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

2 Andreas W. Schäfer^{1*}, Steven R.H. Barrett², Khan Doyme¹, Lynnette M. Dray¹, Albert R.
3 Gnadt², Rod Self³, Aidan O’Sullivan¹, Athanasios P. Synodinos³, Antonio J. Torija³

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

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

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

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

11
12 Ever since the Wright Brothers’ first powered flight in 1903, commercial aircraft have relied on
13 liquid hydrocarbon fuels. However, the need for greenhouse gas emission reductions along with
14 recent progress in battery technology for automobiles has generated strong interest in electric
15 propulsion in aviation. This work provides a first-order assessment of the energy, economic, and
16 environmental implications of all-electric aircraft. We show that batteries with significantly
17 higher specific energy and lower cost, coupled with further reductions of costs and CO₂ intensity
18 of electricity, are necessary for exploiting the full range of economic and environmental benefits
19 provided by all-electric aircraft. A global fleet of all-electric aircraft serving all flights up to a
20 400-600 nmi (741-1,111 km) distance would demand an equivalent of 0.6-1.7% of worldwide
21 electricity consumption in 2015. Whereas lifecycle CO₂ emissions of all-electric aircraft depend

22 on the power generation mix, all direct combustion emissions and thus direct air pollutants and
23 direct non-CO₂ warming impacts would be eliminated.

24

25

26 **Introduction**

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

31

32 However, reliance on oil products comes at an environmental cost. Aircraft CO₂ emissions, due
33 to combustion of jet fuel, are 2.7% of energy use-related CO₂ emissions [1, 2]. It is also
34 estimated that the non-CO₂ warming impacts of aircraft are of the same magnitude as CO₂ from
35 aviation, thus approximately doubling aviation’s contribution to climate change [3, 4, 5]. The
36 single largest non-CO₂ contributor to warming may be the formation of contrails and contrail-
37 cirrus [3]. In addition, aviation combustion emissions that affect air quality, such as NO_x, are set
38 to rise substantially [6]. This may increase the estimated ~16,000 premature mortalities per year
39 attributable to aviation emissions globally [7]. There is also growing evidence that noise from
40 aircraft results in adverse health impacts and premature mortality amongst affected populations
41 [8].

42

43 Various options exist for reducing CO₂ emissions from aircraft. For example, fuel burn per
44 revenue passenger-km (RPK) of the US narrow-body aircraft fleet could be reduced by around
45 2% per year at no cost through 2050 [9], whereas reductions obtainable for wide-body, long-

46 distance aircraft would likely be smaller. However, these rates will be outpaced by the
47 anticipated global aviation demand growth of around 4.5% per year [10, 11]. In contrast to fuel
48 efficiency improvements, low-carbon fuels (e.g., biofuels) could partially decouple CO₂
49 emissions from aviation growth, although these options face cost and scale limitations and do not
50 significantly help with non-CO₂ impacts [12, 13], except for a potential thinning of contrails with
51 an uncertain sign of the effect [14, 15]. Similarly, liquid hydrogen [16] and liquified natural gas
52 [17] could greatly reduce direct CO₂ emissions, but these fuels' higher hydrogen content would
53 result in enhanced contrail and cirrus cloud formation.

54
55 Until recently, energy carriers that do not entail in-flight combustion have not been considered.
56 This work focuses on all-electric aircraft that have the potential to eliminate both direct CO₂
57 emissions and direct non-CO₂ impacts, although the net impact will depend on the power
58 generation mix and associated emissions. However, exploiting these unparalleled benefits
59 requires significant technological advances with respect to especially battery performance and
60 cost.

61

62 **Technology Trajectories Toward All-Electric Aircraft**

63 Two broad technology trajectories appear to lead to all-electric aircraft. The first trajectory builds
64 upon the incremental electrification of jet engines. This class of hybrid-electric aircraft includes
65 designs without batteries (i.e. turbo-electric aircraft), in which the electric propulsion system
66 serves to increase propulsive efficiency and/or provide for some degree of boundary layer
67 ingestion, which entails ingesting and re-energizing the aircraft boundary layer so as to improve
68 efficiency [19, 20]. The extent of fuel burn reductions is then the net effect of the increased

69 propulsive efficiency and the detriment of the additional weight of the electrical components.
70 Hybrid-electric aircraft with batteries are also being considered, where the batteries may provide
71 for additional power or regeneration at limited specific operating conditions. Whereas hybrid-
72 electric aircraft with batteries would entail direct combustion emissions for the majority of
73 flights, they could provide for reduced or eliminated emissions during particularly sensitive parts
74 of a flight – such as flying through ice supersaturated parts of the atmosphere (to reduce
75 contrails) or during takeoff and landing (to reduce near-airport emissions). With sufficient
76 advancements in battery technology, the ultimate design then is an all-electric aircraft, which
77 would have no direct combustion emissions and thus have the potential to remove aviation-
78 specific non-CO₂ impacts and reduce CO₂ emissions depending on the source of the electricity.
79 In contrast, the second technology trajectory builds upon scaling up all-electric air taxis. [21]
80 reports 55 such air vehicle designs, 80% of which being already all-electric. Progress in battery
81 technology, especially specific energy, would then enable scaling up all-electric designs to larger
82 vehicles, first to regional jets and then to narrow-body aircraft.

83

84 **All-Electric Aircraft Energy Use**

85 Aircraft energy use (E) per revenue passenger-km (RPK) during cruise flight can be described
86 conveniently by the Breguet range equation [22, 23]. Rearranged for energy intensity, equations
87 1 and 2 report energy use per RPK for jet engine aircraft (JEA) and all-electric aircraft (AEA),
88 with PAX being the number of passengers transported, L/D the lift-to-drag ratio, η_{total} the total
89 (tank-to-wake) efficiency of the jet engine or electric propulsion system, and W the weight of
90 either fuel, the jet engine aircraft at the beginning (i) or the end (f) of the mission, or of the all-
91 electric aircraft at any point during the mission.

92

$$93 \quad E/RPK_{JEA} = 1/(\eta_{total,JEA} PAX L/D) W_{Fuel}/\ln(W_i/W_f) \quad (1)$$

$$94 \quad E/RPK_{AEA} = 1/(\eta_{total,AEA} PAX L/D) W_{AEA} \quad (2)$$

95

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

108

109 A key enabler of electric flight and a critical determinant of energy intensity is the battery pack
110 specific energy. This variable enters the energy intensity of all-electric aircraft in equation 2 via
111 the aircraft weight. If the on-board battery energy supply is kept constant, a higher specific
112 energy leads to a lower all-electric aircraft weight and thus a lower aircraft energy use per
113 revenue passenger-km, which, in turn, yields a longer range. In addition, a lighter aircraft would

114 allow downsizing other components, such as landing gear, motor power, etc., which yield
115 additional energy intensity reductions and range gains.

116

117 Today's best available Li-ion battery cells have a specific energy of around 250 Wh/kg [26, 27].

118 Assuming a packing efficiency of 80%, which is at the lower end of projected future levels [28]

119 and below that of the recently developed Airbus E-Fan [29], the pack-specific energy would

120 result in roughly 200 Wh/kg and 1.7% of the jet fuel energy content. This battery would be

121 capable of powering electric air taxis with 1-4 passengers over a distance of around 100 km [21].

122 However, short-range electric aircraft demand battery pack specific energies of 750-2,000

123 Wh/kg, which translates into 6-17% of the jet fuel energy content, depending on aircraft size and

124 range [18, 23, 24, 30, 31]. Much of the required 4-10 fold increase in battery pack specific

125 energy could potentially be achieved with advanced Li-S technology, although Li-air chemistry

126 may ultimately be required for the higher end of that range. Both of these battery technologies

127 have low specific power, so an additional, high-power battery or another means of augmenting

128 power may be required for takeoff and climb.

129

130 The historical long-term rate of increase in specific energy of the major battery chemistries has

131 been around 3% per year, a doubling every 23 years [32, 33], although since 2000, specific

132 energy has increased at a rate of 4% per year [33]. Whereas there is no "Moore's Law"

133 equivalent for batteries – since significant advances require entirely new battery chemistries to

134 be made practicable before incremental improvement can occur – this historical observation does

135 suggest that the timescale for such progress to be made could be on the order of decades. Based

136 upon a continuation of the historical increase in specific energy, current levels of specific energy

137 of 250 Wh/kg for advanced Li-ion battery cells, and a packing efficiency of 80%, a battery pack
138 specific energy of 800 Wh/kg could potentially be reached at around midcentury. This is
139 consistent with the timescale of change in the aviation industry – both the infrastructure and
140 aircraft design lifecycles. For the purposes of this work we take the lower end of the above
141 battery pack specific energy range of 800 Wh/kg that is required for Airbus A320/Boeing 737-
142 sized aircraft to be capable of up to 600 nmi (1,111 km) missions, depending on the specific
143 layout and amount of batteries carried [18].

144

145 In addition to battery pack specific energy, all-electric aircraft weight is determined by the
146 power-to-weight ratio of the motors and the supporting infrastructure, consisting mainly of
147 cables and power electronics. Whereas regional jets with about 50 seats are likely to require
148 significantly improved mainstream technology, narrow-body aircraft with 100 seats and above
149 may depend upon lightweight high-temperature superconducting electric motors due to the
150 intrinsically high weight of conventional electric motors and the difficulty in providing cooling
151 [34].

152

153 **Environmental Impacts**

154 All-electric aircraft would completely eliminate direct combustion emissions and thus remove
155 associated direct CO₂ and non-CO₂ warming. The lifecycle CO₂ intensity of all-electric aircraft is
156 determined by the CO₂ intensity of electricity used, losses associated with battery charging and
157 electricity transmission/distribution, and the specific aircraft design and operation. Fig. 1 depicts
158 the warming intensity of a first-generation 180-seat, 150-passenger, all-electric aircraft over a
159 400 nmi (741 km) mission, which is projected to consume 180 Wh/RPK for a battery pack

160 specific energy of 800 Wh/kg [18]. Using the 2015 average US grid CO₂ intensity of 456
161 gCO₂/kWh, this all-electric aircraft would generate 91 gCO₂/RPK, if including losses associated
162 with electricity transmission/distribution and battery charging. This value is 22% higher than the
163 lifecycle CO₂ intensity of its modern, jet engine counterparts (the “US” dashed line in Fig. 1).
164 However, if non-CO₂ impacts are taken into account (by way of a factor of two [3-5]), the
165 overall warming per revenue passenger-km would be reduced by 43%. The lifecycle CO₂
166 intensity of all-electric aircraft would further decline with improved aircraft and battery
167 technology and the potential transition of the grid toward renewable energy. Conversely, a longer
168 range capability would result in a higher energy and thus CO₂ intensity due to the additional
169 battery weight, as visible from equation 2. Note that CO₂ emissions and non-CO₂ impacts (such
170 as cooling related to sulphur emissions from coal-fired power stations [35]) may still occur
171 depending on the power generation mix.

172
173 If greenhouse gas (GHG) emissions from battery production were taken into account, the
174 warming intensity of all-electric aircraft shown in Fig. 1 would be slightly larger. Based on Li-
175 ion battery studies, the increase in warming intensity would be 2-10 gCO₂e/RPK, depending
176 upon the assumptions underlying those studies [36]. However, employing end-of-economic life
177 high-performance batteries in stationary applications would significantly reduce these emission
178 levels, as would the enhanced use of renewable electricity for battery production (see Methods
179 section).

180
181 In addition to removing direct non-CO₂ impacts, all-electric aircraft would also eliminate direct
182 air pollution. While indirect air pollution may occur depending on the power generation

183 technologies employed, there is greater potential for emissions control for ground-based power
184 generation compared to in-flight combustion.

185
186 Noise impacts of all-electric aircraft may be better or worse than conventional aircraft,
187 depending on design decisions made. Assuming a conventional tube and wing configuration,
188 which does not take advantage of the design flexibility offered by electric propulsion, we
189 estimated an overall improved noise performance of all-electric aircraft relying on a battery pack
190 specific energy of 800 Wh/kg compared to best-in-class current-generation short-haul aircraft.
191 Considering both takeoff and landing operations, a 36% reduction in noise contour area is
192 estimated as compared to the best-in-class aircraft (see Methods section). This could allow
193 extended airport operation hours, thus increasing aircraft utilization and airport capacity. During
194 takeoff, aircraft noise is mainly determined by the thrust of the engines required. Due to lower
195 fan pressure ratios and the absence of combustion noise, we anticipate a more than 50%
196 reduction in takeoff noise contour area. In contrast, during landing, the higher weight of all-
197 electric aircraft means that the determinants of noise (principally lift, drag, and landing speed)
198 will result in a 15% larger noise contour area compared to those of best-in-class narrow-body
199 aircraft. Higher battery pack specific energy and future aircraft designs would provide the
200 opportunity for reduced noise through novel aircraft concepts and changes in operational
201 procedures. These include highly distributed propulsion and steep approaches with propulsors in
202 generating mode.

203

204 **All-Electric Aircraft Economics**

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

215

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

228

229 According to Fig. 2, a first-generation all-electric aircraft with a battery pack specific energy of
230 800 Wh/kg and a 400 nmi (741 km) range would only be economically viable with battery costs
231 of around 100 US\$/kWh or less and policies that result in significant reductions in electricity
232 prices or increases in jet fuel prices. For example, jet fuel prices would need to be at least 2.8
233 US\$/gallon (118 US\$/barrel) to achieve cost-effectiveness in light of the lower end of the 2015
234 US electricity price range. The conditions required for cost parity with jet engine aircraft are
235 more relaxed for shorter missions and more stringent for longer missions, due to primarily the
236 extra battery weight and its impact on energy use.

237

238 Fig. 2 illustrates that a carbon tax of 100 US\$/tCO₂, which translates into 0.97 US\$/gallon of jet
239 fuel, would increase the break-even electricity price of the first-generation all-electric aircraft
240 with a battery pack specific energy of 800 Wh/kg to levels observed within the US, if electricity
241 is produced from renewable sources. This suggests that policies that support both low-carbon
242 electricity and the introduction of a carbon tax may be central prerequisites for introducing all-
243 electric aircraft if today's market conditions prevail until all-electric aviation becomes
244 technically feasible. However, as battery pack specific energy increases and costs of renewable
245 power decline, the cost-effectiveness of all-electric aircraft improves and the need for supportive
246 policies diminishes.

247

248 **All-Electric Aircraft Adoption Potential**

249 Since advanced batteries with 5-10 times the pack specific energy of today's Li-ion batteries
250 would still contain only 8-17% of the energy content per unit weight of jet fuel (although this

251 does not credit electrochemical storage with the higher energy conversion efficiency compared to
252 gas turbines), all-electric aircraft would be constrained to short-range missions, at least initially.
253 The limitation to short-distance operations of all-electric aircraft can be seen in Fig. 3, which
254 depicts the global air transportation network in 2015 by distance band. The 600 nmi (1,111 km)
255 range (yellow trajectories) could be covered with all-electric aircraft relying on a battery pack
256 specific energy of 800 Wh/kg [18]. Whereas a higher battery pack specific energy could lead to a
257 more integrated flight network, there are technological limits.

258
259 Operating beyond distances of 1,200 nmi (2,222 km) in a single-stage flight would require a
260 battery pack specific energy of at least 1,600 Wh/kg [18], which may remain a significant
261 technology challenge for decades to come. From today's perspective, the only way to further
262 expand the all-electric aircraft network by operating over flight distances longer than 1,200 nmi
263 would be via multistage flights with at least one intermediate stop. (This, of course, is contingent
264 on achieving a battery pack specific energy of 800 Wh/kg). However, this strategy would likely
265 lead to reduced travel demand due to the associated increase in travel time. In addition,
266 multistage flights may be limited by airport capacity and noise regulations. Thus, all-electric
267 aircraft operations would likely remain limited to intra-continental traffic, absent significant
268 breakthroughs in battery technology or changes in consumer behaviour.

269
270 Yet, a short-range all-electric aircraft market can generate large-scale impacts. As shown in Fig.
271 4, an all-electric aircraft fleet with a useful range of 600 nmi (1,111 km) could substitute up to
272 15% of global revenue passenger-km and up to half of global departures. In addition, it could

273 substitute almost 15% of commercial aircraft fuel use and eliminate around 40% of global
274 landing and takeoff (LTO) related NO_x emissions.

275

276 **Impact on Electricity Generation**

277 Using the aircraft performance characteristics specified by [18], we simulate the electricity
278 demand of a hypothetical, all-electric aircraft fleet operating within the global 2015 flight
279 network. This analysis, using the AIM2015 integrated model [39], suggests that the energy
280 demand by all-electric narrow-body aircraft operating at flight distances up to 400-600 nmi (741-
281 1,111 km) would correspond to 112-344 TWh or 0.6-1.7% of 2015 global electricity
282 consumption (see Methods section). This percentage range reflects the global average of variable
283 country-level data, culminating in slightly higher percentages within the industrialized world of
284 0.6-2.2% of total US electricity consumption and 1.3-3.7% for the UK.

285

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

293

294 **Discussion**

295 All-electric aircraft could greatly reduce the environmental impact of aviation. Most importantly,
296 they could eliminate direct CO₂ and non-CO₂ warming, in addition to removing all air pollutants.
297 Moreover, all-electric aircraft have the potential to mitigate noise, especially during takeoff. The
298 extent to which these benefits can be exploited from the global aircraft fleet will depend
299 critically upon battery pack specific energy. All-electric aircraft with battery packs of 800
300 Wh/kg, enabling a range up to 600 nmi (1,111 km), could replace half of all aircraft departures,
301 mitigate airport area NO_x emissions by 40%, and reduce fuel use and direct CO₂ emissions by
302 15%. Assuming strong progress in battery technology, aircraft with the two-fold endurance
303 leading to a 1,200 nmi (2,222 km) range, could replace more than 80% of all aircraft departures,
304 mitigate airport area NO_x emissions by more than 60%, and reduce fuel use and direct CO₂
305 emissions by around 40%. Although a realization of these prospects may fall well into the second
306 half of this century, they seem too large to ignore.

307
308 This analysis has shown that future, first-generation all-electric narrow-body aircraft may not be
309 economically competitive to jet engine aircraft under today's market conditions. To reach cost-
310 effectiveness with conventional aircraft, jet fuel prices would need to be in excess of 100
311 US\$/barrel. Conversely, if jet fuel prices remain at their 2015 level, end-use electricity prices
312 would need to be below 4-6 cents/kWh, depending on battery costs, to ensure the economic
313 competitiveness of all-electric aircraft. In addition, today's CO₂ intensity of electricity would
314 lead typically to higher lifecycle CO₂ emission levels compared to jet engine aircraft over the
315 same mission, albeit the total warming impact may be reduced in most parts of the world.
316 Since time scales of mutually reinforcing technologies are measured in decades (i.e., new aircraft
317 design, battery development, electricity grid decarbonization, and sufficiently strong decline in

318 electricity prices from renewable power to increase cost-effectiveness), research and
319 development of critical all-electric aircraft components would need to start immediately in order
320 to exploit the opportunities provided by an all-electric aircraft system in the decades to come. A
321 potential path of manageable risk would be the development first of turbo-electric and then
322 hybrid-electric technology, with the possible exception of all-electric regional aircraft, which can
323 rely on less stringent requirements for battery pack specific energy and power and may not
324 require high-temperature superconducting technology. While these transition technologies will
325 not result in significant reductions of greenhouse gas emissions, they are critical enablers of and
326 technology milestones toward an all-electric aircraft system.

327

328

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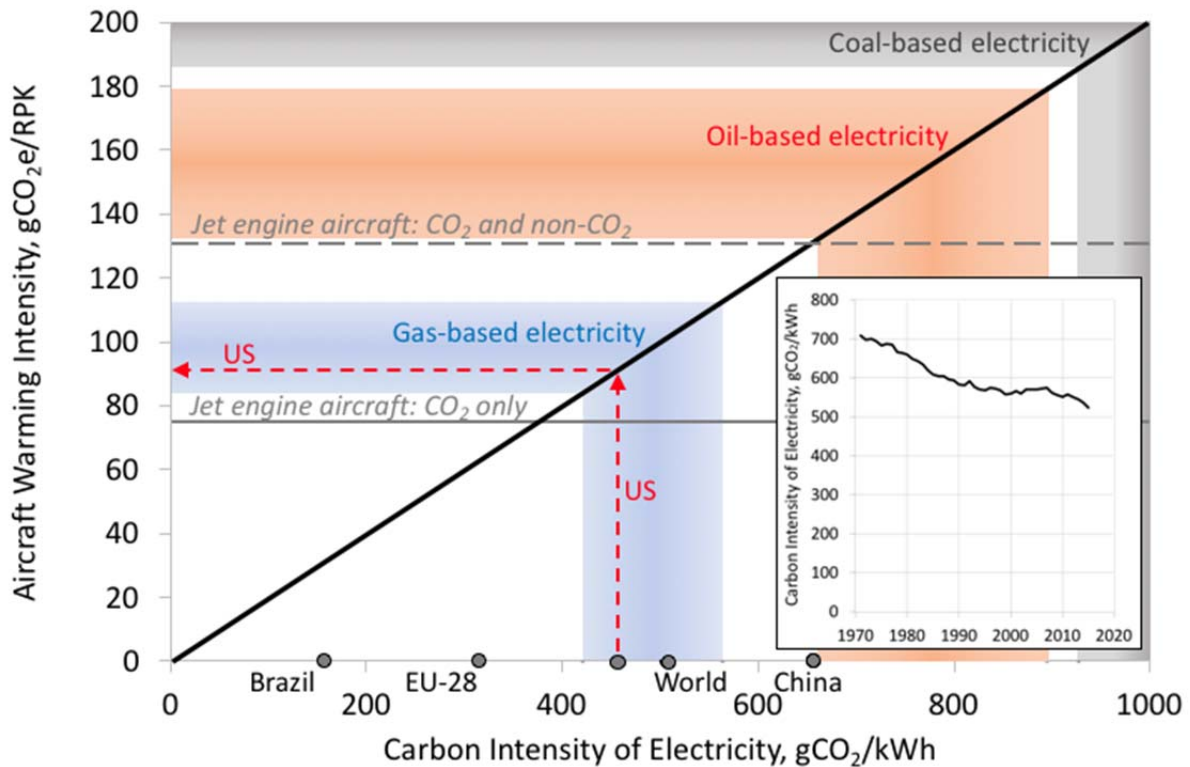
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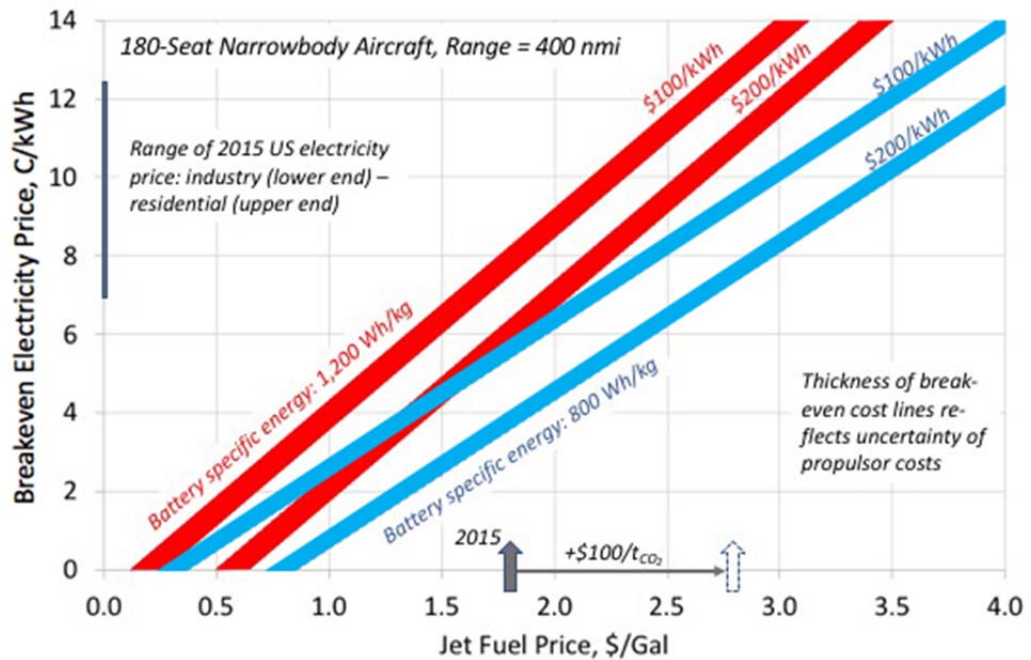
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 489 **Fig. 1.** Warming intensity of a projected first-generation all-electric aircraft with an electricity
 490 intensity of 180 Wh/RPK and current-generation jet engine aircraft (A320neo) vs. carbon
 491 intensity of electricity for a 400 nmi (741 km) mission. The lifecycle CO₂ intensity of all-electric
 492 aircraft is based on a design in [18] and takes into account efficiencies of 95% for battery
 493 charging and 95% for electricity transmission/distribution. In contrast, the lifecycle CO₂ intensity
 494 of the A320neo of 75 gCO₂/RPK is based on an energy intensity of 0.9 MJ/RPK, calculated with
 495 the aircraft performance model Piano-X [40], and a well-to-tank efficiency of 88% [41]; its
 496 warming intensity corresponds to two times its direct CO₂ emissions. The shaded areas represent
 497 the interquartile range of the CO₂ intensity of coal (limited to 1,000 gCO₂/kWh), oil, and natural
 498 gas-based electricity on a country basis in 2015 [2]. The 2015 electricity fuel mix in Brazil, the
 499 EU-28, the US, and the world average would lead to a lower warming intensity of all-electric
 500 aircraft compared to jet engine aircraft (two times the CO₂ intensity), as exemplified by the
 501 dashed red arrows for the US. If only considering long-lived CO₂ emissions, the CO₂ intensity of

502 all-electric aircraft would be below that of their jet engine counterparts for the 2015 EU-28 and
 503 Brazilian fuel mix, but larger in the US, China, and the world as a whole. Meeting the Paris
 504 Climate Agreement requires significantly stronger reductions in the CO₂ intensity of electricity
 505 as experienced historically (see inlay), which would lead to a proportional decline in the CO₂
 506 intensity of all-electric aircraft.

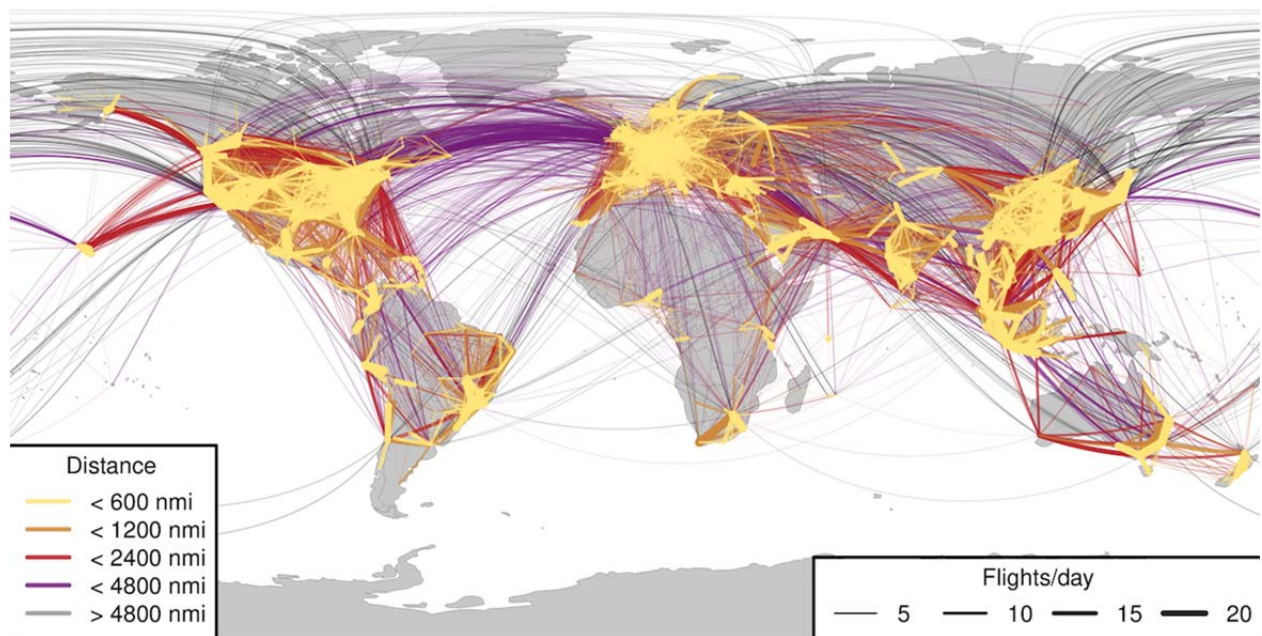
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512 **Fig. 2.** Break-even electricity price for a first-generation all-electric aircraft. The reference jet
 513 engine aircraft is an A320neo. The all-electric aircraft has batteries with a specific energy of 800
 514 Wh/kg (blue lines) or 1,200 Wh/kg (red lines), each with battery costs of 100 or 200 US\$/kWh.
 515

516 On the basis of a battery pack specific energy of 800 Wh/kg, jet fuel prices would need to be at
517 least 2.3 or 2.8 US\$/gallon (97 or 118 US\$/barrel) – depending on the cost of the battery – in
518 order to achieve cost-effectiveness relative to jet engine aircraft in light of the 2015 US
519 electricity end-use prices. Whereas the 2015 US jet fuel price of 1.8 US\$/gallon would lead to
520 breakeven prices below the range of the observed end-use electricity prices in the US, a CO₂
521 price of 100 US\$/tCO₂ (0.97 US\$/gallon of jet fuel) would lead to breakeven electricity prices
522 within the range of observed end-use electricity prices (provided electricity is produced on a
523 carbon-neutral basis). If taking into account non-CO₂ impacts on the basis of an “uplift factor” of
524 2, corresponding to a GHG emissions price of 200 US\$/tCO_{2e}, the cost-effectiveness would
525 further increase. It is apparent that battery costs would need to be around 100 US\$/kWh or less to
526 achieve cost-effectiveness over the longer term. About the same battery cost target exists for
527 automobiles, albeit at a significantly lower specific energy, to achieve cost parity with internal
528 combustion engine vehicles [37]. More advanced batteries with a higher specific energy, more
529 advanced aircraft designs, and repurposing end-of-life batteries for use in other sectors would
530 improve the economics of all-electric aircraft.

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Fig. 3. Global flight network in 2015 by distance band. Initially, all-electric aircraft operations

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would be limited to short distances. The 600 nmi (1,111 km) range, feasible with an all-electric

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aircraft employing a battery with a specific energy of 800 Wh/kg [18], would result in one or

537

more local networks per continent. With rising battery pack specific energy and flight distances,

538

individual continental flight networks would begin to consolidate. However, from today's

539

perspective, it is questionable whether all-electric aircraft will be capable of operating over

540

distances of 1,200 nmi (2,222 km) or more with a single-stage flight, as this would require a

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battery pack specific energy of at least 1,600 Wh/kg [18]. This implies that all-electric aircraft

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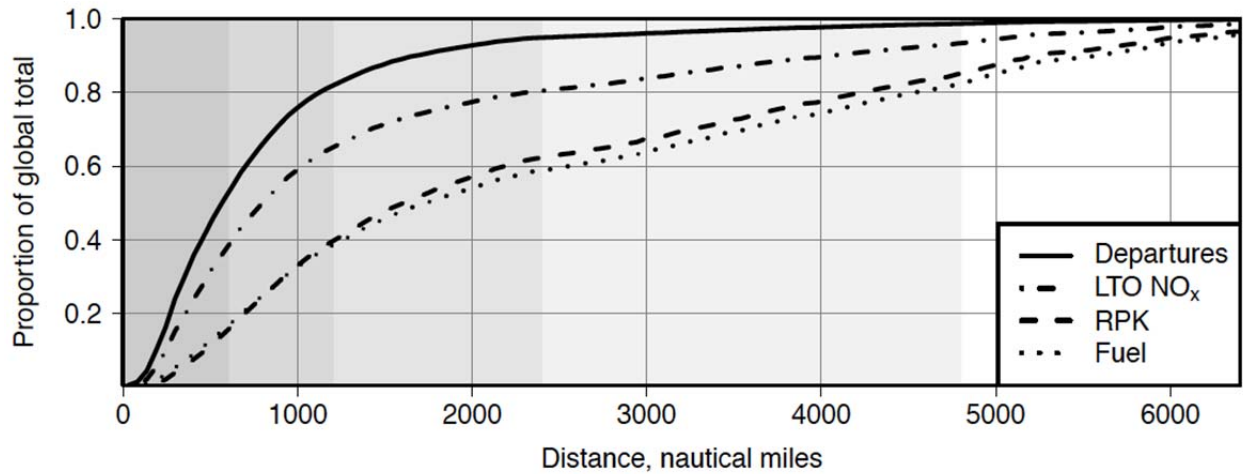
would mostly operate on intra-continental routes rather than the long-distance transatlantic or

543

transpacific routes.

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547 **Fig. 4.** Cumulative distributions of departures, NO_x emissions at landing and takeoff (LTO),
 548 revenue passenger-km (RPK), and fuel consumed by the global commercial aircraft fleet in
 549 2015. The flight distances of multiples of 600 nmi (1,111 km) are shown in terms of shaded
 550 areas. Full adoption of an all-electric aircraft with a range of 600 nmi would account for half of
 551 all aircraft departures and for 15% of all RPK. It would reduce one-third of all narrow-body
 552 related LTO NO_x emissions and 15% of global narrow-body jet fuel use. Extending the range to
 553 1,200 nmi (2,222 km) would significantly increase the impact. All numbers were derived with
 554 the Aviation Integrated Model AIM2015 [39].

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563 **Methods**

564

565 **Distribution of passenger-km and fuel burn by distance.** Departures and fuel burn by
566 distance is derived from flight schedules and passenger numbers from the Sabre Market
567 Intelligence Database [42], assuming great circle routing. To estimate fuel burn and LTO NO_x
568 emissions, we use the aircraft performance model from the Aviation Integrated Model AIM2015
569 [43], the updated version of AIM [44].

570

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

576

577 In the present study, the all-electric aircraft NPD curves have been derived from those of a
578 baseline A320-232 aircraft using a novel method, which accounts for both operational and
579 technological variations of the aircraft from the baseline case [46, 47, 48, 49]. The all-electric
580 aircraft airframe and propulsor fans are assumed to behave acoustically in a similar manner to
581 their conventional equivalents. Propulsor weight is estimated based on the method of [50].
582 Together with nacelle drag and an estimation of battery and cabling weight, the NPD curves for a
583 number of distributed propulsion configurations and missions can be calculated [51]. In these
584 calculations, airframe, fan and jet mixing noise are considered but motor noise has been ignored.
585 Based on predictions by [52], motor noise can be presumed negligible compared to fan and jet

586 mixing noise contributions. From the NPDs, aircraft noise contours have been calculated using a
587 method known as RANE (Rapid Airport Noise Estimation) that has been benchmarked against
588 INM [53]. Typical results are illustrated in the Supplementary Information.

589

590

591 **Aircraft Warming Impact of Battery Production.** The warming intensity in Fig. 1 excludes
592 greenhouse gas emissions associated with battery production. According to [54], the literature-
593 based values range from 39-196 kgCO₂e per kWh, depending on the methodological approach,
594 the method for imputing missing data, the carbon intensity of electricity, and other factors. Given
595 a battery capacity of 64,000 kWh [18], the amount of GHG emissions due to battery production
596 would result in 2,500-12,500 tonnes of CO₂e. Assuming an average of 150 passengers per
597 aircraft, a block speed of 800 km per hour, an average utilization of 10 hours per day, and a
598 battery lifetime of 3 years, battery production related GHG emissions would result in 2-10
599 gCO₂e per RPK or 2-10% of the warming intensity of an all-electric aircraft provided the carbon
600 intensity of electricity corresponds to the world average of around 500 gCO₂ per kWh. Note that
601 this range represents an upper limit, as end-of-life high-performance batteries will likely
602 experience a second life in stationary applications. In addition, a lower carbon intensity of
603 electricity will result in further reductions [55].

604

605 **Cost-effectiveness of all-electric aircraft.** The key difference between the A320NEO reference
606 aircraft and the derivative all-electric aircraft is the energy storage and propulsion system. Our
607 all-electric aircraft capital cost estimate (only referring to recurring costs) is based upon the
608 reference aircraft average retail price of US\$46 million, which includes the price of two gas

609 turbine engines at US\$5.5 million, after a whole-aircraft discount of 57% [56]. Not taking into
610 account the credit for the obsolete fuel system and APU, we add the cost of batteries at
611 US\$100/kWh and US\$200/kWh. These numbers reflect the projected future and current costs of
612 Li-ion batteries. Given the projected battery capacity of 28 MWh, the total cost of batteries
613 results in US\$2.8 million and US\$5.6 million, respectively. The replacement costs of the
614 batteries after their useful life of 5,000 cycles is then accounted for in the maintenance costs.

615
616 Our estimate of the cost range of the electric propulsion system is based upon two limiting cases.
617 The lower-end estimate assumes electric propulsor costs without high-temperature super-
618 conducting (HTS) motors. It is based upon electric propulsion system costs of US\$8/kW, which
619 corresponds to the 2022 DOE target for electric motors plus inverters for automobile applications
620 [57]. Based upon a maximum aircraft power requirement of 12.5 MW for each of the 4
621 propulsion units during take-off, the cost of one electric motor plus inverter amounts to
622 US\$100,000. These costs exclude the fan, which costs about 15% of the cost of a gas turbine
623 engine [58] or US\$410,000. Hence, the costs of one propulsion system totals US\$510,000, which
624 translates into around US\$2 million for the 4 units.

625
626 The higher-end cost case accounts for a HTS electric propulsion system. Perhaps conservatively,
627 it corresponds to the cost of two jet engines, or US\$5.5 million. Subtracting the costs of four fans
628 would lead to motor plus power electronics costs of US\$3.9 million. In light of the maximum
629 aircraft power requirement of 50 MW, these costs would then translate into US\$78/kW. The
630 latter are within the range of the HTS motor costs cited by Hoelzen *et al.* [59]. However, with

631 progress in especially HTS wire technology and increase in production scale, HTS motor costs
632 are expected to decline drastically [60, 61].

633
634 Whereas estimating the cost of all-electric aircraft propulsors in decades is highly uncertain,
635 these numbers may be indicative of the order of magnitude cost. The results imply (see Fig. 2 in
636 the main body) that the uncertainty in the electric propulsion system costs is unimportant relative
637 to the uncertainty in battery cost or overall aircraft performance, even if propulsion system costs
638 are a factor of two or more greater than our higher case.

639
640 In addition to capital costs, the cost-effectiveness analysis takes into account maintenance costs
641 and energy costs. Expenditures for crew and airport/airspace were assumed to be identical
642 between the two competing aircraft types. Maintenance costs of the A320neo were computed
643 with data from Aircraft Commerce on the basis of the A320-200 [62] and resulted in US\$960 per
644 flight hour. This number compares well with US Form 41 data [63]. In contrast, the maintenance
645 costs of the all-electric aircraft amount to US\$1,270 per flight hour for battery costs of
646 US\$100/kWh and US\$1,570 per flight hour for battery costs of US\$200/kWh. Their higher
647 maintenance costs can be attributed to mainly battery maintenance, accounting for US\$300 and
648 US\$600 per flight hour for the US\$100 and US\$200/kWh battery costs, respectively.

649
650 **Impact on electricity generation.** The hypothetical year-2015 and 2050 electricity demand
651 projections are obtained using the global aviation systems model AIM [39]. For 2015, we take
652 the baseline global network as represented in AIM, which is obtained from a global scheduled
653 passenger and flight database for 2015 [42]. For each flight segment up to an assumed 400-600

654 nmi range, we calculate the electricity demand under the assumption that all passengers are
655 carried on all-electric narrow-body aircraft of the type and size specified in [18]. We use a
656 performance model fit to the electricity demand of an all-electric aircraft with a battery specific
657 energy of 800 Wh/kg, a 400 or 600 nmi design range, and different passenger load factors and
658 assume passenger load factors similar to those historically flown on each segment. This
659 procedure provides an estimate of the electricity demand per airport.

660

661 We use the central SSP2 reference case from [39] to project demand by flight segment in 2050.
662 The mid-range trends for future socioeconomic characteristics underlying this projection results
663 in 2017-2037 demand growth rates consistent to those from the most recent Airbus and Boeing
664 forecasts [10, 11]. Total revenue passenger-km (RPK) in 2050 is around 3.7 times the value in
665 2015. The same procedure as for 2015 is used to estimate electricity demand; the increase in
666 electricity demand is lower compared to total RPK because of a shift towards longer-haul flights
667 which cannot be served by all-electric aircraft.

668

669 **Data Availability Statement**

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

672

673 **Competing Financial Interests**

674 The authors declare no competing financial interests.

675

676 **Author Contributions**

677 A.W.S. led the overall study, the analysis of the results and the preparation of the manuscript.
678 S.R.H.B. led the all-electric aircraft performance study and contributed to the analysis of the
679 results and to the preparation of the manuscript. R.S. led the all-electric aircraft noise study and
680 contributed to the preparation of the manuscript. A.R.G. carried out the all-electric aircraft
681 performance simulations and contributed to the preparation of the manuscript. L.M.D. carried out
682 the analysis of the results. K.D. and A.O'S. contributed to the analysis of the results. A.P.S. and
683 A.J.T. contributed to the all-electric aircraft noise study.
684