Technological, economic and environmental prospects of all-electric aircraft

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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 Analysis 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 distance of 400–600 nautical miles (741–1,111 km) would demand an equivalent of 0.6–1.7% of worldwide electricity consumption in 2015. Although 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.

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, owing to combustion of jet fuel, comprise 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 aircraft CO_2 emissions, thus approximately doubling aviation's contribution to climate change[3–5]. The single largest non-CO_2 contributor to warming may be the formation of contrails and contrail cirrus clouds[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 among affected populations[8].

Various options exist for reducing CO_2 emissions from aircraft. For example, fuel burn per revenue passenger kilometre (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 probably 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 (for example, biofuels) could partially decouple CO_2 emissions from aviation growth, although these options face cost and scale limitations and do not much help with non-CO_2 impacts[12,13], except for a potential thinning of contrails (the effect of which has an uncertain sign)[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 substantial technological advances, especially in battery performance and cost.

Technology trajectories towards 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 (that is, turbo-electric aircraft), in which the electric propulsion system serves to increase propulsive efficiency and provide for some degree of boundary-layer ingestion (in which ingestion and re-energizing of the aircraft boundary layer improves efficiency)[18,19]. The extent of fuel burn reductions is then the net effect of the increased propulsive efficiency and 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. Although 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, however, the ultimate design 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. Ref. [20] reports 55 such air vehicle designs, 80% of which are already all-electric. Progress in battery technology, especially specific energy, would then enable the scaling up of all-electric designs to larger vehicles, first to regional jets and then to narrow-body aircraft.

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All-electric aircraft energy use

Aircraft energy use (E) per RPK during cruise flight can be described conveniently by the Breguet range equation[21,22]. 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.

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

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

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[23,24]. 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 mitigated by the roughly two-fold tank-to-wake efficiency of electric propulsion systems compared to their jet engine counterparts[22,25]. We 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 RPK, which, in turn yields a longer range. In addition, a lighter aircraft would allow the downsizing of other components, such as landing gear, motor power, and so on, 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⁻¹ (refs [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⁻¹ 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[20]. However, short-range electric aircraft demand battery-pack specific energies of 750–2,000 Wh kg⁻¹, which translates into 6–17% of the jet fuel energy content, depending on aircraft size and range[22–24,30,31]. 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]. Although 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 of the order of decades. On the basis of a continuation of the historical increase in specific energy, current levels of specific energy of 250 Wh kg⁻¹ for advanced Li-ion battery cells, and a packing efficiency of 80%, a battery-pack specific energy of 800 Wh kg⁻¹ could potentially be reached at around mid-century. This is consistent with the timescale of change in the aviation industry—for 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⁻¹ that is required for Airbus A320/Boeing 737-sized aircraft to be capable of up to 600 nautical miles (1,111 km) missions, depending on the specific layout and amount of batteries carried[23].

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. Figure 1 depicts the warming intensity of a first-generation 180-seat, 150-passenger, all-electric aircraft over a mission of 400 nautical miles (741 km), which is projected to consume 180 Wh per RPK for a battery-pack specific energy of 800 Wh kg⁻¹ (ref. [23]). Using the 2015 average US grid CO_2 intensity of 456 g of CO_2 per kWh, this all-electric aircraft would generate 91 g of CO_2 per RPK, if losses associated with electricity transmission/distribution and battery charging are included. This value is about 20% 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 RPK would be reduced by around 30%. 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 towards renewable energy. Conversely, a longer range capability would result in a higher energy and thus CO_2 intensity owing 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 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 g of CO_2 equivalent per RPK, depending upon the underlying assumptions[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).

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 of 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 the design decisions made. Assuming a conventional tube and wing configuration, which
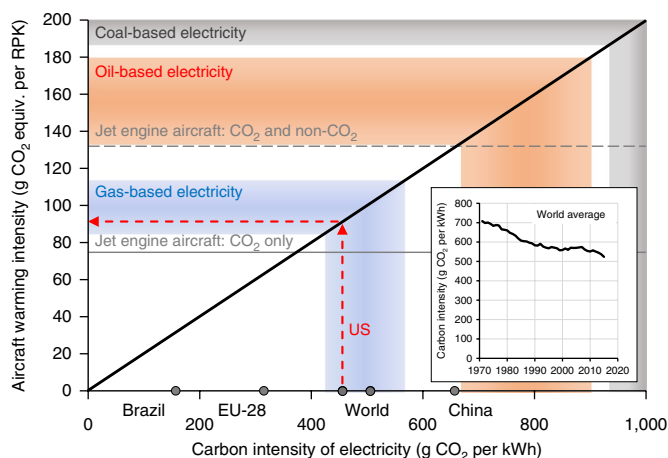
Fig. 1 | Warming intensity of a projected first-generation all-electric aircraft and of a current-generation jet engine aircraft versus carbon intensity of electricity. The mission length is 400 nautical miles (741 km). The lifecycle CO_2 intensity of the all-electric aircraft with an electricity intensity of 180 Wh per RPK is based on a design in ref. [23] and takes into account efficiencies of 95% for battery charging and 95% for electricity transmission or distribution. In contrast, the lifecycle CO_2 intensity of the A320neo of 75 g of CO_2 per RPK is based on an energy intensity of 0.9 MJ per RPK, calculated with the aircraft performance model Piano-X[61], and a well-to-tank efficiency of 88%[62]; 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-based (limited to 1,000 g of CO_2 per kWh), oil-based 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 we consider only 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 Agreement on climate requires significantly stronger reductions in the CO_2 intensity of electricity as experienced historically (see inset), which would lead to a proportional decline in the CO_2 intensity of all-electric aircraft.

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^{-1} 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, compared to the best-in-class aircraft (see Methods). 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. Owing 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 design concepts and changes in operational procedures (such as 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-
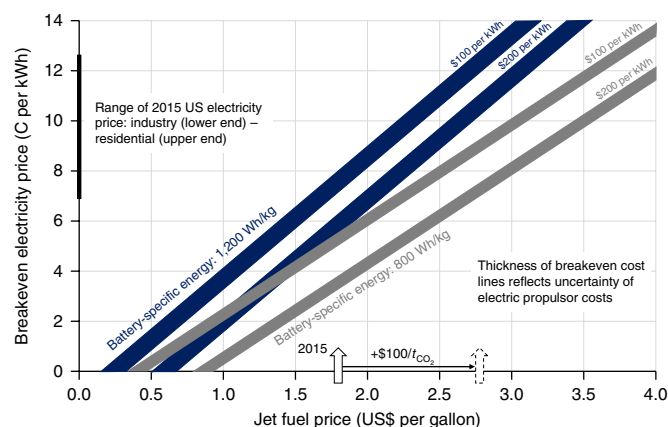

Fig. 2 | Break-even electricity price for a first-generation all-electric aircraft. The reference jet engine aircraft is an Airbus A320neo. The all-electric aircraft has batteries with a specific energy of 800 Wh kg^{-1} (grey lines) or 1,200 Wh kg^{-1} (blue lines), each with battery costs of US$ 100 kWh^{-1} or US$ 200 kWh^{-1}. On the basis of a battery-pack specific energy of 800 Wh kg^{-1}, jet fuel prices would need to be at least US$ 2.3 or 2.8 per gallon (US$ 97 or US$ 118 per 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 US$ 1.8 per gallon would lead to breakeven prices below the range of the observed end-use electricity prices in the USA, a CO_2 price of US$ 100 per tonne of tCO_2 (US$ 0.97 per 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 doubling of the greenhouse gasemissions price (here, to US$ 200 per tonne of CO_2 equivalent), the cost effectiveness would increase further. It is apparent that battery costs would need to be around US$ 100 kWh^{-1} or less to achieve cost effectiveness over the longer term. About the same battery cost target exists for automobiles, albeit at a much 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. Costs in the graph are in 2015 US$.

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 the 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 (auxiliary power unit) for generating electricity, engine starting, and so on. 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.

Taking into account only 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 range of 400 nautical miles (741 km). Two sets of lines are shown with different levels of specific energy. Each set represents battery costs of US$ 100 kWh^{-1} and US$ 200 kWh^{-1}, which reflect the target and 2017 level of Li-ion batteries[37]. At the 2015
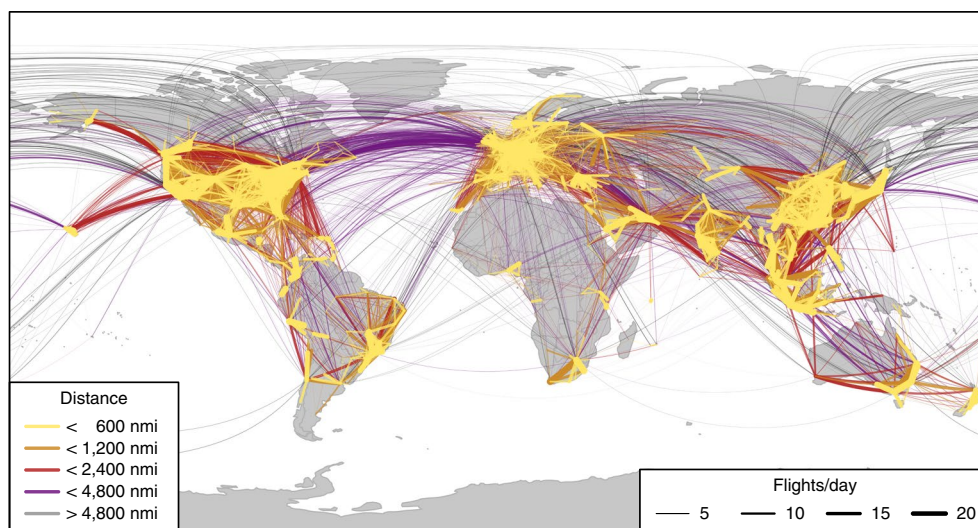
Fig. 3 | Global flight network in 2015 by distance band. Initially, all-electric aircraft operations would be limited to short distances. The range of 600 nautical miles (1,111 km), feasible with an all-electric aircraft employing a battery with a specific energy of 800 Wh kg^{-1} (ref. [23]), would 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 nautical miles (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^{-1} (ref. [23]). This implies that all-electric aircraft would mostly operate on intra-continental routes rather than the long-distance transatlantic or transpacific routes.

US jet fuel price of US\$ 1.8 per gallon, the breakeven electricity prices of only the all-electric aircraft with a battery-pack specific energy of 1,200 Wh kg^{-1} and battery costs of US\$ 100 kWh^{-1} would fall within the 2015 US electricity price range of 6.9–12.7 cents per kWh, depending on the end-use sector[38]. In contrast, a first-generation all-electric aircraft with a battery-pack specific energy of 800 Wh kg^{-1} and a range of 400 nautical miles (741 km) would be economically viable only with battery costs of around US\$ 100 kWh^{-1} or less and policies that result in significant reductions in electricity prices or increases in jet fuel prices. A carbon tax of US\$ 100 per tonne of CO_2, which translates into US\$ 0.97 per 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^{-1} to levels observed within the USA, if electricity is produced from renewable sources. This suggests that policies that support both low-carbon electricity and the introduction of 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 will improve and the need for supportive policies will diminish. The conditions required for cost parity with jet engine aircraft are also more relaxed for shorter missions but more stringent for longer missions, primarily owing to the extra battery weight and its impact on energy use.

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 range of 600 nautical miles (1,111 km) (yellow trajectories) could be covered with all-electric aircraft relying on a battery-pack specific energy of 800 Wh kg^{-1} (ref. [23]). Although

a higher battery pack specific energy could lead to a more integrated flight network, there are technological limits.

Operating beyond distances of 1,200 nautical miles (2,222 km) in a single-stage flight would require a battery-pack specific energy of at least 1,600 Wh kg^{-1} (ref. [23]), which may remain a significant technological 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 nautical miles 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^{-1}). However, this strategy would probably lead to reduced travel demand owing 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 probably remain limited to intra-continental traffic, in the absence of notable 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 nautical miles (1,111 km) could substitute up to 15% of global RPK 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-related NO$_x$ emissions.

Impact on electricity generation
Using the aircraft performance characteristics specified by ref. [23], 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 nautical miles (741–1,111 km) would correspond to 112–344 TWh or 0.6–1.7% of 2015 global electricity consumption (see Methods). 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.
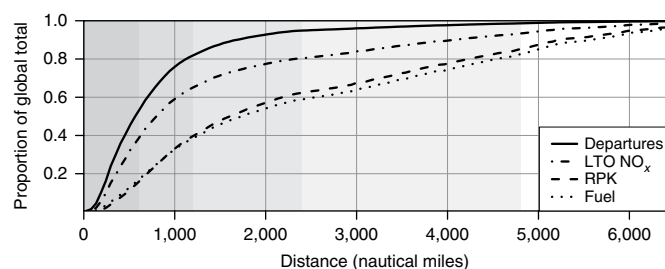
Fig. 4 | Cumulative distributions of key operational variables by the global commercial aircraft fleet in 2015. The variables consist of departures, NO_x emissions at landing and takeoff (LTO), RPK and fuel consumed. The flight distances of multiples of 600 nautical miles (1,111 km) are shown in terms of shaded areas. Full adoption of an all-electric aircraft with a range of 600 nautical miles would account for half of all aircraft departures and for 15% of all RPK. It would eliminate one-third of all narrow-body-related landing and takeoff NO_x emissions and 15% of global narrow-body jet fuel use. Extending the range to 1,200 nautical miles (2,222 km) would greatly increase the impact. All numbers were derived with the Aviation Integrated Model AIM2015[39].

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 nautical miles, 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^{-1}, enabling a range up to 600 nautical miles (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 range of 1,200 nautical miles (2,222 km) 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 US$ 100 per barrel. Conversely, if jet fuel prices remain at their 2015 level, end-use electricity prices would need to be below 4–6 cents per 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, although the total warming impact may be reduced in most parts of the world.

Since timescales of mutually reinforcing technologies are measured in decades (that is, 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. Although these transition technologies will not result in significant reductions of greenhouse gas emissions, they are critical enablers of and technology milestones towards an all-electric aircraft system.

Methods

Distribution of passenger kilometres 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[40], assuming great circle routing. To estimate fuel burn and landing- and- takeoff NO_x emissions, we use the aircraft performance model from the Aviation Integrated Model AIM2015[41], the updated version of AIM[42].

Electric aircraft noise assessment. The impact of aircraft noise on communities near airports depends not only on noise levels from 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[43] but for novel aircraft, they need to be estimated.

In the present study, the all-electric aircraft NPD curves have been derived from those of a baseline A320-232 aircraft using a method that accounts for both operational and technological variations of the aircraft from the baseline case[44–47]. 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 ref. [48]. 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[49]. In these calculations, airframe, fan and jet mixing noise are considered but motor noise has been ignored. Based on predictions by ref. [50], motor noise can be presumed to be 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 the US Federal Aviation Administration's Integrated Noise Model (INM 7.0c)[51]. 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 ref. [36], the literature-based values range from 39–196 kg of CO_2 equivalent 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[23], the amount of greenhouse gas emissions due to battery production would result in 2,500–12,500 tonnes of CO_2 equivalent. Assuming an average of 150 passengers per aircraft, a block speed of 800 km per hour, an average utilization of 10 h per day, and a battery lifetime of 3 years, battery-production-related greenhouse gas emissions would result in 2–10 g of CO_2 equivalent 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 g of CO_2 per kWh. Note that this range represents an upper limit, because end-of-life high-performance batteries will probably experience a second life in stationary applications. In addition, a lower carbon intensity of electricity will result in further reductions[52].

Cost-effectiveness of all-electric aircraft. The key difference between the A320neo reference aircraft and the derived all-electric aircraft is the energy storage and propulsion system. Our all-electric aircraft capital cost estimate (referring only 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%[53]. Not taking into account the credit for the obsolete fuel system and auxiliary power unit, we add the cost of batteries at US$ 100 kWh^{-1} and US$ 200 kWh^{-1}. These numbers reflect the projected future and current costs of Li-ion batteries. Given the projected battery capacity of 28 MWh (21 MWh) for first-generation all-electric aircraft with a battery specific energy of 800 Wh kg^{-1} (1,200 Wh kg^{-1}), the total cost of batteries results in US$ 2.8 million (US$ 2.1 million) and US$ 5.6 million (US$ 4.2 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 superconducting motors. It is based upon electric propulsion system costs of US$ 8 kW^{-1}, which corresponds to the 2022 US Department of Energy target for electric motors plus inverters for automobile applications[54]. Based upon a maximum power requirement of 12.5 MW for each of the four propulsion units during take-off for the aircraft with a battery specific energy of 800 Wh kg^{-1}, 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[55] or US$ 410,000. Hence, the cost of one propulsion system totals US$ 510,000, which translates into around US$ 2 million for the four units. For the aircraft with a battery specific energy of 1,200 Wh kg^{-1}, the lower maximum power requirement leads to propulsion system costs that are only around half as high.

The higher-end cost case accounts for a high-temperature super-conducting 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^{-1}. The latter are within the range of the high-temperature super-conducting motor costs cited by Hoelzen et al.[56]. However, with progress in high-temperature super-conducting wire technology, especially, and increases in production scale, high-temperature super-conducting motor costs are expected to decline drastically[57,58].

Although 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) 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 for the two competing aircraft types. Maintenance costs of the A320neo were computed with data from Aircraft Commerce on the basis of the A320–200[59] and resulted in US$ 960 per flight hour. This number compares well with US Form 41 data[60]. In contrast, the maintenance costs of the all-electric aircraft range from US$ 1,170 per flight hour for batteries with a specific energy of 1,200 Wh kg^{-1} and costs of US$ 100 kWh^{-1} to US$ 1,500 per flight hour for batteries with a specific energy of 800 Wh kg^{-1} and costs of US$ 200 kWh^{-1}. The higher maintenance costs of all-electric aircraft can be attributed mainly to battery maintenance. Using a discount rate of 7%, maintenance costs for the aircraft with 800 Wh kg^{-1} batteries result in US$ 265 and US$ 530 per flight hour for the US$ 100 and US$ 200 kWh^{-1} battery costs, respectively. Owing to the required smaller battery capacity, maintenance costs for the aircraft with 1,200 Wh kg^{-1} batteries result in US$ 205 and US$ 410 per flight hour.

Impact on electricity generation. The hypothetical year-2015 and year-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[40]. For each flight segment up to an assumed range of 400–600 nautical miles, 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 ref. [23]. We use a performance model fitted to the electricity demand of an all-electric aircraft with a battery specific energy of 800 Wh kg^{-1}, a 400- or 600- nautical-mile design range, and different passenger load factors, assuming 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 ref. [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 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
The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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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.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information is available for this paper at https://doi.org/10.1038/s41560-018-0294-x.

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