Energy, Economic, and Environmental Prospects of All-Electric Aircraft

Andreas W. Schäfer[1]*, Steven R.H. Barrett[2], Khan Doyme[1], Lynnette M. Dray[1], Albert R. Gnadt[2], Rod Self[3], Aidan O'Sullivan[1], Athanasios P. Synodinos[3], Antonio J. Torija[3]

[1] Air Transportation Systems Laboratory, UCL Energy Institute, University College London, Central House, 14 Upper Woburn Place, London, WC1H ONN, UK.

[2] Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA.

[3] Institute of Sound and Vibration Research, Engineering and the Environment, University of Southampton, Highfield, Southampton SO17 1BJ, UK.

*Correspondence to: a.schafer@ucl.ac.uk

Ever since the Wright Brothers' first powered flight in 1903, commercial aircraft have relied on liquid hydrocarbon fuels. However, the need for greenhouse gas emission reductions along with recent progress in battery technology for automobiles has generated strong interest in electric propulsion in aviation. This work provides a first-order assessment of the energy, economic, and environmental implications of all-electric aircraft. We show that batteries with significantly higher specific energy and lower cost, coupled with further reductions of costs and CO_2 intensity of electricity, are necessary for exploiting the full range of economic and environmental benefits provided by all-electric aircraft. A global fleet of all-electric aircraft serving all flights up to a 400-600 nmi (741-1,111 km) distance would demand an equivalent of 0.6-1.7% of worldwide electricity consumption in 2015. Whereas lifecycle CO_2 emissions of all-electric aircraft depend

on the power generation mix, all direct combustion emissions and thus direct air pollutants and direct non-CO_2 warming impacts would be eliminated.

Introduction

Owing to their high energy content per unit weight and volume, easy handling, global availability, and manageable costs, liquid hydrocarbons have been a key enabler of commercial flight over the past century. In 2015, the global aircraft fleet consumed 276 million tonnes of jet fuel – 7% of global oil products [1].

However, reliance on oil products comes at an environmental cost. Aircraft CO_2 emissions, due to combustion of jet fuel, are 2.7% of energy use-related CO_2 emissions [1, 2]. It is also estimated that the non-CO_2 warming impacts of aircraft are of the same magnitude as CO_2 from aviation, thus approximately doubling aviation's contribution to climate change [3, 4, 5]. The single largest non-CO_2 contributor to warming may be the formation of contrails and contrail-cirrus [3]. In addition, aviation combustion emissions that affect air quality, such as NO_x, are set to rise substantially [6]. This may increase the estimated ~16,000 premature mortalities per year attributable to aviation emissions globally [7]. There is also growing evidence that noise from aircraft results in adverse health impacts and premature mortality amongst affected populations [8].

Various options exist for reducing CO_2 emissions from aircraft. For example, fuel burn per revenue passenger-km (RPK) of the US narrow-body aircraft fleet could be reduced by around 2% per year at no cost through 2050 [9], whereas reductions obtainable for wide-body, long-distance aircraft would likely be smaller. However, these rates will be outpaced by the anticipated global aviation demand growth of around 4.5% per year [10, 11]. In contrast to fuel efficiency improvements, low-carbon fuels (e.g., biofuels) could partially decouple CO_2 emissions from aviation growth, although these options face cost and scale limitations and do not significantly help with non-CO_2 impacts [12, 13], except for a potential thinning of contrails with an uncertain sign of the effect [14, 15]. Similarly, liquid hydrogen [16] and liquified natural gas [17] could greatly reduce direct CO_2 emissions, but these fuels' higher hydrogen content would result in enhanced contrail and cirrus cloud formation.

Until recently, energy carriers that do not entail in-flight combustion have not been considered. This work focuses on all-electric aircraft that have the potential to eliminate both direct CO_2 emissions and direct non-CO_2 impacts, although the net impact will depend on the power generation mix and associated emissions. However, exploiting these unparalleled benefits requires significant technological advances with respect to especially battery performance and cost.

Technology Trajectories Toward All-Electric Aircraft

Two broad technology trajectories appear to lead to all-electric aircraft. The first trajectory builds upon the incremental electrification of jet engines. This class of hybrid-electric aircraft includes designs without batteries (i.e. turbo-electric aircraft), in which the electric propulsion system serves to increase propulsive efficiency and/or provide for some degree of boundary layer ingestion, which entails ingesting and re-energizing the aircraft boundary layer so as to improve efficiency [19, 20]. The extent of fuel burn reductions is then the net effect of the increased propulsive efficiency and the detriment of the additional weight of the electrical components. Hybrid-electric aircraft with batteries are also being considered, where the batteries may provide for additional power or regeneration at limited specific operating conditions. Whereas hybrid-electric aircraft with batteries would entail direct combustion emissions for the majority of flights, they could provide for reduced or eliminated emissions during particularly sensitive parts of a flight – such as flying through ice supersaturated parts of the atmosphere (to reduce contrails) or during takeoff and landing (to reduce near-airport emissions). With sufficient advancements in battery technology, the ultimate design then is an all-electric aircraft, which would have no direct combustion emissions and thus have the potential to remove aviation-specific non-CO_2 impacts and reduce CO_2 emissions depending on the source of the electricity. In contrast, the second technology trajectory builds upon scaling up all-electric air taxis. [21] reports 55 such air vehicle designs, 80% of which being already all-electric. Progress in battery technology, especially specific energy, would then enable scaling up all-electric designs to larger vehicles, first to regional jets and then to narrow-body aircraft.

All-Electric Aircraft Energy Use

Aircraft energy use (E) per revenue passenger-km (RPK) during cruise flight can be described conveniently by the Breguet range equation [22, 23]. Rearranged for energy intensity, equations 1 and 2 report energy use per RPK for jet engine aircraft (JEA) and all-electric aircraft (AEA), with PAX being the number of passengers transported, L/D the lift-to-drag ratio, η_{total} the total (tank-to-wake) efficiency of the jet engine or electric propulsion system, and W the weight of either fuel, the jet engine aircraft at the beginning (i) or the end (f) of the mission, or of the all-electric aircraft at any point during the mission.

$$E/RPK_{JEA} = 1/(\eta_{total,JEA}\, PAX\ L/D)\ W_{Fuel}/ln(W_i/W_f) \quad (1)$$

$$E/RPK_{AEA} = 1/(\eta_{total,AEA}\, PAX\ L/D)\ W_{AEA} \quad (2)$$

Assuming the same passenger count and lift-to-drag ratio between the jet engine and all-electric aircraft, equations 1 and 2 differ by only the propulsion system efficiencies and the weight factor. The latter is about 50-100% larger for all-electric aircraft as a consequence of the relatively low-specific energy batteries [18, 24]. For narrow-body jet engine aircraft W_i/W_f is typically 1.1-1.3; with W_{Fuel} accounting for typically 10-30% of a narrow-body aircraft takeoff weight, the weight factor then roughly corresponds to the narrow-body aircraft takeoff weight. The resulting 50-100% higher energy intensity of all-electric aircraft is being mitigated by the roughly two-fold tank-to-wake efficiency of electric propulsion systems compared to their jet engine counterparts [23, 25]. Note that this calculation does not include the energy use associated with takeoff and climb, nor does it account for the upstream efficiency losses associated primarily with electricity generation. The latter strongly depend on the power generation technology and accounting practices for renewable energy.

A key enabler of electric flight and a critical determinant of energy intensity is the battery pack specific energy. This variable enters the energy intensity of all-electric aircraft in equation 2 via the aircraft weight. If the on-board battery energy supply is kept constant, a higher specific energy leads to a lower all-electric aircraft weight and thus a lower aircraft energy use per revenue passenger-km, which, in turn, yields a longer range. In addition, a lighter aircraft would allow downsizing other components, such as landing gear, motor power, etc., which yield additional energy intensity reductions and range gains.

Today's best available Li-ion battery cells have a specific energy of around 250 Wh/kg [26, 27]. Assuming a packing efficiency of 80%, which is at the lower end of projected future levels [28] and below that of the recently developed Airbus E-Fan [29], the pack-specific energy would result in roughly 200 Wh/kg and 1.7% of the jet fuel energy content. This battery would be capable of powering electric air taxis with 1-4 passengers over a distance of around 100 km [21]. However, short-range electric aircraft demand battery pack specific energies of 750-2,000 Wh/kg, which translates into 6-17% of the jet fuel energy content, depending on aircraft size and range [18, 23, 24, 30, 31]. Much of the required 4-10 fold increase in battery pack specific energy could potentially be achieved with advanced Li-S technology, although Li-air chemistry may ultimately be required for the higher end of that range. Both of these battery technologies have low specific power, so an additional, high-power battery or another means of augmenting power may be required for takeoff and climb.

The historical long-term rate of increase in specific energy of the major battery chemistries has been around 3% per year, a doubling every 23 years [32, 33], although since 2000, specific energy has increased at a rate of 4% per year [33]. Whereas there is no "Moore's Law" equivalent for batteries – since significant advances require entirely new battery chemistries to be made practicable before incremental improvement can occur – this historical observation does suggest that the timescale for such progress to be made could be on the order of decades. Based upon a continuation of the historical increase in specific energy, current levels of specific energy of 250 Wh/kg for advanced Li-ion battery cells, and a packing efficiency of 80%, a battery pack specific energy of 800 Wh/kg could potentially be reached at around midcentury. This is consistent with the timescale of change in the aviation industry – both the infrastructure and aircraft design lifecycles. For the purposes of this work we take the lower end of the above battery pack specific energy range of 800 Wh/kg that is required for Airbus A320/Boeing 737-sized aircraft to be capable of up to 600 nmi (1,111 km) missions, depending on the specific layout and amount of batteries carried [18].

In addition to battery pack specific energy, all-electric aircraft weight is determined by the power-to-weight ratio of the motors and the supporting infrastructure, consisting mainly of cables and power electronics. Whereas regional jets with about 50 seats are likely to require significantly improved mainstream technology, narrow-body aircraft with 100 seats and above may depend upon lightweight high-temperature superconducting electric motors due to the intrinsically high weight of conventional electric motors and the difficulty in providing cooling [34].

Environmental Impacts

All-electric aircraft would completely eliminate direct combustion emissions and thus remove associated direct CO_2 and non-CO_2 warming. The lifecycle CO_2 intensity of all-electric aircraft is determined by the CO_2 intensity of electricity used, losses associated with battery charging and electricity transmission/distribution, and the specific aircraft design and operation. Fig. 1 depicts the warming intensity of a first-generation 180-seat, 150-passenger, all-electric aircraft over a 400 nmi (741 km) mission, which is projected to consume 180 Wh/RPK for a battery pack specific energy of 800 Wh/kg [18]. Using the 2015 average US grid CO_2 intensity of 456 gCO_2/kWh, this all-electric aircraft would generate 91 gCO_2/RPK, if including losses associated with electricity transmission/distribution and battery charging. This value is 22% higher than the lifecycle CO_2 intensity of its modern, jet engine counterparts (the "US" dashed line in Fig. 1). However, if non-CO_2 impacts are taken into account (by way of a factor of two [3-5]), the overall warming per revenue passenger-km would be reduced by 43%. The lifecycle CO_2 intensity of all-electric aircraft would further decline with improved aircraft and battery technology and the potential transition of the grid toward renewable energy. Conversely, a longer range capability would result in a higher energy and thus CO_2 intensity due to the additional battery weight, as visible from equation 2. Note that CO_2 emissions and non-CO_2 impacts (such as cooling related to sulphur emissions from coal-fired power stations [35]) may still occur depending on the power generation mix.

If greenhouse gas (GHG) emissions from battery production were taken into account, the warming intensity of all-electric aircraft shown in Fig. 1 would be slightly larger. Based on Li-ion battery studies, the increase in warming intensity would be 2-10 gCO_2e/RPK, depending upon the assumptions underlying those studies [36]. However, employing end-of-economic life high-performance batteries in stationary applications would significantly reduce these emission levels, as would the enhanced use of renewable electricity for battery production (see Methods section).

In addition to removing direct non-CO_2 impacts, all-electric aircraft would also eliminate direct air pollution. While indirect air pollution may occur depending on the power generation technologies employed, there is greater potential for emissions control for ground-based power generation compared to in-flight combustion.

Noise impacts of all-electric aircraft may be better or worse than conventional aircraft, depending on design decisions made. Assuming a conventional tube and wing configuration, which does not take advantage of the design flexibility offered by electric propulsion, we estimated an overall improved noise performance of all-electric aircraft relying on a battery pack specific energy of 800 Wh/kg compared to best-in-class current-generation short-haul aircraft. Considering both takeoff and landing operations, a 36% reduction in noise contour area is estimated as compared to the best-in-class aircraft (see Methods section). This could allow extended airport operation hours, thus increasing aircraft utilization and airport capacity. During takeoff, aircraft noise is mainly determined by the thrust of the engines required. Due to lower fan pressure ratios and the absence of combustion noise, we anticipate a more than 50% reduction in takeoff noise contour area. In contrast, during landing, the higher weight of all-electric aircraft means that the determinants of noise (principally lift, drag, and landing speed) will result in a 15% larger noise contour area compared to those of best-in-class narrow-body aircraft. Higher battery pack specific energy and future aircraft designs would provide the opportunity for reduced noise through novel aircraft concepts and changes in operational procedures. These include highly distributed propulsion and steep approaches with propulsors in generating mode.

All-Electric Aircraft Economics

Compared to gas turbine engine aircraft, all-electric aircraft will have a different operating cost structure. Over its lifetime, an all-electric aircraft may require several generations of potentially expensive batteries, a factor that contributes to upfront investments (via the first set of batteries) and maintenance costs (via replacement batteries). In addition, its higher weight could increase maintenance requirements of landing gear components. On the other hand, all-electric aircraft may also experience cost savings. For example, they would not require a fuel system or an additional gas turbine (APU) for generating electricity, engine starting, etc. In addition, there may be potential for reductions in engine maintenance costs owing to the relative mechanical simplicity of electric motors, although this is uncertain for narrow-body aircraft due to the challenges of cooling high-temperature superconducting electric motors.

Only taking into account the differences in the largest expenditure items between an all-electric aircraft and a jet engine aircraft in terms of capital costs (energy storage and propulsion system) and maintenance costs (landing gear and battery replacement), Fig. 2 depicts the potential range of breakeven electricity prices for a first-generation Airbus A320/Boeing 737-sized all-electric aircraft with a 400 nmi (741 km) range. Two sets of lines are shown, with each set representing battery costs of 100 and 200 US$/kWh. These costs represent the target and current (2017) level of Li-ion batteries [37]. The set of blue lines represent a battery pack specific energy of 800 Wh/kg, whereas the steeper-sloped pair of red lines indicate 1,200 Wh/kg. At the 2015 US jet fuel price of 1.8 US$/gallon, the breakeven electricity prices of only the all-electric aircraft with a battery pack specific energy of 1,200 Wh/kg and battery costs of 100 US$/kWh would fall within the 2015 US electricity price range of 6.9-12.7 cents/kWh, depending on the end-use sector [38].

According to Fig. 2, a first-generation all-electric aircraft with a battery pack specific energy of 800 Wh/kg and a 400 nmi (741 km) range would only be economically viable with battery costs of around 100 US$/kWh or less and policies that result in significant reductions in electricity prices or increases in jet fuel prices. For example, jet fuel prices would need to be at least 2.8 US$/gallon (118 US$/barrel) to achieve cost-effectiveness in light of the lower end of the 2015 US electricity price range. The conditions required for cost parity with jet engine aircraft are more relaxed for shorter missions and more stringent for longer missions, due to primarily the extra battery weight and its impact on energy use.

Fig. 2 illustrates that a carbon tax of 100 US$/t$CO_2$, which translates into 0.97 US$/gallon of jet fuel, would increase the break-even electricity price of the first-generation all-electric aircraft with a battery pack specific energy of 800 Wh/kg to levels observed within the US, if electricity is produced from renewable sources. This suggests that policies that support both low-carbon electricity and the introduction of a carbon tax may be central prerequisites for introducing all-electric aircraft if today's market conditions prevail until all-electric aviation becomes technically feasible. However, as battery pack specific energy increases and costs of renewable power decline, the cost-effectiveness of all-electric aircraft improves and the need for supportive policies diminishes.

All-Electric Aircraft Adoption Potential

Since advanced batteries with 5-10 times the pack specific energy of today's Li-ion batteries would still contain only 8-17% of the energy content per unit weight of jet fuel (although this does not credit electrochemical storage with the higher energy conversion efficiency compared to gas turbines), all-electric aircraft would be constrained to short-range missions, at least initially. The limitation to short-distance operations of all-electric aircraft can be seen in Fig. 3, which depicts the global air transportation network in 2015 by distance band. The 600 nmi (1,111 km) range (yellow trajectories) could be covered with all-electric aircraft relying on a battery pack specific energy of 800 Wh/kg [18]. Whereas a higher battery pack specific energy could lead to a more integrated flight network, there are technological limits.

Operating beyond distances of 1,200 nmi (2,222 km) in a single-stage flight would require a battery pack specific energy of at least 1,600 Wh/kg [18], which may remain a significant technology challenge for decades to come. From today's perspective, the only way to further expand the all-electric aircraft network by operating over flight distances longer than 1,200 nmi would be via multistage flights with at least one intermediate stop. (This, of course, is contingent on achieving a battery pack specific energy of 800 Wh/kg). However, this strategy would likely lead to reduced travel demand due to the associated increase in travel time. In addition, multistage flights may be limited by airport capacity and noise regulations. Thus, all-electric aircraft operations would likely remain limited to intra-continental traffic, absent significant breakthroughs in battery technology or changes in consumer behaviour.

Yet, a short-range all-electric aircraft market can generate large-scale impacts. As shown in Fig. 4, an all-electric aircraft fleet with a useful range of 600 nmi (1,111 km) could substitute up to 15% of global revenue passenger-km and up to half of global departures. In addition, it could substitute almost 15% of commercial aircraft fuel use and eliminate around 40% of global landing and takeoff (LTO) related NO_x emissions.

Impact on Electricity Generation

Using the aircraft performance characteristics specified by [18], we simulate the electricity demand of a hypothetical, all-electric aircraft fleet operating within the global 2015 flight network. This analysis, using the AIM2015 integrated model [39], suggests that the energy demand by all-electric narrow-body aircraft operating at flight distances up to 400-600 nmi (741-1,111 km) would correspond to 112-344 TWh or 0.6-1.7% of 2015 global electricity consumption (see Methods section). This percentage range reflects the global average of variable country-level data, culminating in slightly higher percentages within the industrialized world of 0.6-2.2% of total US electricity consumption and 1.3-3.7% for the UK.

Assuming that the aircraft batteries for each first morning flight would be charged overnight, around 85% of recharging would occur over the course of a day. This would lead to extra power generation capacity requirements of 1.2-3.6 GW in the UK, 6.6-27 GW in the US, and 31-118 GW globally for aircraft operating ranges of 400-600 nmi, assuming a 35% capacity factor as typical for renewable power systems. If world population and income levels follow the IPCC SSP2 "Middle-of-the-Road" Scenario, the resulting increase in air travel demand would imply that electricity requirements triple by 2050.

Discussion

All-electric aircraft could greatly reduce the environmental impact of aviation. Most importantly, they could eliminate direct CO_2 and non-CO_2 warming, in addition to removing all air pollutants. Moreover, all-electric aircraft have the potential to mitigate noise, especially during takeoff. The extent to which these benefits can be exploited from the global aircraft fleet will depend critically upon battery pack specific energy. All-electric aircraft with battery packs of 800 Wh/kg, enabling a range up to 600 nmi (1,111 km), could replace half of all aircraft departures, mitigate airport area NO_x emissions by 40%, and reduce fuel use and direct CO_2 emissions by 15%. Assuming strong progress in battery technology, aircraft with the two-fold endurance leading to a 1,200 nmi (2,222 km) range, could replace more than 80% of all aircraft departures, mitigate airport area NO_x emissions by more than 60%, and reduce fuel use and direct CO_2 emissions by around 40%. Although a realization of these prospects may fall well into the second half of this century, they seem too large to ignore.

This analysis has shown that future, first-generation all-electric narrow-body aircraft may not be economically competitive to jet engine aircraft under today's market conditions. To reach cost-effectiveness with conventional aircraft, jet fuel prices would need to be in excess of 100 US$/barrel. Conversely, if jet fuel prices remain at their 2015 level, end-use electricity prices would need to be below 4-6 cents/kWh, depending on battery costs, to ensure the economic competitiveness of all-electric aircraft. In addition, today's CO_2 intensity of electricity would lead typically to higher lifecycle CO_2 emission levels compared to jet engine aircraft over the same mission, albeit the total warming impact may be reduced in most parts of the world. Since time scales of mutually reinforcing technologies are measured in decades (i.e., new aircraft design, battery development, electricity grid decarbonization, and sufficiently strong decline in electricity prices from renewable power to increase cost-effectiveness), research and development of critical all-electric aircraft components would need to start immediately in order to exploit the opportunities provided by an all-electric aircraft system in the decades to come. A potential path of manageable risk would be the development first of turbo-electric and then hybrid-electric technology, with the possible exception of all-electric regional aircraft, which can rely on less stringent requirements for battery pack specific energy and power and may not require high-temperature superconducting technology. While these transition technologies will not result in significant reductions of greenhouse gas emissions, they are critical enablers of and technology milestones toward an all-electric aircraft system.

References

1 International Energy Agency (IEA), 2017. *World Energy Statistics 2017*.

2 International Energy Agency (IEA), 2017. *CO_2 Emissions from Fuel Combustion 2017*.

3 Lee, D.S., *et al*., 2009. Aviation and global climate change in the 21st century. Atmos. Environ. **43**, 3520–3537.

4 Dorbian, C.S., Wolfe, P.J., Waitz, I.A., 2011. Estimating the climate and air quality benefits of aviation fuel and emissions reductions. Atmos. Environ. **45**, 2750-2759.

5 Brasseur, G.P., *et al*., 2016. Impact of Aviation on Climate: FAA's Aviation Climate Change Research Initiative (ACCRI) Phase II. Bulletin of the American Meteorological Society.

6 European Aviation Safety Agency (EASA), 2016. *European Aviation Environmental Report 2016*.

7 Yim, S.H.L., *et al*., 2015. Global, regional and local health impacts of civil aviation emissions. Environ. Res. Lett. **10**, 034001.

8 Wolfe, P.J., Kramer, J.L., Barrett, S.R.H., 2017. Current and future noise impacts of the UK hub airport. J. Air Transp. Manag. **58**, 91–99.

9 Schäfer, A.W., Evans, A.D., Reynolds, T.G., Dray, L., 2016. Costs of mitigating CO_2 emissions from passenger aircraft. Nature Clim. Change **6**, 412–417.

10 Airbus, 2017. *Global Market Forecast 2017-2037*. Airbus Commercial Aircraft, Toulouse, France.

11 Boeing, 2017. *Current Market Outlook 2017-2036*. Boeing Commercial Airplanes, Seattle, WA, USA.

12 Bann, S.J., *et al.,* 2017. The costs of production of alternative jet fuel: a harmonized stochastic assessment. Bioresource Technol. **227**,179–187.

13 Stratton, R.W., Wolfe, P.J., Hileman, J.I., 2011. Impact of Aviation Non-CO_2 Combustion Effects on the Environmental Feasibility of Alternative Jet Fuels. Environ. Sci. Technol. **45**,10736–10743.

14 Moore, R.H., *et al*., 2017. Biofuel blending reduces particle emissions from aircraft engines at cruise conditions. Nature **543**, 411–415.

15 Caiazzo, F., Agarwal, A., Speth, R.L., Barrett, S.R.H., 2017. Impact of biofuels on contrail warming. Environ. Res. Lett. **12**, 114013.

16 Brewer, G.D., 1990. *Hydrogen Aircraft Technology*, CRC Press.

17 Withers, M.R., *et al*., 2014. Economic and environmental assessment of liquified natural gas as a supplemental aircraft fuel. Prog. Aerosp. Sci. **66**, 17–36.

18 Gnadt, A.R., 2018. *Technical and Environmental Assessment of All-Electric 180-Passenger Commercial Aircraft*. S.M. Thesis, Massachusetts Institute of Technology.

19 Drela, M., 2009. Power Balance in Aerodynamic Flows. AIAA Journal **47**, 1761–1771.

20 Hall, D.K., *et al*., 2017. Boundary Layer Ingestion Propulsion Benefit for Transport Aircraft. J. Propul. Power **33**, 1118–1129.

21 Datta, A., 2018. *Commercial Intra-City On-Demand Electric-VTOL Status of Technology*. Pre-publication copy, University of Maryland at College Park.

22 Lee, J.J., Lukachko, S.P., Waitz, I.A., Schäfer, A., 2001. Historical and Future Trends in Aircraft Performance, Cost, and Emissions. Annu. Rev. Energ. Env. **26**, 167–200.

23 Hepperle M., 2012. Electric Flight – Potential and Limitations. DLR Electronic Library, German Aerospace Centre. https://elib.dlr.de/78726/

24 Hornung, M., Isikveren, A.T., Cole, M., Sizmann, A., 2013. Ce-Liner – Case Study for eMobility in Air Transportation. 13th AIAA Aviation Technology, Integration, and Operations Conference, Los Angeles, CA, USA. https://doi.org/10.2514/6.2013-4302

25 Delhaye, J.L., Rostek, P., 2015. Electrical Technologies for the Aviation of the Future. Europe-Japan Symposium, Tokyo, Japan.

26 Panasonic, 2012. Panasonic Lithium Ion NCR18650B.

27 Muenzel, V., et al., 2015. A Comparative Testing Study of Commercial 18650-Format Lithium-Ion Battery Cells, Journal of The Electrochemical Society, **162**, A1592-A1600.

28 Dever, T.P., et al. 2015. Assessment of Technologies for Noncryogenic Hybrid Electric Propulsion. NASA Glenn Research Center, Cleveland OH.

29 Airbus, 2015. *E-FAN, The New Way to Fly*. Airbus Group, Corporate Technical Office, Munich.

30 Bradley, M.K., Droney, C.K., 2011. *Subsonic Ultra Green Aircraft Research: Phase I Final Report*, NASA/CR-2011-216847. Boeing Research & Technology, Huntington Beach, CA, USA.

31 Bradley, M.K., Droney, C.K., 2012. *Subsonic Ultra Green Aircraft Research Phase II: N+4 Advanced Concept Development*, NASA/CR-2012-217556. Boeing Research & Technology, Huntington Beach, CA, USA.

32 Koh, H., Magee, C.L., 2008. A functional approach for studying technological progress: Extension to energy technology. Technol. Forecast. Soc. **75**, 735–758.

33 Crabtree, G., Kócs, E., Trahey, L., 2015. The energy-storage frontier: Lithium-ion batteries and beyond. MRS Bulletin **40**, 1067-1076.

34 Sinsay, J.D., *et al*., 2012. 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, USA. https://doi.org/10.2514/6.2012-5404.

35 Unger, N., *et al*., 2010. Attribution of climate forcing to economic sectors. Proceedings of the National Academy of Sciences **107**, 3382–3387.

36 Kim, H.C., *et al*., 2016. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis, Environ. Sci. Technol. **50**, 7715−7722.

37 Chediak, M., 2017. The Latest Bull Case for Electric Cars: the Cheapest Batteries Ever. Bloomberg, https://www.bloomberg.com/news/articles/2017-12-05/latest-bull-case-for-electric-cars-the-cheapest-batteries-ever.

38 Energy Information Administration (EIA), 2017. United States Electricity Profile 2015 – Table 1. 2015 Summary statistics (United States), https://www.eia.gov/electricity/state/unitedstates/

39 Dray, L.M., 2018. AIM2015 Documentation. Air Transportation Systems Laboratory, UCL. http://www.atslab.org/wp-content/uploads/2018/08/AIM-2015-Documentation-v9-30082018.pdf

40 Piano-X, 2010. http://www.lissys.demon.co.uk/PianoX.html

41 Schäfer, A.W., Heywood, J.B., Jacoby, H.D., Waitz, I.A., 2009. *Transportation in a Climate-Constrained World*, MIT Press.

42 Sabre, 2017. Market Intelligence Schedule and Passenger database. https://www.sabreairlinesolutions.com/home/software_solutions/product/market_competitive_intelligence/

43 Dray, L.M., Schäfer, A.W., Al Zayat, K., 2018. The Global Potential for CO_2 Emissions Reduction from Jet Engine Passenger Aircraft. Transp. Res. Record, 1-12. Paper Number 18-04002.

44 Reynolds, T.G., *et al*., 2007. Modelling Environmental and Economic Impacts of Aviation: Introducing the Aviation Integrated Modelling Project. Proceedings of the 7th AIAA/ATIO Conference, 2007. https://doi.org/10.2514/6.2007-7751

45 Eurocontrol Experimental Centre, 2016. Aircraft noise and performance (ANP) database v2.1. [Online]. Available: http://www.aircraftnoisemodel.org

46 Synodinos, P.A., Self, R.H., Flindell, I.H., Torija, A.J., 2015. Estimating variation in community noise due to variation in aircraft operations. Proceedings of the 10th European Congress and Exposition on Noise Control Engineering (EURONOISE), Maastricht, NL 31 May 2015-3 June 2015.

47 Synodinos, P.A., Self, R.H., Torija, A.J., 2016. A new method for estimating community noise changes due to aircraft technology variations. Proceedings of the 23rd International Congress on Sound and Vibration (ICSV), Athens, Greece, 10-14 July 2016.

48 Synodinos, P.A., Self, R.H., Torija, A.J., 2018. A framework for predicting Noise-Power-Distance curves for novel aircraft designs. J. Aircraft **55**, 781-791.

49 Synodinos, P.A., Self, R.H., Torija, A.J., 2017. Noise assessment of aircraft with distributed electric propulsion using a new noise estimation framework. Proceedings of the 24th International Congress on Sound and Vibration (ICSV), London, UK, 24-27 July 2017.

50 Liu, C.X., Teng, J., Ihiabe, D., 2016. Method to explore the design space of a turbo-electric distributed propulsion system. J. Aerospace Eng. **29**, 04016027.

51 Synodinos, P.A., 2017. *A new framework for estimating the noise impact of novel aircraft*. PhD Thesis, University of Southampton.

52 Huff, D.L., Henderson, B.S., Envia, E., 2016. A first look at electric motor noise for future propulsion systems. Oral/visual presentation GRC-E-DAA-TN31506, NASA Glenn Research Center, Cleveland, Ohio, USA.

53 Torija, A.J., Self, R.H., Flindell, I.H., 2017. A Model for the Rapid Assessment of the Impact of Aviation Noise Near Airports. J. Acoust. Soc. Am. **141**, 981–995.

54 Kim, H.C., *et al*., 2016. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-ion Battery: A Comparative Analysis. Environ. Sci. Technol. **50**, 7715−7722.

55 Ager-Wick Ellingsen, L., Singh, B., Hammer Strømman, A., 2016. The size and range effect: lifecycle greenhouse gas emissions of electric vehicles. Environ. Res. Lett. **11**, 1-8.

56 FlightGlobal, 2017. Ascend Fleets. [Online] Available at: ttps://www.flightglobal.com/products/

57 Howell, D., Cunningham, B., Duong, T., Faguy, P., 2016. Overview of the DOE VTO Advanced Battery R&D Program. US Department of Energy, Vehicle Technologies Office.

58 Fancher, D., 1999. Defining Technologies for the next Millennium. GE Aircraft Engines.

59 Hoelzen, J., *et al*., 2018. Conceptual Design of Operation Strategies for Hybrid Electric Aircraft. Energies **11**, 217.

60 Schiferl, R., Flory, A., Livoti, W.C., Umans, S.D., 2008. High-Temperature Superconducting Synchronous Motors: Economic Issues for Industrial Applications. IEEE T. Ind. Appl. **44**, 1376-1384.

61 Haran, K.S., *et al.*, 2017. High power density superconducting rotating machines—development status and technology roadmap. Supercond. Sci. Tech. **30**, 123002.

62 Aircraft Commerce, 2017. Maintenance and Engineering. [Online] Available at: http://www.aircraft-commerce.com/default.asp

63 US Bureau of Transportation Statistics, 2017. Air Carrier Financial: Schedule P-5.2. [Online] Available at: https://www.transtats.bts.gov/DL_SelectFields.asp

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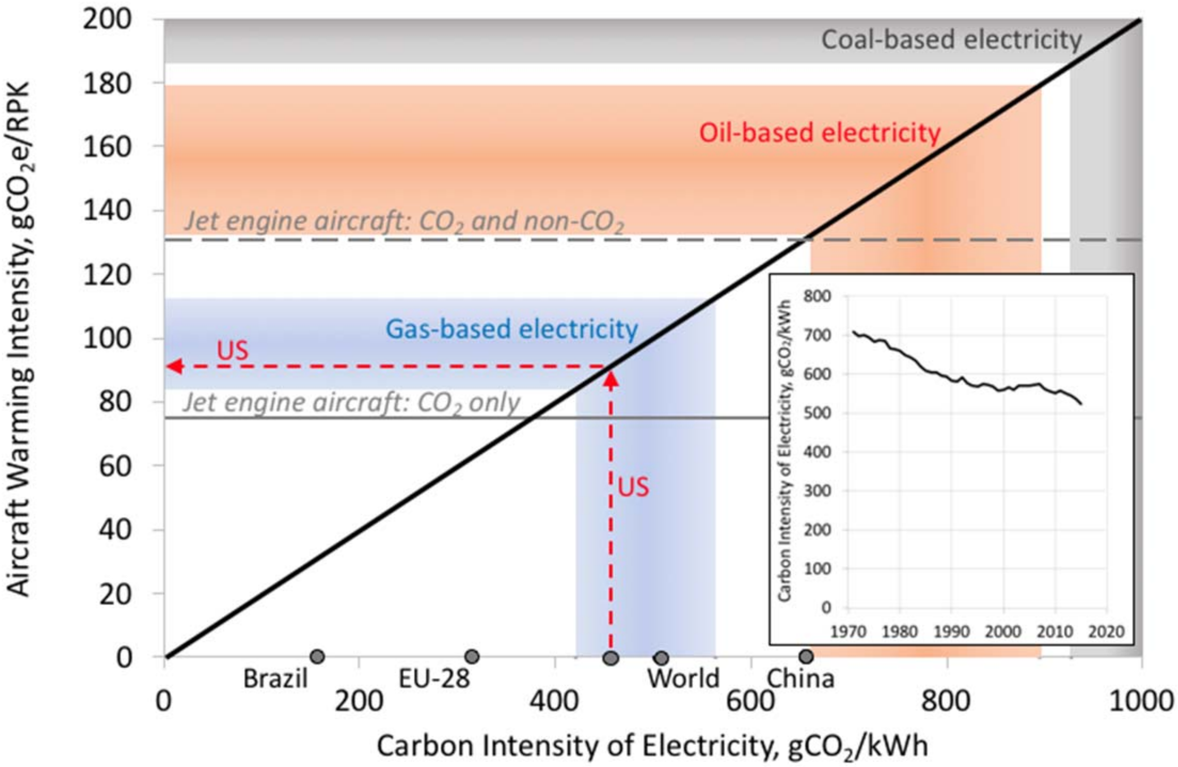

Fig. 1. Warming intensity of a projected first-generation all-electric aircraft with an electricity intensity of 180 Wh/RPK and current-generation jet engine aircraft (A320neo) vs. carbon intensity of electricity for a 400 nmi (741 km) mission. The lifecycle CO_2 intensity of all-electric aircraft is based on a design in [18] and takes into account efficiencies of 95% for battery charging and 95% for electricity transmission/distribution. In contrast, the lifecycle CO_2 intensity of the A320neo of 75 gCO_2/RPK is based on an energy intensity of 0.9 MJ/RPK, calculated with the aircraft performance model Piano-X [40], and a well-to-tank efficiency of 88% [41]; its warming intensity corresponds to two times its direct CO_2 emissions. The shaded areas represent the interquartile range of the CO_2 intensity of coal (limited to 1,000 gCO_2/kWh), oil, and natural gas-based electricity on a country basis in 2015 [2]. The 2015 electricity fuel mix in Brazil, the EU-28, the US, and the world average would lead to a lower warming intensity of all-electric aircraft compared to jet engine aircraft (two times the CO_2 intensity), as exemplified by the dashed red arrows for the US. If only considering long-lived CO_2 emissions, the CO_2 intensity of

all-electric aircraft would be below that of their jet engine counterparts for the 2015 EU-28 and Brazilian fuel mix, but larger in the US, China, and the world as a whole. Meeting the Paris Climate Agreement requires significantly stronger reductions in the CO_2 intensity of electricity as experienced historically (see inlay), which would lead to a proportional decline in the CO_2 intensity of all-electric aircraft.

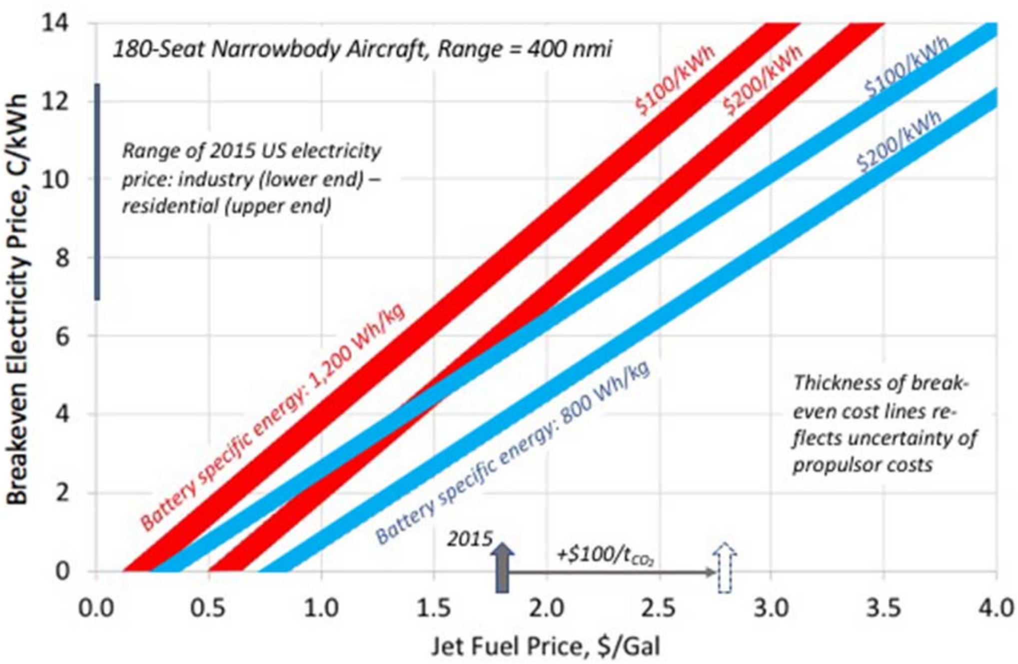

Fig. 2. Break-even electricity price for a first-generation all-electric aircraft. The reference jet engine aircraft is an A320neo. The all-electric aircraft has batteries with a specific energy of 800 Wh/kg (blue lines) or 1,200 Wh/kg (red lines), each with battery costs of 100 or 200 US$/kWh.

On the basis of a battery pack specific energy of 800 Wh/kg, jet fuel prices would need to be at least 2.3 or 2.8 US$/gallon (97 or 118 US$/barrel) – depending on the cost of the battery – in order to achieve cost-effectiveness relative to jet engine aircraft in light of the 2015 US electricity end-use prices. Whereas the 2015 US jet fuel price of 1.8 US$/gallon would lead to breakeven prices below the range of the observed end-use electricity prices in the US, a CO_2 price of 100 US$/t$CO_2$ (0.97 US$/gallon of jet fuel) would lead to breakeven electricity prices within the range of observed end-use electricity prices (provided electricity is produced on a carbon-neutral basis). If taking into account non-CO_2 impacts on the basis of an "uplift factor" of 2, corresponding to a GHG emissions price of 200 US$/t$CO_2$e, the cost-effectiveness would further increase. It is apparent that battery costs would need to be around 100 US$/kWh or less to achieve cost-effectiveness over the longer term. About the same battery cost target exists for automobiles, albeit at a significantly lower specific energy, to achieve cost parity with internal combustion engine vehicles [37]. More advanced batteries with a higher specific energy, more advanced aircraft designs, and repurposing end-of-life batteries for use in other sectors would improve the economics of all-electric aircraft.

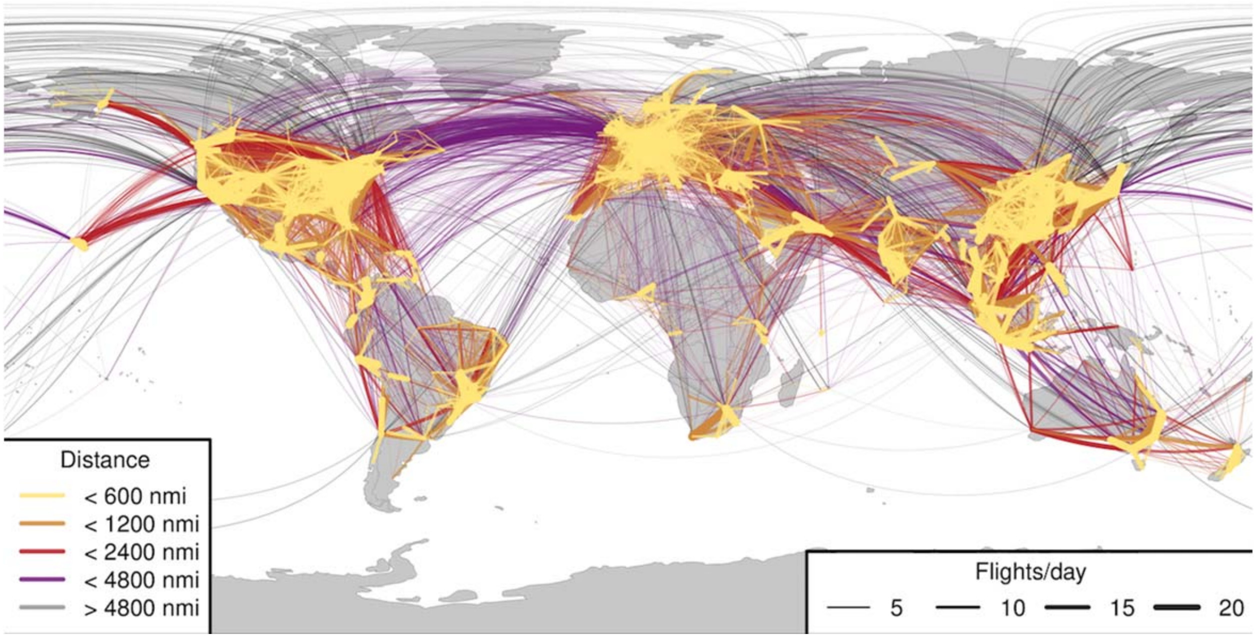

Fig. 3. Global flight network in 2015 by distance band. Initially, all-electric aircraft operations would be limited to short distances. The 600 nmi (1,111 km) range, feasible with an all-electric aircraft employing a battery with a specific energy of 800 Wh/kg [18], would result in one or more local networks per continent. With rising battery pack specific energy and flight distances, individual continental flight networks would begin to consolidate. However, from today's perspective, it is questionable whether all-electric aircraft will be capable of operating over distances of 1,200 nmi (2,222 km) or more with a single-stage flight, as this would require a battery pack specific energy of at least 1,600 Wh/kg [18]. This implies that all-electric aircraft would mostly operate on intra-continental routes rather than the long-distance transatlantic or transpacific routes.

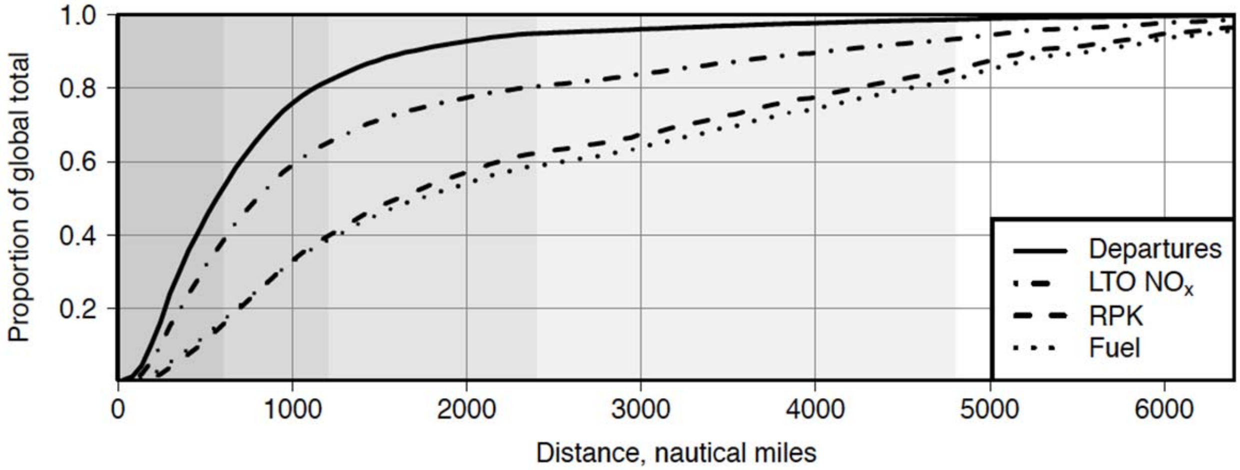

Fig. 4. Cumulative distributions of departures, NO_x emissions at landing and takeoff (LTO), revenue passenger-km (RPK), and fuel consumed by the global commercial aircraft fleet in 2015. The flight distances of multiples of 600 nmi (1,111 km) are shown in terms of shaded areas. Full adoption of an all-electric aircraft with a range of 600 nmi would account for half of all aircraft departures and for 15% of all RPK. It would reduce one-third of all narrow-body related LTO NO_x emissions and 15% of global narrow-body jet fuel use. Extending the range to 1,200 nmi (2,222 km) would significantly increase the impact. All numbers were derived with the Aviation Integrated Model AIM2015 [39].

Methods

Distribution of passenger-km and fuel burn by distance. Departures and fuel burn by distance is derived from flight schedules and passenger numbers from the Sabre Market Intelligence Database [42], assuming great circle routing. To estimate fuel burn and LTO NO_x emissions, we use the aircraft performance model from the Aviation Integrated Model AIM2015 [43], the updated version of AIM [44].

Electric aircraft noise assessment. The impact of aircraft noise on communities near airports depends not only on noise source levels of the aircraft but also on its operational characteristics. Quantification of this impact is usually mapped using noise contours, which, in turn, depend upon the Noise Power Distance (NPD) curves of the aircraft. For existing aircraft NPD curves are publicly available [45] but need to be estimated for novel aircraft.

In the present study, the all-electric aircraft NPD curves have been derived from those of a baseline A320-232 aircraft using a novel method, which accounts for both operational and technological variations of the aircraft from the baseline case [46, 47, 48, 49]. The all-electric aircraft airframe and propulsor fans are assumed to behave acoustically in a similar manner to their conventional equivalents. Propulsor weight is estimated based on the method of [50]. Together with nacelle drag and an estimation of battery and cabling weight, the NPD curves for a number of distributed propulsion configurations and missions can be calculated [51]. In these calculations, airframe, fan and jet mixing noise are considered but motor noise has been ignored. Based on predictions by [52], motor noise can be presumed negligible compared to fan and jet mixing noise contributions. From the NPDs, aircraft noise contours have been calculated using a method known as RANE (Rapid Airport Noise Estimation) that has been benchmarked against INM [53]. Typical results are illustrated in the Supplementary Information.

Aircraft Warming Impact of Battery Production. The warming intensity in Fig. 1 excludes greenhouse gas emissions associated with battery production. According to [54], the literature-based values range from 39-196 kgCO_2e per kWh, depending on the methodological approach, the method for imputing missing data, the carbon intensity of electricity, and other factors. Given a battery capacity of 64,000 kWh [18], the amount of GHG emissions due to battery production would result in 2,500-12,500 tonnes of CO_2e. Assuming an average of 150 passengers per aircraft, a block speed of 800 km per hour, an average utilization of 10 hours per day, and a battery lifetime of 3 years, battery production related GHG emissions would result in 2-10 gCO_2e per RPK or 2-10% of the warming intensity of an all-electric aircraft provided the carbon intensity of electricity corresponds to the world average of around 500 gCO_2 per kWh. Note that this range represents an upper limit, as end-of-life high-performance batteries will likely experience a second life in stationary applications. In addition, a lower carbon intensity of electricity will result in further reductions [55].

Cost-effectiveness of all-electric aircraft. The key difference between the A320NEO reference aircraft and the derivative all-electric aircraft is the energy storage and propulsion system. Our all-electric aircraft capital cost estimate (only referring to recurring costs) is based upon the reference aircraft average retail price of US$46 million, which includes the price of two gas turbine engines at US$5.5 million, after a whole-aircraft discount of 57% [56]. Not taking into account the credit for the obsolete fuel system and APU, we add the cost of batteries at US$100/kWh and US$200/kWh. These numbers reflect the projected future and current costs of Li-ion batteries. Given the projected battery capacity of 28 MWh, the total cost of batteries results in US$2.8 million and US$5.6 million, respectively. The replacement costs of the batteries after their useful life of 5,000 cycles is then accounted for in the maintenance costs.

Our estimate of the cost range of the electric propulsion system is based upon two limiting cases. The lower-end estimate assumes electric propulsor costs without high-temperature super-conducting (HTS) motors. It is based upon electric propulsion system costs of US$8/kW, which corresponds to the 2022 DOE target for electric motors plus inverters for automobile applications [57]. Based upon a maximum aircraft power requirement of 12.5 MW for each of the 4 propulsion units during take-off, the cost of one electric motor plus inverter amounts to US$100,000. These costs exclude the fan, which costs about 15% of the cost of a gas turbine engine [58] or US$410,000. Hence, the costs of one propulsion system totals US$510,000, which translates into around US$2 million for the 4 units.

The higher-end cost case accounts for a HTS electric propulsion system. Perhaps conservatively, it corresponds to the cost of two jet engines, or US$5.5 million. Subtracting the costs of four fans would lead to motor plus power electronics costs of US$3.9 million. In light of the maximum aircraft power requirement of 50 MW, these costs would then translate into US$78/kW. The latter are within the range of the HTS motor costs cited by Hoelzen *et al*. [59]. However, with progress in especially HTS wire technology and increase in production scale, HTS motor costs are expected to decline drastically [60, 61].

Whereas estimating the cost of all-electric aircraft propulsors in decades is highly uncertain, these numbers may be indicative of the order of magnitude cost. The results imply (see Fig. 2 in the main body) that the uncertainty in the electric propulsion system costs is unimportant relative to the uncertainty in battery cost or overall aircraft performance, even if propulsion system costs are a factor of two or more greater than our higher case.

In addition to capital costs, the cost-effectiveness analysis takes into account maintenance costs and energy costs. Expenditures for crew and airport/airspace were assumed to be identical between the two competing aircraft types. Maintenance costs of the A320neo were computed with data from Aircraft Commerce on the basis of the A320-200 [62] and resulted in US$960 per flight hour. This number compares well with US Form 41 data [63]. In contrast, the maintenance costs of the all-electric aircraft amount to US$1,270 per flight hour for battery costs of US$100/kWh and US$1,570 per flight hour for battery costs of US$200/kWh. Their higher maintenance costs can be attributed to mainly battery maintenance, accounting for US$300 and US$600 per flight hour for the US$100 and US$200/kWh battery costs, respectively.

Impact on electricity generation. The hypothetical year-2015 and 2050 electricity demand projections are obtained using the global aviation systems model AIM [39]. For 2015, we take the baseline global network as represented in AIM, which is obtained from a global scheduled passenger and flight database for 2015 [42]. For each flight segment up to an assumed 400-600 nmi range, we calculate the electricity demand under the assumption that all passengers are carried on all-electric narrow-body aircraft of the type and size specified in [18]. We use a performance model fit to the electricity demand of an all-electric aircraft with a battery specific energy of 800 Wh/kg, a 400 or 600 nmi design range, and different passenger load factors and assume passenger load factors similar to those historically flown on each segment. This procedure provides an estimate of the electricity demand per airport.

We use the central SSP2 reference case from [39] to project demand by flight segment in 2050. The mid-range trends for future socioeconomic characteristics underlying this projection results in 2017-2037 demand growth rates consistent to those from the most recent Airbus and Boeing forecasts [10, 11]. Total revenue passenger-km (RPK) in 2050 is around 3.7 times the value in 2015. The same procedure as for 2015 is used to estimate electricity demand; the increase in electricity demand is lower compared to total RPK because of a shift towards longer-haul flights which cannot be served by all-electric aircraft.

Data Availability Statement

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

Competing Financial Interests

The authors declare no competing financial interests.

Author Contributions

A.W.S. led the overall study, the analysis of the results and the preparation of the manuscript. S.R.H.B. led the all-electric aircraft performance study and contributed to the analysis of the results and to the preparation of the manuscript. R.S. led the all-electric aircraft noise study and contributed to the preparation of the manuscript. A.R.G. carried out the all-electric aircraft performance simulations and contributed to the preparation of the manuscript. L.M.D. carried out the analysis of the results. K.D. and A.O'S. contributed to the analysis of the results. A.P.S. and A.J.T. contributed to the all-electric aircraft noise study.