, needs to be assessed. These aircraft aim to alleviate road congestion by carrying 1-4 passengers on short routes across urban and suburban areas.

Infrastructure requirements to power electric aircraft at airports have not been addressed in this study. Development of charging infrastructure for aircraft could benefit from existing efforts to electrify airport ground operations. Quantifying the costs and the kinds of charging stations required to provide the rapid turnaround for electric aircraft is an area the ICCT expects to research soon.

Battery electric aircraft have been the sole focus of this research. Hydrogen-powered fuel cells are another way to leverage the efficiency improvements of electric propulsion systems. They sidestep the problem of low specific energy of batteries but must confront the challenges of hydrogen production, storage, and delivery. Investigating the potential performance characteristics and GHG mitigation potential of fuel cell powered aircraft is an opportunity for future work. Design innovations made possible by electric motors, such as distributed propulsion, also merit further investigation.

Electric aircraft will be limited to a small share of passenger aviation. Still, electric aircraft can service short routes and provide zero-emission flights soon. They will be more energy efficient than their hydrocarbon-fueled alternatives. They can reduce carbon emissions on replaceable routes by as much as 95% and would eliminate direct air pollution from aviation.

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APPENDIX A: ELECTRIC RANGE EQUATION

The range of an aircraft (R) can be expressed as the product of the aircraft's velocity (v) and the time spent flying (t):

$$R = v \times t \tag{A1}$$

For an electric aircraft, the time spent flying is the time taken to drain the battery. Given the battery's mass m_b, its specific energy e_b, and the power drawn from it P_b, time to drain the battery is

$$t = \frac{m_b e_b}{P_b} \tag{A2}$$

The overall energy conversion efficiency of the aircraft is defined as

$$\eta_{total} = \frac{P_a}{P_b} \tag{A3}$$

where P_a is the power being used to propel the aircraft forward. This power is used to overcome the resistance offered by the air and is equal to the product of the thrust (T) provided by the propulsion system and the velocity of the aircraft.

$$P_a = T \times v$$

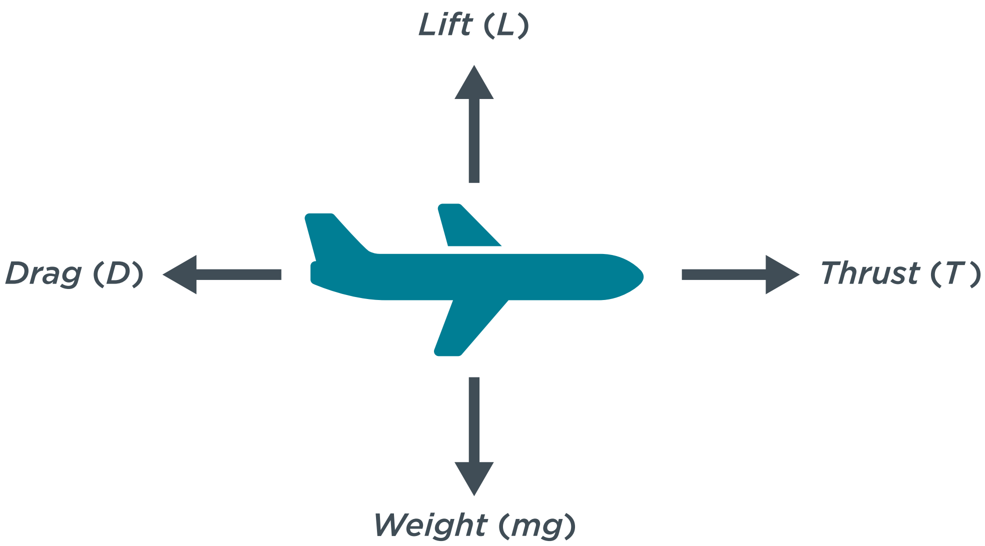

Figure A1. Force balance for an aircraft

Figure A1 presents a simplified force-balance model for aircraft. For constant speed in level flight, all the forces will be balanced. That means the lift generated by the aircraft balances out the aircraft's weight ($L = mg$), while the thrust from the aircraft's propulsion system balances the drag experienced by the aircraft ($T = D$). A key performance metric for an aircraft's design is its lift-to-drag ratio (L/D). A more efficient aircraft design can generate more lift for the same drag and, consequently, has a higher L/D ratio. Putting these together, the thrust required to maintain constant speed level flight can be expressed as:

$$T = \frac{mg}{L/D} \tag{A4}$$

Substituting equations (A2) - (A5) into equation (A1):

$$R = \frac{1}{g} \times L/D \times \frac{m_b}{MTOM} \times e_b \times \eta_{total} \tag{A5}$$

APPENDIX B: EMPTY MASS FRACTION CALCULATION

The empty mass fraction (EMF) of an aircraft is defined as the ratio of the operating empty weight (OEW) and the maximum takeoff mass (MTOM). It is an indication of the aircraft's structural efficiency. A lower empty mass fraction is desirable in an electric aircraft because it allows a higher battery mass fraction (BMF). The BMF is directly proportional to the range of the electric aircraft. Therefore, any reduction in the EMF improves an electric aircraft's range.

The EMFs for the aircraft modeled in this work are calculated using existing aircraft data. **Figure A2** presents the empty mass fractions of current aircraft as a function of their MTOMs. The aircraft are split into two weight classes: $< 10^4 kg$ and $10^4 kg < MTOM < 10^5 kg$. A linear regression provides the average trend for EMF vs. MTOM for each weight class (the solid lines). The electric aircraft's MTOM and the linear regression trend yield an EMF value.

For the central case explored in this study, a 15% improvement in EMF is applied to represent potential weight savings due to a lighter electric propulsion system and the use of composites. These improved EMF values are shown as green dots for each electric aircraft model. To investigate the sensitivity of aircraft performance to the EMF, two additional scenarios are considered: no improvement in EMF, and a 30% improvement in EMF. This range is shown as the green error bars. The corresponding EMF and operating empty weights (OEW) are shown in **Table A1**.

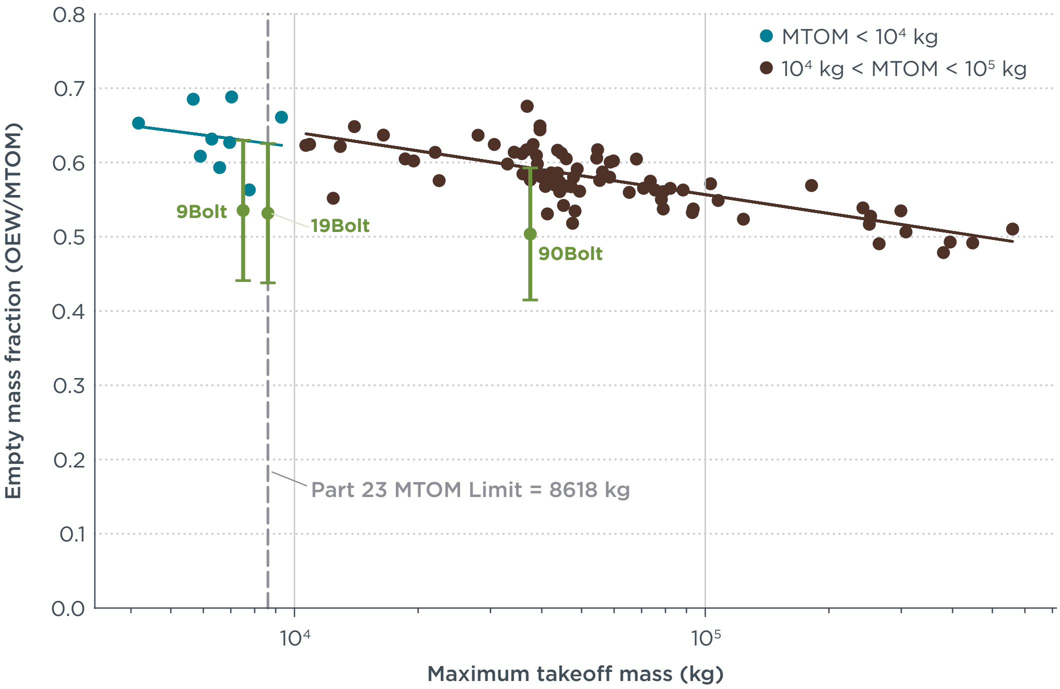

Figure A2. Determining empty mass fractions for electric aircraft

Table A1. Range of empty mass fractions investigated

	9Bolt		19Bolt		90Bolt	
	EMF	OEW (kg)	EMF	OEW (kg)	EMF	OEW (kg)
No reduction in EMF	0.63	4,700	0.63	5,400	0.59	24,000
15% reduction in EMF	0.54	4,000	0.53	4,600	0.50	20,000
30% reduction in EMF	0.44	3,300	0.44	3,800	0.41	17,000

APPENDIX C: LOITER VELOCITY CALCULATION

Loitering at the lowest possible velocity reduces the reserve energy requirement and frees up more battery energy for the mission. The aircraft must produce enough lift to maintain altitude. The lift produced by an aircraft is expressed as

$$L = \frac{1}{2} C_L \rho v^2 S_w \qquad \textbf{(A7)}$$

where C_L is the lift coefficient of the aircraft, S_w is the wing area, ρ is the density of the air, and v is the velocity of the aircraft. To maintain altitude, the lift produced must be equal to the force of gravity on the aircraft, *mg*. This gives us the expression for the required loiter velocity:

$$v_{loiter} = \sqrt{\frac{2mg}{C_L S_w \rho}} \qquad \textbf{(A8)}$$

The mass for the electric aircraft is always the takeoff mass as there is no fuel being combusted to make the aircraft lighter over the duration of the mission. **Table A2** lists the parameters used for the different aircraft and the resulting loiter velocity that is calculated. The assumptions on wing area are based on similar configuration aircraft, and the lift coefficient is chosen to be high, but not too close to stall.

Table A2. Parameters for loiter speed calculation

	9Bolt	19Bolt	100Bolt
Mass (kg)	7,500	8,618	37,500
Wing area, S_w (m^2)	30	35	75
Lift coefficient, C_L		0.9	
Density, ρ(kg/m^3)		1.1	
Loiter velocity, v_{loiter} (m/s)	70	70	98

APPENDIX D: A CASE STUDY OF DOMESTIC NORDIC AVIATION

The Nordic nations of Denmark, Finland, Iceland, Norway, and Sweden have made electrification a focus of their sustainable aviation planning. They created the Nordic Network for Electric Aviation (NEA) to investigate and develop the technology and infrastructure needed to support domestic and regional electric flights. Due to the short flight distances of many domestic routes, electric aviation could be a real option (**Table A3**). Based on 2019 data from ICCT's Global Aviation Carbon Assessment (GACA) model, seven out of ten commercial flights within the Nordic region had distances of 500 km or less (Graver et al., 2020)

Table A3. Share of 2019 departures by flight distance

Route	Flights ≤ 150 km	Flights ≤ 500 km
Denmark domestic *excluding Faroe Islands & Greenland*	33%	100%
Finland domestic	15%	58%
Iceland domestic	20%	100%
Norway domestic	17%	85%
Sweden domestic	2%	70%
Intra-Nordic *excluding Faroe Islands & Greenland*	1%	42%
Total	**11%**	**71%**

An additional boon is the clean electricity available in the region. **Table A4** includes the greenhouse gas (GHG) emission factors for electricity generation in 2019 for the Nordic countries and the five largest European economies (Association of Issuing Bodies (AIB), 2020), as well as the United States (U.S. Environmental Protection Agency (EPA), 2021). Iceland, Norway, and Sweden have large proportions of their electricity coming from renewable sources, leading to low GHG emission factors.

Table A4. GHG emission factors, electricity production, 2019

Country	GHG Emissions [g CO_2e per kWh]
Denmark	154.44
Finland	136.22
Iceland	0.11
Norway	11.18
Sweden	11.89
France	38.95
Germany	378.62
Italy	323.84
Spain	220.26
United Kingdom	226.70
United States	410.93

This Appendix assesses the Nordic routes that could be operated with our 9-passenger 9Bolt electric commuter aircraft with both current battery technology (specific energy of batteries at the pack level (e_b) being 250 Wh/kg) and future ambition (e_b=500 Wh/kg).

Some domestic routes in Finland, Norway, and Sweden are operated under Public Service Obligations (PSOs). These routes are government-subsidized to ensure passenger connectivity. In Norway, nearly all PSOs are operated by Widerøe (Widerøe, n.d.) which has committed to buying the Tecnam P-VOLT (Tecnam, 2021). Based on data for our 9Bolt, more than 40% of Norway's PSOs could be served with current battery technology, increasing to all existing PSO routes with future ambition battery technology. For Finland and Sweden, the PSO routes are longer (European Commission, 2019) and more progress in batteries would be needed to serve them. Under the future ambition scenario, 55% and 83% of current Sweden and Finland PSOs, respectively, could be operated by the 9Bolt.

However, electric aircraft could be used on routes not currently served because of improved economics compared to conventional commuter aircraft. **Figure A3** to **Figure A11** depict routes the 9Bolt could operate from various Nordic airports based on current battery technology (140 km inner ovals) and future ambition (495 km outer ovals). The maps were created from the Great Circle Mapper website.

All domestic flights in Iceland and Denmark (excluding the Faroe Islands and Greenland) could be flown with the 9Bolt under the future battery ambition scenario, as shown in **Figure A3** and **Figure A4**.

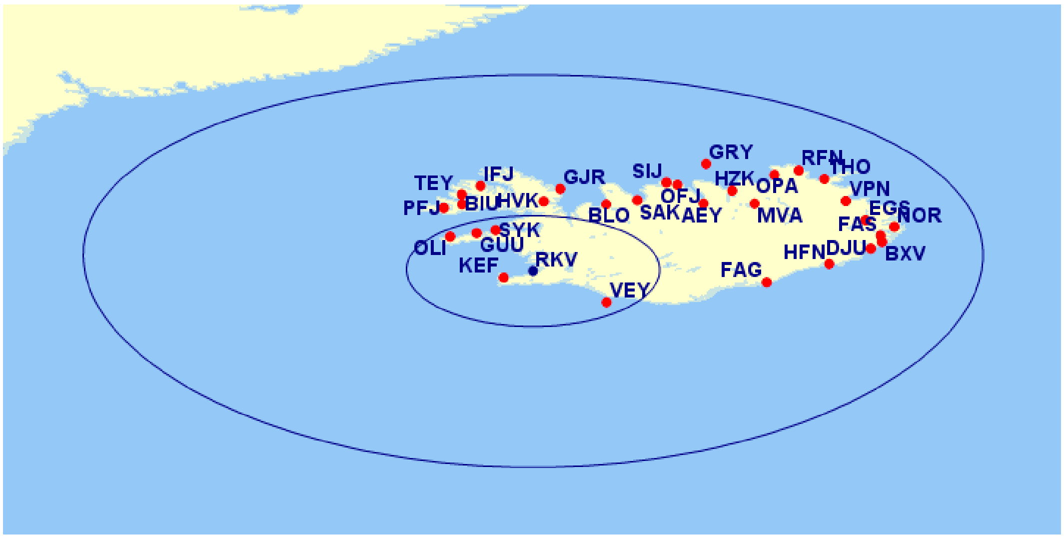

Figure A3. Possible airports served from Reykjavík Airport (RKV) in Iceland based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

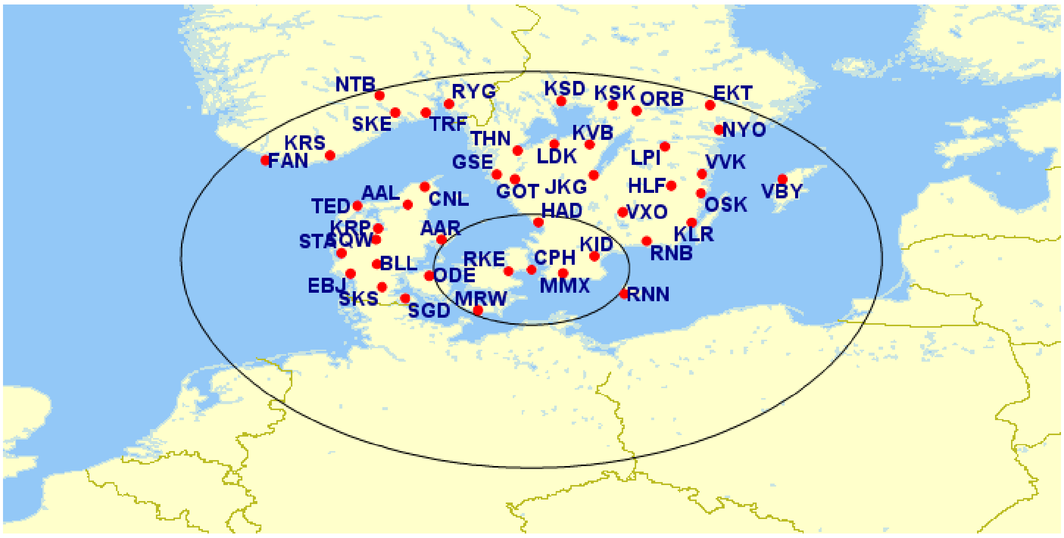

Figure A4. Possible airports served from Copenhagen Airport, Kastrup (CPH) in Denmark based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

Norway would be ideal for deploying electric aircraft under the future battery ambition scenario. Oslo can serve as a hub for electric aviation due to its geographic location, with the ability to serve airports in southern Norway and Sweden and northern Denmark, under current battery technology and future ambition (**Figure A5**). With the inclusion of three other primary airports—Bodø, Tromsø, and Trondheim—the entire length of Norway could be covered, and nearly all of Sweden and northernmost Finland (**Figure A6** to **Figure A8**). From Bodø, four airports in the Lofoten and Vesterålen archipelagos could be reached, given the current battery technology.

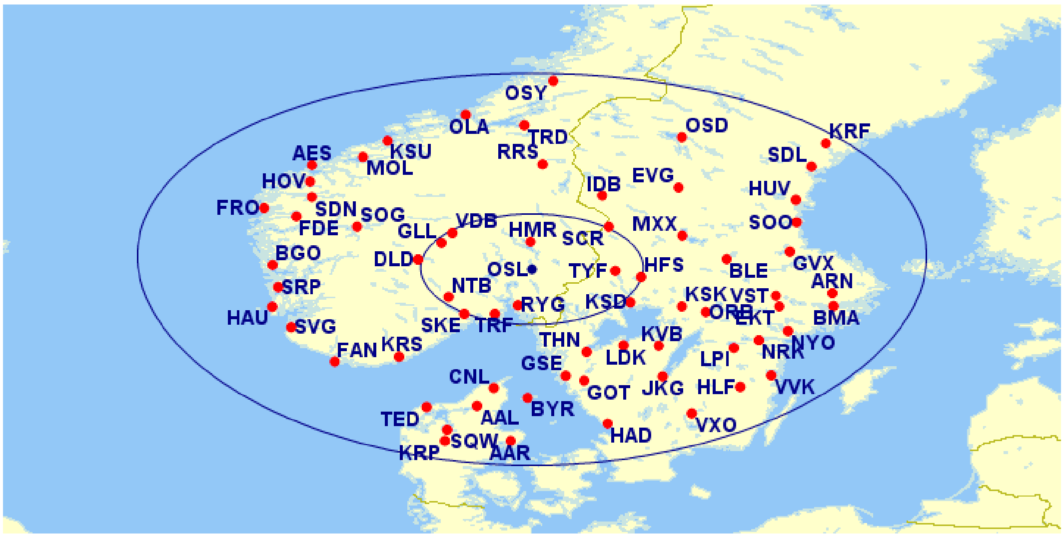

Figure A5. Possible airports served from Oslo Airport, Gardermoen (OSL) in Norway based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

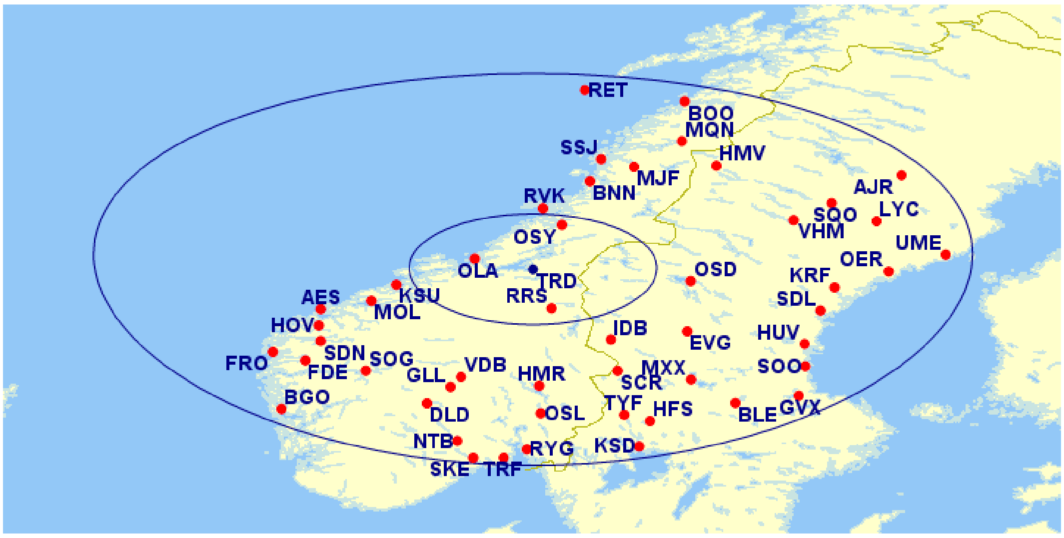

Figure A6. Possible airports served from Trondheim Airport (TRD) in Norway based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

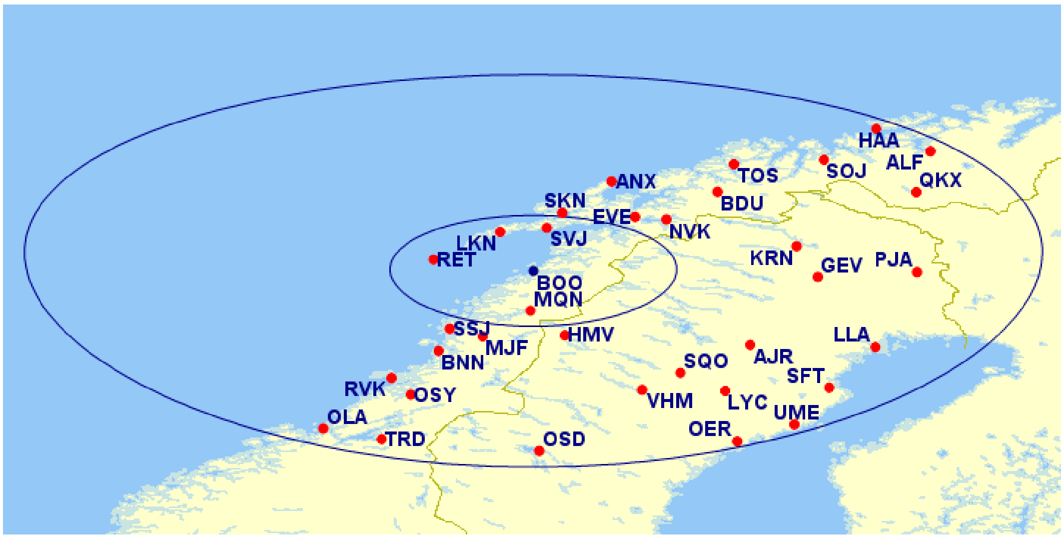

Figure A7. Possible airports served from Bodø Airport (BOO) in Norway based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

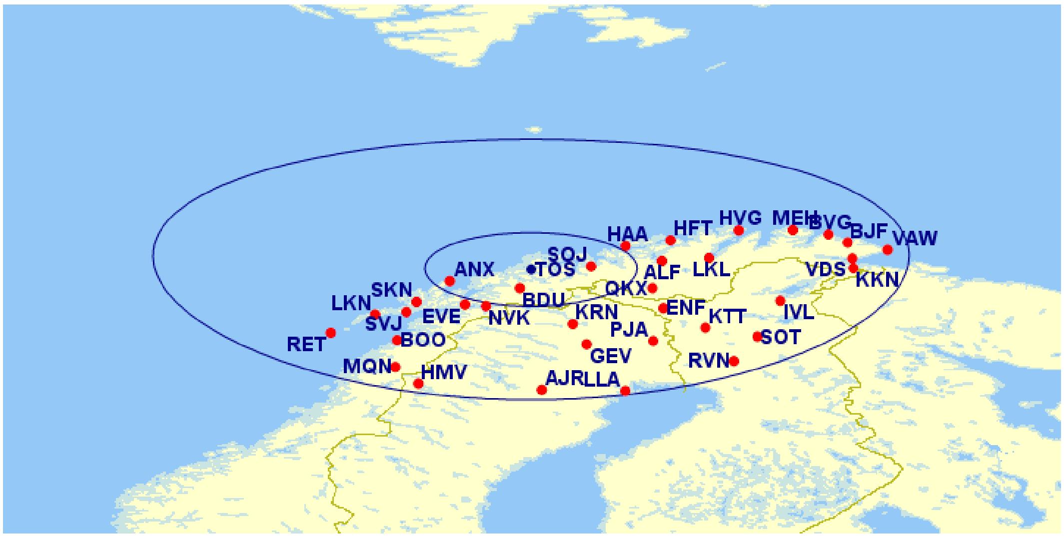

Figure A8. Possible airports served from Tromsø Airport (TOS) in Norway based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

Nearly all Southern Sweden could be served from Stockholm (**Figure A9**) and numerous airports in Finland and Norway (including Helsinki and Oslo).

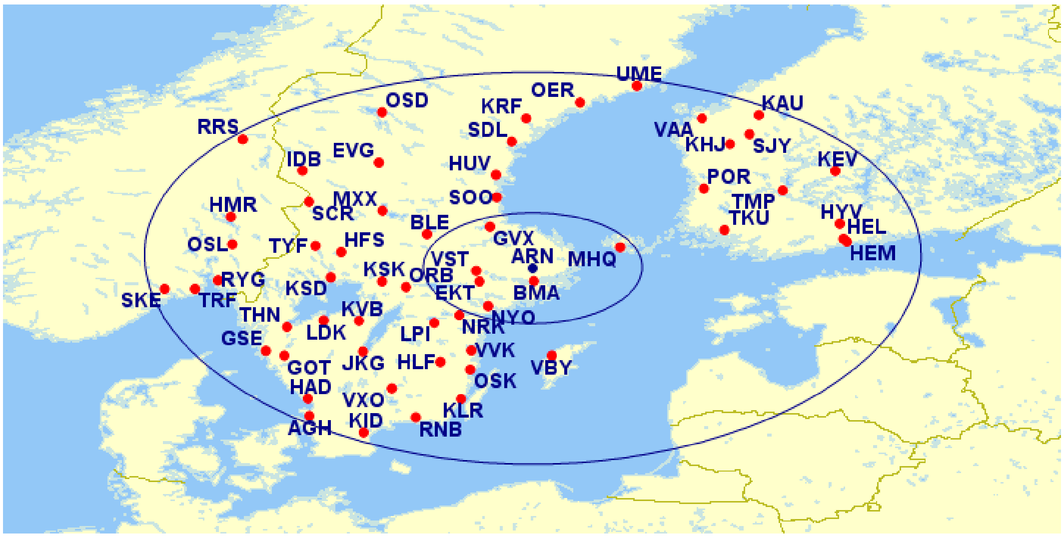

Figure A9. Possible airports served from Stockholm-Arlanda Airport (ARN) in Sweden based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

Once battery technology improves, most of Finland's airports can be reached from just two airports—Helsinki and Oulu (**Figure A10** and **Figure A11**). However, more advancements would be needed to connect these two airports, given a great circle distance of 514 km. Several airports in Sweden could be reached as well.

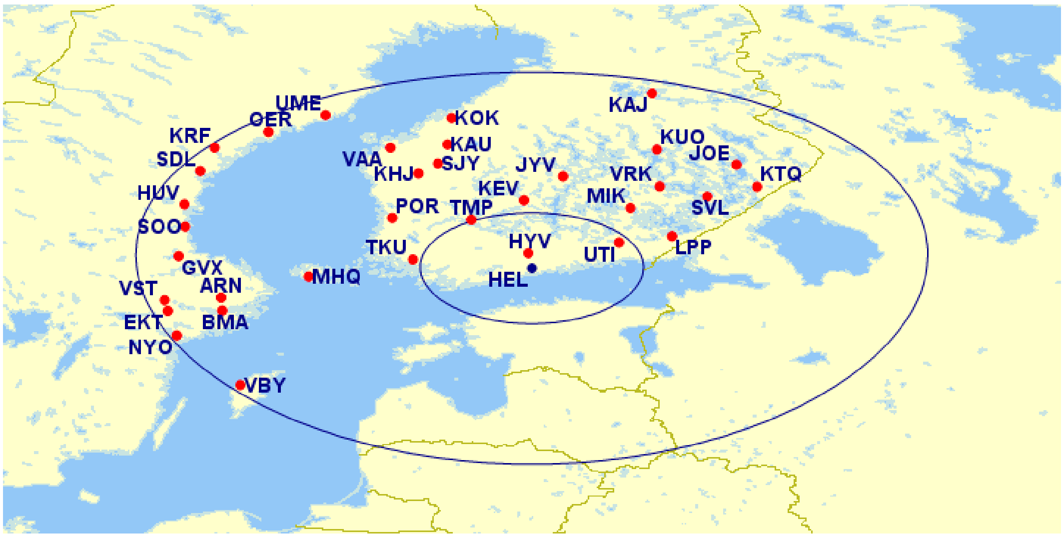

Figure A10. Possible airports served from Helsinki Airport (HEL) in Finland based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)

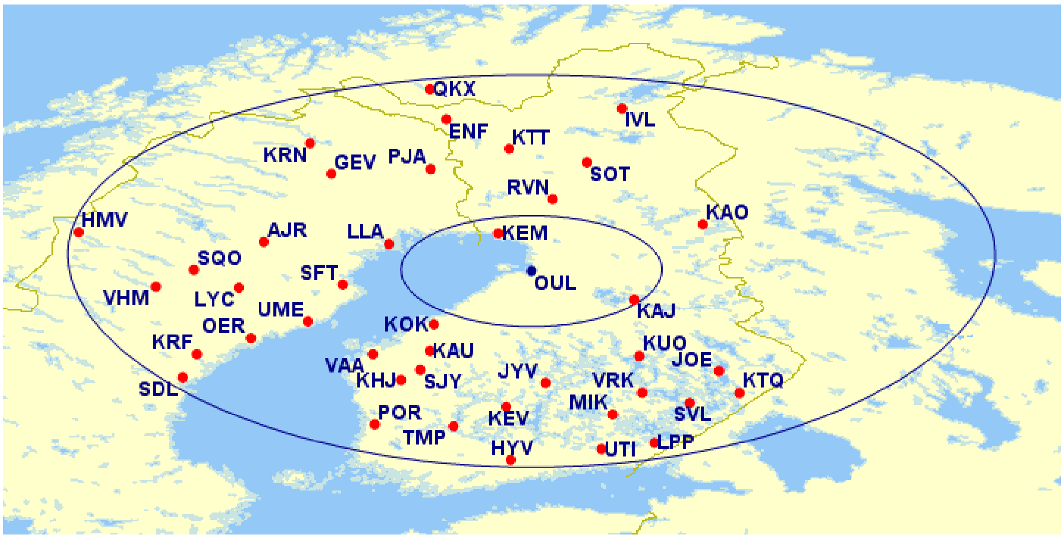

Figure A11. Possible airports served from Oulu Airport (OUL) in Finland based on current battery technology (140 km inner oval) and future ambition (495 km outer oval)