



**electric dreams**

**the carbon**

**mitigation potential**

**of electric aviation in**

**the UK air travel market**

**fellow  
travellers**

## about

### **fellow travellers**

Fellow Travellers is a not-for-profit, unincorporated association campaigning for fair and equitable solutions to the growing environmental damage caused by air travel. We aim to protect access to reasonable levels of flying for the less well-off, whilst maintaining aviation emissions within safe limits for the climate.

Fellow Travellers  
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# introduction


'Electrify everything' has become something of a rallying cry in the energy and environmental world lately. Wind and solar power have come down in price far more rapidly than anyone had predicted, and it has become clear that we are more than capable of running grids on a generation mix that is dominated by intermittent renewables. One of the harder sectors to decarbonise to date has been transportation, but it is hoped that electrification, coupled with a very low carbon electricity supply, could deliver major benefits in terms of carbon mitigation, noise reduction and air quality improvements.

In the automotive sector, electric vehicles (EVs) are finally having their day in the sunshine as virtually every major manufacturer, along with an insurgency of smaller, ambitious new entrants, release an ever-growing selection of desirable and practical vehicles onto the market. Battery technology is now following similar cost curves to solar and wind, meaning EVs have recently become more cost effective than internal combustion engines for usage in intensive applications such as light commercial vehicles and taxis.

Recently, the idea of electrifying aviation has also been gaining considerable attention in the press. Companies are emerging from stealth mode on a regular basis, unveiling exotic designs for personal air vehicles and business jet-sized commuter designs, with some companies even looking at electric and hybrid regional airliners.

Norwegian airport operator Avinor recently announced that all short-haul flights should be entirely electric by 2040<sup>1</sup> and in 2017 Easyjet announced a partnership with US electric aircraft manufacturing start-up Wright Electric<sup>2</sup>, while familiar names such as Airbus, Rolls Royce and Siemens are also working on a hybrid regional jet demonstrator.<sup>3</sup>





Measures to reduce greenhouse gases from the aviation sector are sorely needed. In February 2018 the International Air Transport Association (IATA), which represents 280 airlines accounting for 83% of global air traffic, announced that in 2017 the number of revenue passenger kilometres (RPKs) grew 7.6% compared with 2016 and that the 10 year average growth rate stands at 5.5%.<sup>4</sup> Over the next 20 years IATA forecasts that the number of passengers flying will nearly double from the current 4 billion to 8.2 billion, growing at an average rate of 3.5%.<sup>5</sup>

Even here, one of the most mature air travel markets in the world, the number of passengers using UK airports has increased by 15% over the past five years, while emissions from UK aviation grew 1.2% in 2016. Without major reductions in aircraft emissions, these levels of traffic growth will have serious implications for efforts to decarbonise the global economy.

The ability to fly away to nearly anywhere in the world on holiday or on business within a day is cherished by many who are in the fortunate position to be able to do so. The prospect of electrification making a meaningful reduction in the environmental impact of aviation (which remains a blind spot for many politicians and citizens alike) is therefore a tantalising one.

In this report we make an attempt to evaluate the potential for electric aircraft to contribute to reductions in the sector's greenhouse gas emissions. Reliable global data is difficult to obtain, but the UK keeps particularly high quality records of air traffic movements.

Using data covering the UK aviation industry we assess what level of performance electric aircraft would need to attain in order to have a meaningful impact on the sector's greenhouse gas emissions in the UK. We also review progress to date in the nascent electric aviation industry and the current direction of technological and market development.

## methodology

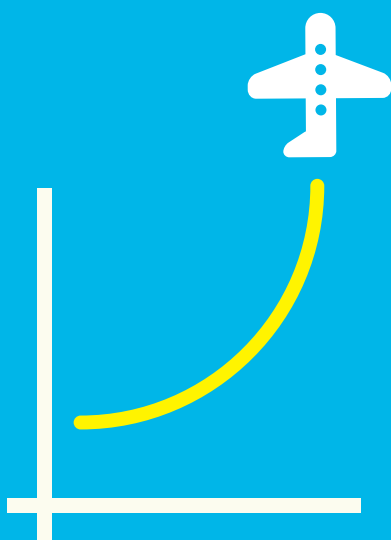
In common with electric road transport, one of the key performance metrics of electric aircraft is range. The further electric aircraft can fly, the more routes they can be deployed on and the greater potential there is for the displacement of Jet A-1, the kerosene-type fuel used by the airline industry and the source of aviation's greenhouse gas emissions.

In order to assess the potential for greenhouse gas mitigation in the UK aviation sector from electric aviation, we produced a data set which describes how far people travel on aircraft originating or terminating in the UK. This data is derived from the Civil Aviation Authority's Airport Data 2016<sup>6</sup> which contains both a domestic and international air passenger route analysis. These two tables give the number of passengers who flew on all domestic and international routes in 2016.

Using a database of airport latitude and longitude<sup>7</sup> it is possible to calculate the great circle distance (the shortest distance between two points on earth) between the origin and destination airports. However aircraft do not generally take the great circle route, and instead follow defined corridors known as air routes, as well as adjusting their flightpath to take advantage of beneficial winds. This indirect routing is accounted for by using the UK Department for Transport's uplifts of 5% for short range (defined as Western Europe) and 6% for long range<sup>8</sup>.

By multiplying the number of passengers flown between each pair of airports by the uplifted great circle distance we can obtain an estimate of the total passenger-km flown on each route in 2016.

In order to estimate CO<sub>2</sub> emissions from this passenger activity we applied emission factors calculated for the Government Greenhouse Gas Conversion Factors for Company Reporting Methodology<sup>9</sup>. Passenger emission factors vary between different routes, with domestic flights having the highest emission factor followed by long haul and then short haul flights.



The final emission factors used for company reporting of greenhouse gas emissions take into account the freight carried in the belly of passenger aircraft and adjust the passenger emission factors down accordingly. For this analysis we have used the unadjusted emission factors in order to obtain a better estimate of total aviation emissions (including emissions usually attributed to belly freight) generated by aircraft operating out of UK airports:

### emission factor gCO<sub>2</sub>/pkm

haul	freight weighted	no freight weighting
domestic	144.6	144.9
short	78.7	80.2
long	103.1	122.1

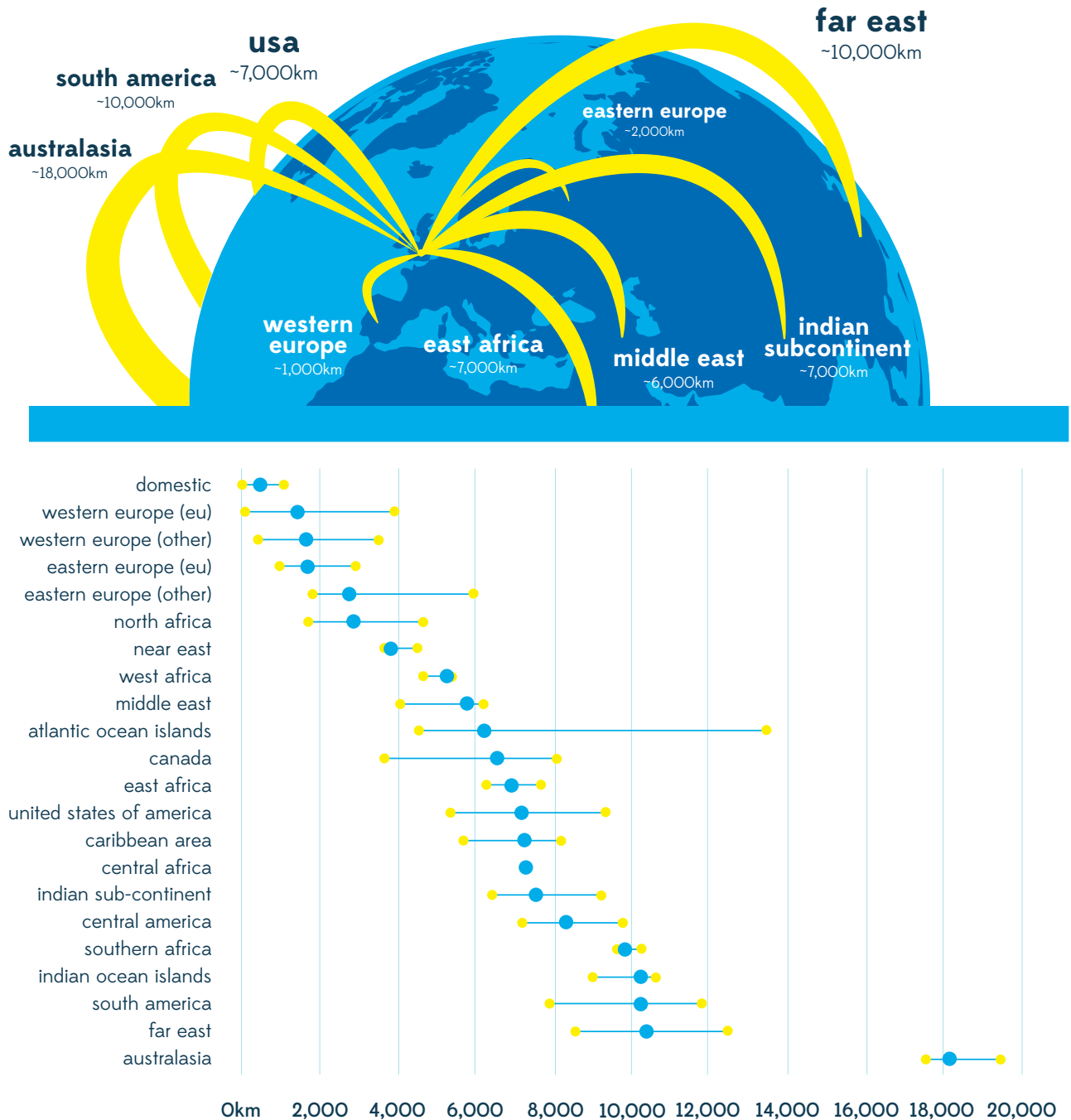
The CAA Airport Data represents the number of passengers flying both from and to airports in the UK. The UK's greenhouse gas inventory only considers the emissions generated by fuel uplifted in the UK, with emissions from fuel uplifted in other countries attributable to their inventories. We have therefore halved the emissions calculated on international routes in order to align our estimates with the UK's emissions inventory data for aviation. As both the outbound and inbound leg of a domestic flight are within the UK, these emissions were left the same. We find that our estimates for total domestic and international emissions are acceptably close to the official data<sup>10</sup>:

	domestic	international
<b>CO<sub>2</sub> estimate</b> (MtCO <sub>2</sub> )	1.5	35.4
<b>2016 emissions inventory</b> (MtCO <sub>2</sub> )	1.5	33.7

## results

The following chart shows the minimum, mean and maximum route length from UK airports to each region:

figure 1.

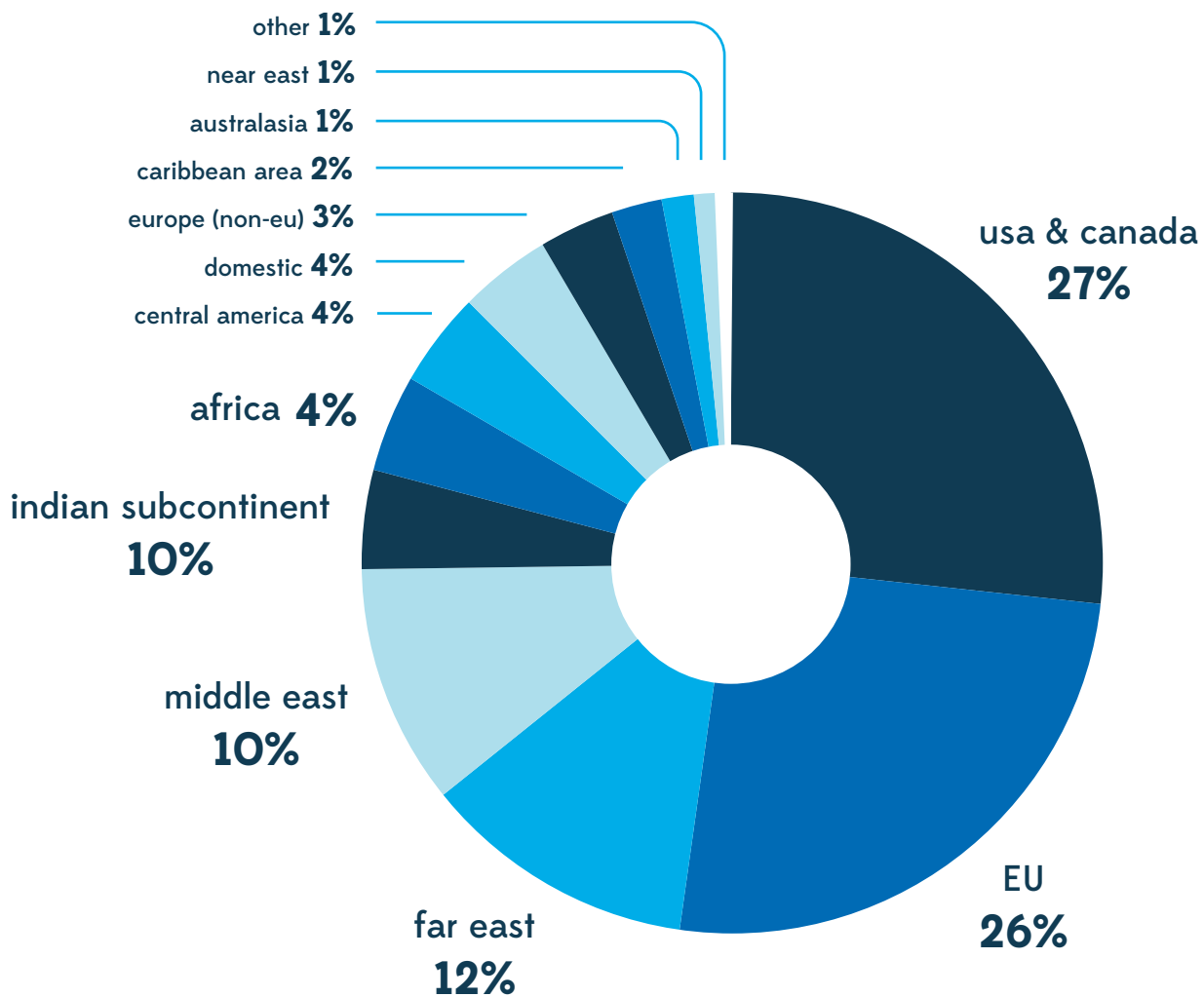


**source:** authors' analysis of UK Civil Aviation Authority route analysis data and the OpenFlights database of airport locations

**Note** the majority of flights to Australasia are flown in two stages with fuel being uplifted at an intermediary stop. A small number of flights from Perth in Western Australia are now flown in a single stage.

The breakdown of aviation emissions by destination region is given below. Travel to and from two regions, the USA and Canada and the European Union, accounts for more than half of the UK's aviation emissions:

**figure 2. Proportion of UK Aviation Emissions by Region**

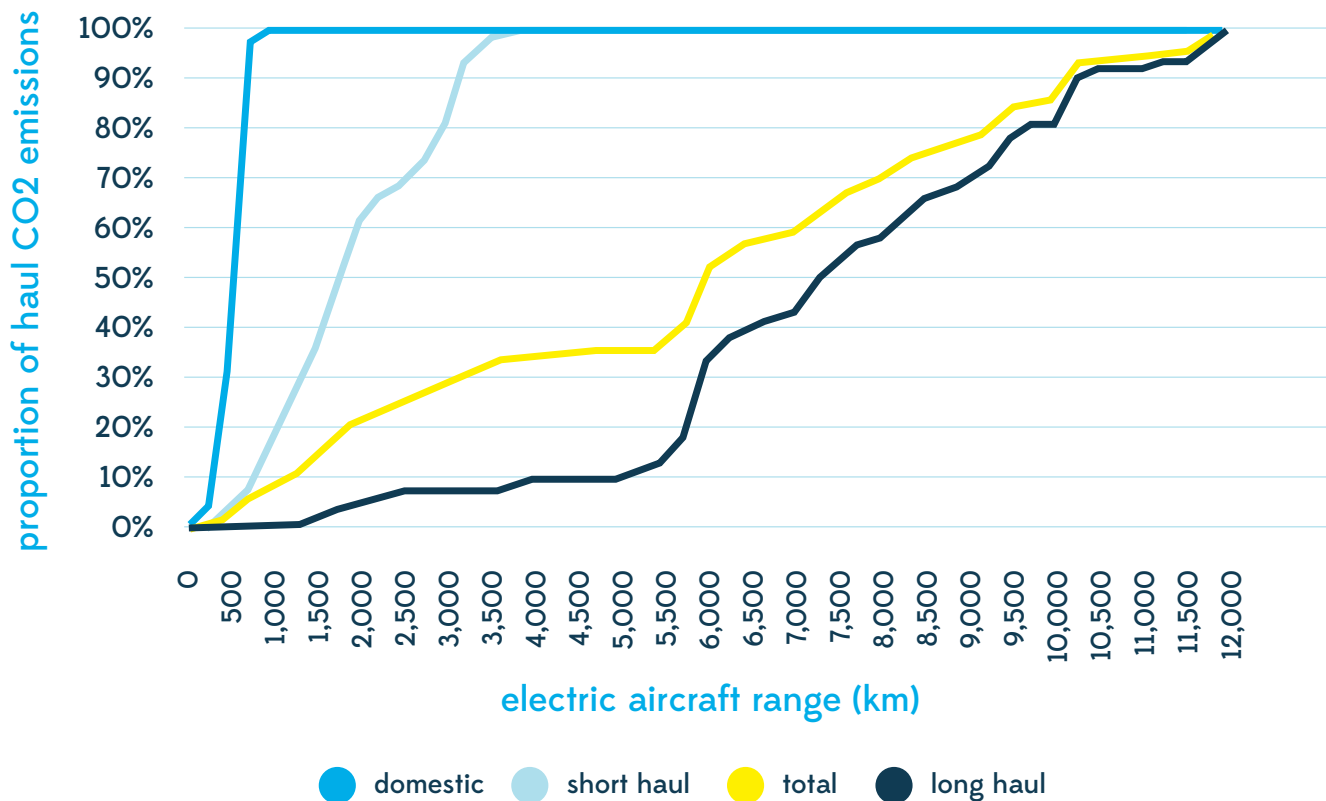


**Source:** authors' analysis of UK Civil Aviation Authority route analysis data and the OpenFlights database of airport locations and using emission factors for passenger aviation from 2018 government GHG conversion factors for company reporting

In order to visualise how different ranges of electric aircraft impact on UK aviation emissions, we have produced a graph which divides emissions by range, divided into 250km buckets:



figure 3. CO2 Mitigation Potential by Increasing Electric Aircraft Range by Haul



**Source:** authors' analysis of UK Civil Aviation Authority route analysis data and the OpenFlights database of airport locations and using emission factors for passenger aviation from 2018 government GHG conversion factors for company reporting

This graph shows the technical potential for mitigation if all aircraft up to a given range were switched to battery electric aircraft and were charged using zero carbon electricity. Any fossil fuels used in conventional or hybrid electric aircraft or electricity generated by non-zero carbon fuels would eat into this mitigation potential. Although UK grid carbon intensity has been falling rapidly in recent years, and current carbon budgets require grid carbon of 50-100gCO<sub>2</sub>/kWh in 2030, there is growing uncertainty over how this threshold will be achieved in light of the removal of policy support for renewables and ongoing troubles plaguing ambitions for a new fleet of nuclear power plants.

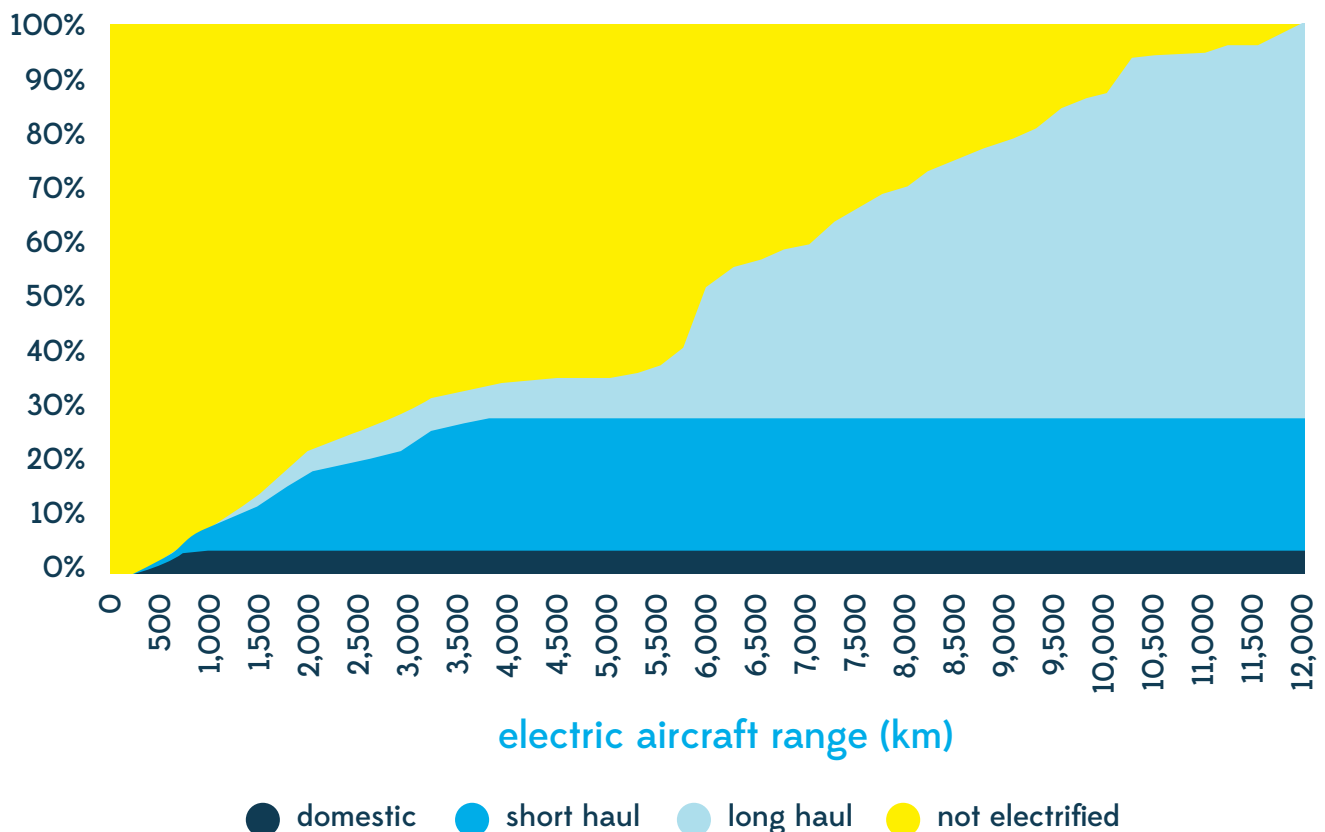
Domestic operations, which account for around 4% of UK aviation CO<sub>2</sub> emissions, have the shortest route distances and could be electrified completely with aircraft with a range

of around 1,000km (620 miles). This falls into the range proposed for some of the small electric aircraft models being developed for market entry in the 2020s, although these would need to substitute for the much larger aircraft which currently operate these routes. This level of performance could enable the mitigation of 16% of short haul international CO<sub>2</sub>, leading to a total technical potential saving of around 8% of UK aviation emissions. Short haul international travel currently accounts for around 24% of UK aviation emissions.

Doubling the range to 2,000km (1,240 miles) would see as much as 60% of short haul CO<sub>2</sub> and 5% of long haul CO<sub>2</sub> having the potential for electrification, but this would represent just 22% of total UK aviation CO<sub>2</sub> emissions. Beyond 2,000km the benefits are harder won, with trips between 3,000km and 5,000km only accounting for around 6% of UK aviation emissions (3,000km takes travellers to the Eastern Mediterranean while 5,000km takes them to the Middle East and across the Atlantic). It would take a range of 4,000km to be able to electrify 10% of long haul emissions, which currently account for 72% of UK aviation emissions.

The data can be reworked to show how electrifying the different hauls could contribute to mitigating UK aviation emissions. This drives home the extent to which long haul aviation dominates UK aviation's emissions:

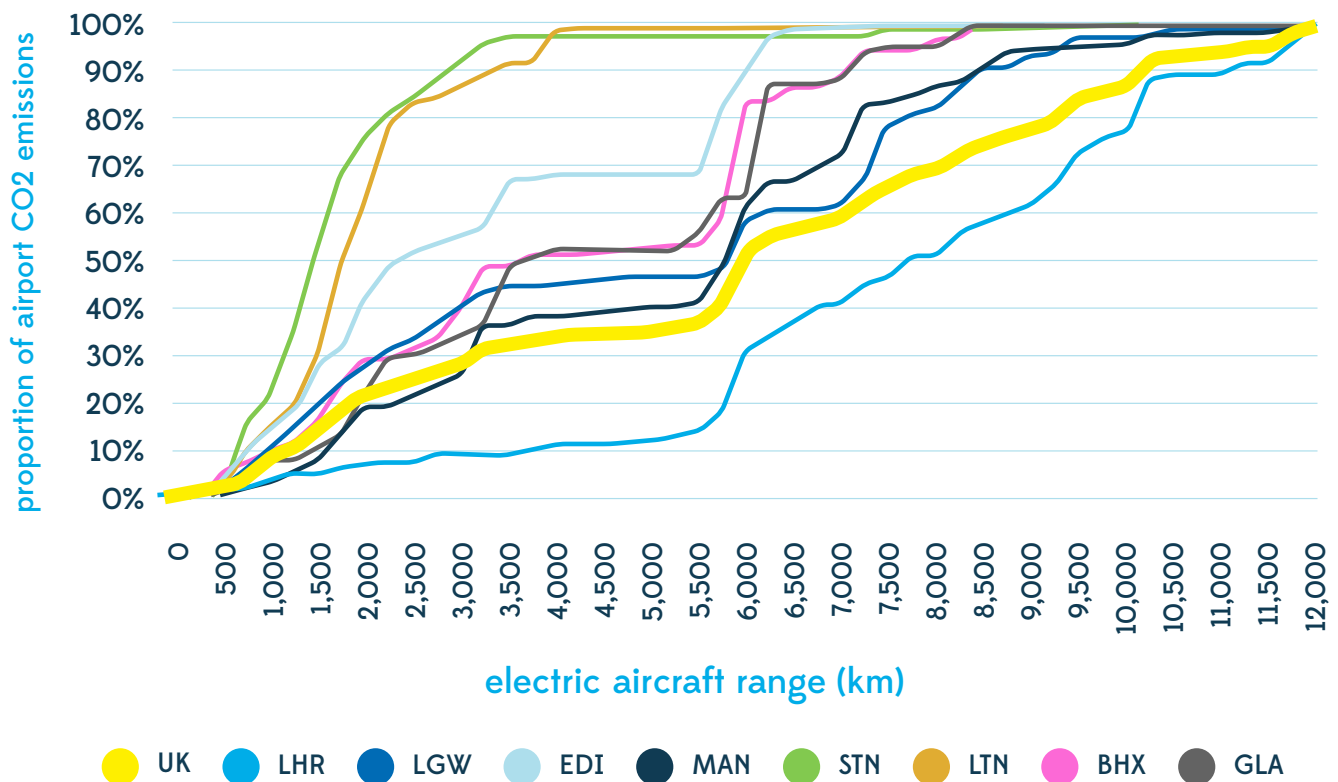
**figure 4. Proportion of UK aviation CO<sub>2</sub> which could theoretically be mitigated by electrifying operations at UK airports**



We can also see what the impact of electric aircraft could potentially be at the top 8 UK airports, which collectively account for over 90% of UK aviation CO2 emissions. As can be seen in the chart below, airports such as Stansted (STN) and Luton (LTN) have greater potential for electric aircraft operations as their route network is dominated by short haul flights to European airports.

Heathrow (LHR), on the other hand, has a route network which is dominated by long haul flights to North America, the Middle East and Far East. Electric aircraft with transatlantic range (5,500km or 3,420 miles or more) would only be able to mitigate 15% of Heathrow's emissions, and as Heathrow generates more than half of UK aviation CO2, it has a big impact on the total UK potential. Electric aviation will struggle to make a significant impact at Heathrow for a long time to come, but this hasn't stopped the airport trying to generate some favourable press coverage with its recent announcement that the first battery or hybrid electric aircraft will not have to pay landing fees for the first year<sup>11</sup>.

figure 5. CO2 Mitigation Potential from Increasing Electric Aircraft Range by UK Airport



source: authors' analysis of UK Civil Aviation Authority route analysis data and the OpenFlights database of airport locations and using emission factors for passenger aviation from 2018 government GHG conversion factors for company reporting

# electric aviation development

There are five main markets where electric and hybrid electric aircraft can potentially make inroads:

## 1. personal air vehicles / evtol

The first market is where the most activity in the electric aviation space is to be found. There is an ever-growing number of electric vertical take-off and landing (eVTOL) aircraft at various stages of development (ranging from nothing more than renders of 3D models, to flying prototypes). The publication Electric VTOL News lists more than 100 projects which have been announced to date<sup>12</sup>.

These aircraft are sometimes labelled ‘flying cars’ or ‘flying taxis’ by the media but are much closer to general aviation aircraft and drones than cars, and all but a handful are not capable of driving on public roads. The only categories of aircraft currently operating in this sector are helicopters and General Aviation aircraft and the size of the market is currently very limited.

eVTOL have a limited range, typically anything up to 100km and are designed for short range flights within and between urban centres. Promoters of these eVTOL aircraft make claims of lower operating costs, noise, emissions and increased reliability through electrification. They hope to make this kind of urban and inter-urban transport accessible to more than just the very richest who can currently afford it. There is no shortage of scepticism about the scale and viability of the market, but also no shortage of companies trying to make it work.

eVTOL aircraft will not operate in the same market as civil aviation and have no scope to make a material impact on UK aviation’s greenhouse gas emissions.



## 2. commuter / air taxi / thin haul

The next market which electric aviation is expected to start breaking into is commuter and air taxi operations serving point-to-point routes between small regional airports. This market is currently small in the UK and is served by small turboprops and business jets.

ZUNUM Aero, a company backed by aircraft manufacturer Boeing, airline JetBlue and charter business jet operator JetSuite, has a proposed design for an aircraft carrying up to 12 passengers and capable of flying a total range (using both battery and fuel) of 700 miles (1,100km). The design looks familiar and similar to business jet designs, with two electric ducted fans mounted on the rear fuselage, and a v-tail in place of the more traditional combination of horizontal and vertical stabilisers. The powertrain will be a series hybrid with a battery taking up 20% of the total weight of the aircraft, supplemented by a 500kW turbogenerator burning liquid fuel to extend the range.

The Eviation Alice is a battery electric design with no fuel burning engine, which is more unconventional looking than the ZUNUM Aero. It is a 9 passenger aircraft designed to fly 650 miles (just over 1,000km). It is a much more streamlined design of aircraft, with round porthole windows and a large v-tail. It is powered by three 260kW motors, one at the rear of the fuselage and one mounted on each of the wing tips, all driving pusher propellers. Energy storage comes in the form of a 900kWh lithium-ion battery pack which accounts for 60% of the aircraft's maximum weight.

The Ampaire TailWind is the most unconventional looking of the three, with very high aspect ratio wings mounted on top of the fuselage and a ducted electric fan mounted at the rear. The initial design is for a 9 passenger aircraft, with both battery electric and hybrid electric powerplants being investigated. The company has dispensed with the vertical and horizontal stabilisers at the rear and is instead planning on controlling their aircraft with vectored thrust.

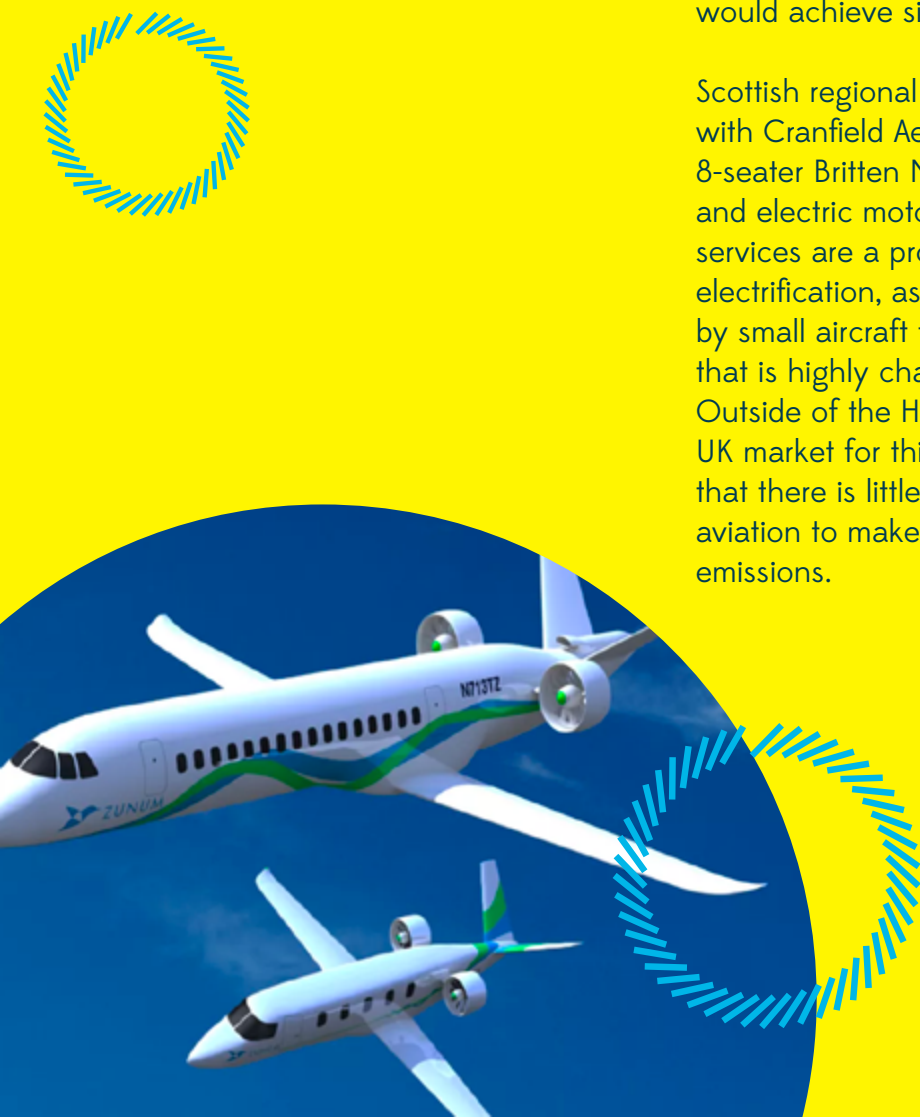


Some of the manufacturers of small electric aircraft have very high hopes for this market. ZUNUM Aero suggests that “quiet electric propulsion cuts community and cabin noise by 75%, emissions by 80%, which means that by the 2030s we can eliminate 40% of all commercial aviation emissions.”<sup>13</sup>

The claim that 40% of all commercial aviation emissions can be eliminated does not chime with our analysis of the UK market. In order to electrify 40% of UK aviation emissions we would need aircraft capable of flying over 5,000km. The company may be referring to the US market where there is a lot more domestic aviation, but the source of this claim is unclear. ZUNUM Aero is very bullish about the ability of electric aircraft operating from small, local airports, to draw travellers on trips of 1,000 miles or less away from surface modes.<sup>14</sup>

We would expect these surface modes to be electrified before aviation and, in the case of rail and bus transport in particular, these modes will be more efficient than flying, so it is questionable that switching from surface modes to electric aviation would achieve significant emissions reductions.

Scottish regional airline Loganair is currently working with Cranfield Aerospace Solutions to modify an 8-seater Britten Norman Islander to run on batteries and electric motors. The Scottish remote airport services are a promising, albeit niche, market for electrification, as they are predominantly operated by small aircraft travelling short distances over terrain that is highly challenging for surface transport. Outside of the Highlands and Islands, the limited UK market for this type of aircraft operation means that there is little scope for this category of electric aviation to make a material impact on UK aviation emissions.



### 3. regional

The company with the greatest exposure to date in the regional electric aircraft market is Wright Electric. This US manufacturer has teamed up with low cost operator Easyjet to promote their concept for a 150 seat battery electric aircraft. Wright Electric's design is so far the only attempt at developing an electric aircraft that is similar in terms of capacity to existing regional aircraft. Aspects of its design will be familiar to current air travellers although its propulsion system is made up of a number of distributed motors mounted in the wing and at the rear of the fuselage and a v-tail. It is, however, limited in terms of performance with a reported 500km range.



#### RANGE

**1,500km**

#### PASSENGERS

**Up to 150**

#### UNDER DEVELOPMENT

Wright Electric,  
ZUNUM Aero,  
Airbus E-Fan X

#### CURRENT

Dash 8, Embraer E-Jet  
Family, BAe 146

#### % UK EMISSIONS

**13%**

Wright Electric's goal is "for every short flight to be zero-emissions within 20 years"<sup>15</sup> but little information beyond some renderings and occasional news stories is available about their aircraft and it is uncertain how far development has progressed. Wright Electric is reported to be developing a 9 seat aircraft which is due to fly in 2019. The company hopes to have aircraft flying operationally within 10 years.

ZUNUM Aero has a second hybrid design that is expected to carry around 50 passengers with a possible range of around 1,000 miles (1,600km) and in some publicity images, a larger aircraft with a wider body than the rest of the ZUNUM Aero family is visible in the background but no information has been released about this concept.

The Airbus E-Fan X is a demonstration project testing a hybrid electric propulsion system developed as a collaboration between Airbus, Siemens and Rolls Royce. The project will see one of the four engines on a British Aerospace RJ100 regional jet being replaced with a 2MW electric motor and fan. The motor will be powered by a liquid fuel-powered turbogenerator and energy storage system. The E-Fan X demonstrator is expected to start undergoing testing in 2020.

UK domestic flights and international flights up to 1,500km together account for around 13% of UK aviation emissions (although not all of this is flown in regional jets). The short journey distances and small size of regional jets suggest that this market could see some successful electrification in the coming decades.





#### RANGE

**4,000km**

#### PASSENGERS

**Up to 200**

#### UNDER DEVELOPMENT

**None**

#### CURRENT

Single aisle aircraft  
(e.g. Airbus A320 and  
Boeing B737 families)

#### % UK EMISSIONS

**15%**

### **4. short haul**

There are currently no companies known to be developing battery or hybrid electric aircraft for the short haul commercial aircraft market. Some design concepts were produced by Airbus (the E-Thrust) and Boeing (the Sugar Volt) around five years ago and there has also been some research work undertaken by universities and research institutes such as NASA.

Short haul aviation above 1,500km accounts for around 15% of UK aviation emissions.





#### RANGE

**~12,000km**

#### PASSENGERS

**250+**

#### UNDER DEVELOPMENT

**None**

#### CURRENT

Twin aisle aircraft  
(e.g. Boeing 747, 767, 787  
and Airbus A330,  
A350, A380)

#### % UK EMISSIONS

**72%**

### **5. long haul**

There are currently no companies known to be developing battery or hybrid electric aircraft for the long haul commercial aircraft market and we are not aware of any design concepts with capabilities comparable to the large twin aisle long haul aircraft.

Long haul aviation accounts for around 72% of UK aviation emissions.

# factors affecting electric aircraft range

One of the fundamental equations of aeronautical engineering is the Breguet range equation and this equation can be adapted for electric aircraft<sup>16</sup>:

$$R = E^* \cdot \eta_{\text{total}} \cdot \frac{1}{g} \cdot \frac{L}{D} \cdot \frac{m_{\text{battery}}}{m} \cdot$$

In this equation:

- **R** represents the aircraft's range
- **E\*** is the battery's gravimetric energy density or energy per unit mass<sup>17</sup>
- **η<sub>total</sub>** is the efficiency of the entire propulsion system
- **g** is the acceleration due to gravity
- **L/D** is the Lift to Drag ratio, a measure of the efficiency of the airframe
- **m<sub>battery</sub>/m** is the battery mass fraction, i.e. the mass of the battery divided by the total mass of the aircraft

In order to maximise the range aircraft designers therefore have four aspects of the aircraft's design which they can maximise:

- battery energy density
- the efficiency of the propulsion system
- the aerodynamic efficiency of the airframe
- the proportion of the airframe's mass which is taken up by the battery.

## battery energy density

Like most fossil fuels Jet A-1, the aviation turbine fuel which powers commercial aircraft, packs a lot of energy, with a net calorific value of 44GJ/tonne<sup>18</sup> or 12,200kWh/kg. This extremely high energy density is what allows commercial aircraft to fly such extreme distances on a daily basis. Battery energy density has seen significant improvements in recent years, but it currently lags far behind the energy density of Jet A-1.

When considering the energy density of a battery it is important to be clear what is being talked about. Many of the quoted values for energy density are at the individual cell level. Cell energy density for lithium-ion batteries is increasing at a steady rate each year and for the best performing production cells, such as the Panasonic NCR18650GA, is now in the 250Wh/kg-275Wh/kg range<sup>19</sup>.

However once these cells are packaged up into modules and the modules are packaged up into battery packs with their associated battery management and cooling systems, the pack energy density ends up being substantially lower than the cell energy density. Tesla's Model 3 battery has an energy density of 150Wh/kg according to filings with the US EPA<sup>20</sup>, substantially lower than the more than 250Wh/kg that the 2170 cells that make up the battery are understood to have.

18650 cell



Jet A-1 therefore has an energy density about 60 times greater than that of today's best electric vehicle batteries. This gap in performance will reduce over time as the energy density of lithium-ion batteries has improved at a fairly consistent rate of about 10Wh/kg per year, but the technology is expected to be limited by the chemistry to around 400Wh/kg<sup>21</sup>.

Incremental battery improvements (for example gradual improvements in the energy density of lithium-ion batteries) are expected to increase electric aircraft range over time and it is likely that aircraft will be designed in such a way that batteries can be removed so in service aircraft could potentially benefit from these improvements, not just new aircraft.

New battery chemistries (for example lithium-sulphur or lithium-air), which are hoped to push battery energy density towards the mid to high hundreds of Wh/kg are being actively researched around the world. Lithium-sulphur battery manufacturers such as Sion Power<sup>22</sup> and Oxis Energy<sup>23</sup> are reportedly achieving cell energy densities over 400Wh/kg, and are targeting electric unmanned air vehicles.

These new chemistries will need to be extensively tested before they can be used in a passenger aviation context so it is likely that it will be some time before novel battery chemistries are deployed in passenger-carrying aircraft.

## propulsion system efficiency

Modern electric motors now have very high specific power (or power-to-weight ratio, a measure of power per unit mass) of 5 to 10kW/kg, similar to the specific power of large turbofans, and electric aviation enables a move away from the current model of hanging two or four large engines under the wings.

The simplicity and compact nature of the electric motor compared to the turbofan means that designers can take a distributed approach to propulsion, with many smaller motors mounted at different points in the fuselage, wings and even out to the wingtips. This can lead to benefits ranging from improved aerodynamic efficiency and control to reduced weight through lighter structures and increased safety through greater redundancy.

While battery energy density is a fraction of the

energy density of aviation turbine fuel, an electric propulsion system would have a considerable efficiency advantage over the turbofans and turboprops used in modern aircraft. The turbofans which power modern aircraft are a lot more efficient now than the turbojets which powered aircraft in the early days of the jet age, however modern turbofans which power aircraft such as the Boeing 787 and Airbus A350 have an overall efficiency approaching 40%<sup>24</sup>.

An electric propulsion system comprising the battery, controller, electric motor, gearbox and propeller could be designed with an overall efficiency of between 80% and 90% which would mean that an aircraft powered in this way would require less than half the energy to do the same amount of work as the equivalent aircraft powered by a turbofan. Researchers are aiming at even higher efficiency targets with proposals for cryogenically cooled superconducting components to electric propulsion systems in order to handle the power demands of larger electric aircraft.

## airframe efficiency

Aircraft manufacturers have already made big improvements in airframe efficiency over the history of powered flight. Little definitive data is available on the aerodynamic performance of modern passenger aircraft but they are generally thought to have lift to drag ratios (L/D) of between 15 and 20, with the most efficient designs such as the Boeing 787 thought to have L/D of around 21. At the extreme end of aircraft design are gliders which typically have L/D ratios in the region of 40 to 50, with the highest performance examples though to have L/D of around 70.

The reason why gliders have such high aerodynamic efficiency is primarily because their wings have a high aspect ratio. The aspect ratio of a wing is the ratio of the wingspan to the wing chord (the average distance between the wing's leading and trailing edge). Increasing the wingspan and aspect ratio of a wing reduces the aircraft's induced drag. Induced drag, the rearward acting component of an aircraft's lift is one of the major components that make up an aircraft's total drag.

The other major component is parasitic drag which is the drag due to the aircraft moving through the atmosphere and is influenced by the aircraft's frontal area, shape and skin surface area. Increasing wingspan in order to increase aspect ratio increases the frontal area and skin surface area, thus increasing the parasitic drag component of the aircraft's total drag.

Furthermore high aspect ratio wings pose other challenges for aeronautical engineers including:



- **Structural** - high aspect ratio wings have a tendency to bend upwards as the centre of lift acts further from the centre of the fuselage. This can be overcome through the use of stiff materials and through the use of struts or trusses between the wing and the bottom of the fuselage which brace the wing.



- **Dynamic** - high aspect ratio wings are less stiff than low aspect ratio wings so are more prone to experiencing an aerodynamic condition known as flutter. This can be overcome through the application of stiffer materials or active controls that suppress flutter.



- **Geometric** - airports are currently capable of handling aircraft that fit into an 80m by 80m box. The Airbus A380 was designed to just fit into this box however if large aircraft with high aspect ratio wings are to be used then it could necessitate modifications to existing airports in order to accommodate them.

Other approaches to increasing aerodynamic efficiency include blended wing body designs, which merge the fuselage and wing into a single flying body, and boundary layer ingestion, which involves embedding the fans into the rear of the fuselage to reduce parasitic drag.

All of these approaches to increasing aircraft efficiency have been known about for decades but for various reasons have not yet been adopted by aeronautical engineers in production aircraft. If electric aircraft with meaningful range are to come about then it is likely that these radical changes in aircraft design will be needed.

## battery mass fraction

Typical fuel mass fractions, the percentage of the aircraft's maximum take-off weight (MTOW) that is fuel, range from 20% to 30% for short range aircraft up to 40% to 50% for long range aircraft. The rest of the weight of the aircraft is made up by the payload of passengers, baggage and cargo and the airframe and cabin fittings.

All aircraft have a maximum weight which they are allowed to operate at. This is known as the maximum take-off weight (MTOW). Pilots are not allowed to exceed the aircraft's MTOW as there will be structural or performance limitations which would make doing so dangerous. The MTOW is not a fixed weight and depends on the airport elevation, ambient temperature and runway length, amongst other things. The combination of the weight of the empty aircraft, the payload and fuel cannot exceed the MTOW.

Another important measure of an aircraft's weight is the maximum landing weight (MLW). An aircraft cannot take off and immediately land again as the weight of the aircraft, payload and fuel would be too great for the landing gear and aircraft structure. This is why aircraft which encounter a problem straight after take off must circle and dump fuel before returning to land. Typically the MLW is around 65% to 75% of MTOW in large long haul aircraft, 75% to 85% in short haul aircraft and 90%+ in regional aircraft.


In an electric aircraft, where the battery weight does not change over the course of the flight, the MTOW and MLW are the same. Therefore if aircraft designers were to electrify an existing design of aircraft, this limitation would mean that the aircraft would be unable to carry as much weight in battery as it could carry in fuel. In order to accommodate the full load of battery the aircraft designer would need to strengthen the airframe and landing gear (which would add a significant weight penalty) or the operator would need to carry less payload (which would reduce revenues). A clean sheet design for a new electric aircraft will need to account for this issue of constant battery weight.

Airlines currently have to make a trade-off between payload and fuel. If the airline wants to carry more passengers and cargo, then it must carry less fuel so that the MTOW isn't exceeded. Conversely if the airline wants to fly to airports that are further away the aircraft must carry a smaller payload. An extreme example of this trade-off was reported recently in the press. Australian airline Qantas has commenced operating a Boeing 787-9 non-stop from Perth in Western Australia to London. The airline has had to reconfigure the aircraft with fewer seats so that it can carry a greater fuel load.

Unless electric aircraft can be designed to utilise modular battery packs, they will be less flexible than conventional aircraft as they will have to carry the same weight of battery whether they are flying 1,000 miles or 10,000 miles. Modular battery packs would also be essential as discharged packs could be swapped for charged ones during the brief time available for turnaround between flights. The speed at which aircraft are prepared for the next flight would render conventional charging of on board batteries very challenging.

One obvious approach to maximise range would be to make the aircraft into a flying battery by packing it full of energy storage capacity, however adopting this strategy would necessarily come at the cost of revenue-generating payload. Therefore maximising battery mass fraction while still being able to carry sufficient payload for the aircraft to be financially viable will be a key challenge for electric aircraft designers. There is interesting research ongoing to develop structural batteries which perform a dual structural and energy storage function which could lead to significant improvements but it would not be possible to adopt a battery swap approach to replacing structural batteries at the end of each flight.



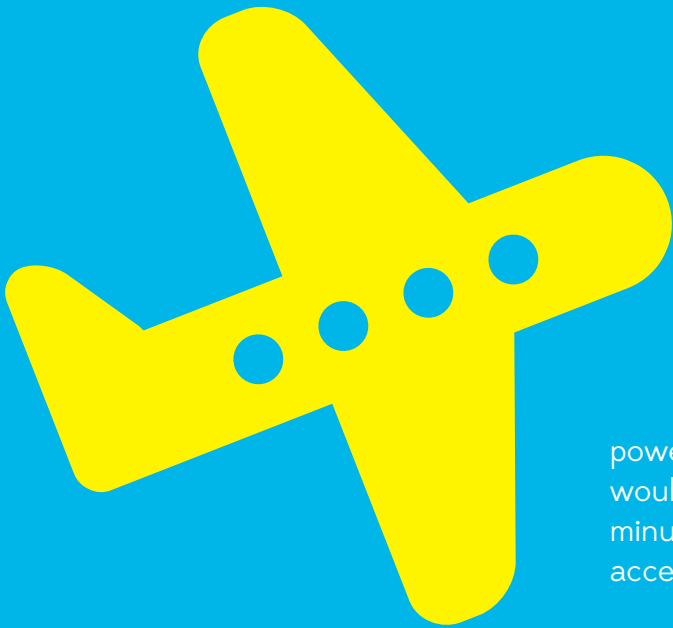


propulsion efficiency, airframe efficiency and battery mass fraction. These range estimates should be treated with caution as they do not take into account a number of important factors which will reduce the real world range of production aircraft.

The first thing to consider when assessing the capabilities of electric aircraft is the requirement to take into account unforeseen circumstances while flying. Aircraft must currently carry not only the fuel required for the trip, but also contingency fuel to allow for unforeseen changes to the flight plan, diversion fuel to get to an alternate destination airport and reserve fuel to allow for holding at the alternate airport. This additional fuel load adds up and will have implications for electric aircraft as a technical range of 1,000 km will end up with an operational range significantly lower in order to account for reserves.

Secondly the Breguet range calculation also only estimates the energy needed to propel the aircraft in a steady state (i.e. in the cruise phase of the flight) and the take-off phase of flight requires a considerable amount of energy to get the aircraft up to its cruising altitude. On short haul flights this phase of the flight makes up a significant proportion of the total flight time.

Thirdly modern aircraft also have a plethora of subsystems including flight control, avionics, communications, environmental control, de-icing and entertainment, amongst many others. These all consume energy (in the case of the 787 more than 1MW of power is needed for its subsystems) which will need to be supplied by the battery. Aircraft batteries would probably also need much more

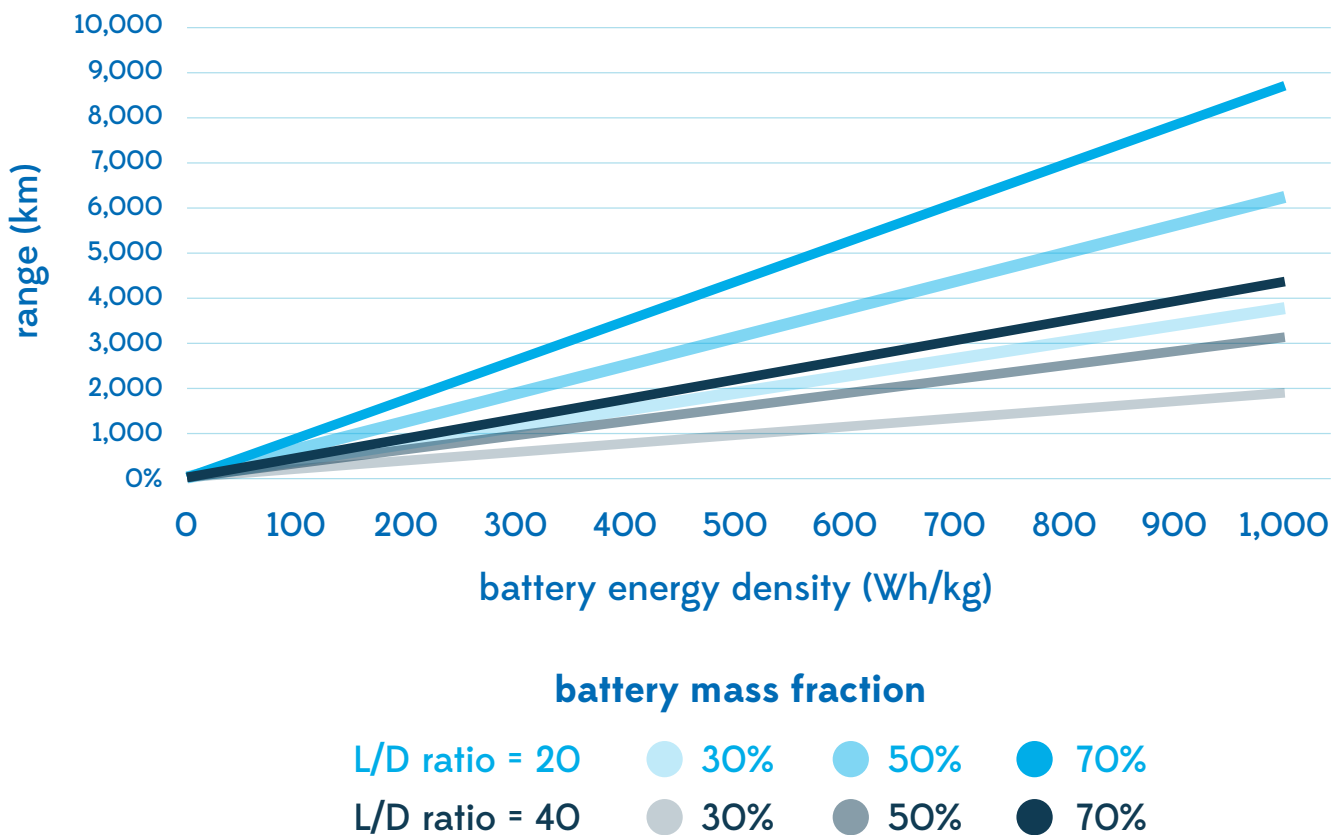


powerful cooling systems than car batteries as they would be operated at peak loads during take-off for minutes rather than the seconds which a car takes to accelerate.

Finally, lithium-ion batteries in particular do not respond well to being completely discharged so a key strategy adopted by electric vehicle manufacturers to extend the life of the battery is to oversize it and then use a proportion of the total capacity. This strategy would lead to electric aircraft carrying around unusable battery capacity unless future battery chemistries can overcome this limitation.

Assuming a propulsion system efficiency of 85% we can calculate estimates of the range which can theoretically be achieved by aircraft with different battery energy density and mass fractions and with different levels of aerodynamic performance ranging from 20 (the blue lines, representing current high performance commercial aircraft design) to 40 (the green lines, representing a doubling in performance compared with today's aircraft):

**figure 6** Electric aircraft range for different battery energy density, mass fraction and L/D ratio



**source:** Authors' calculations using modified Breguet range equation from "Electric Flight – Potential and Limitations" Hepperle, Martin. NATO. 2012

As can be seen from this chart, the range estimates of around 500km to 1,000km for the first crop of electric aircraft appear to be plausible if we assume a battery energy density of about 200Wh/kg. In order to achieve a range which has a material impact on UK aviation's greenhouse gas emissions (for example a 30% reduction would require a range of around 3,500km) we would need to see some combination of greatly increased battery energy density coupled with radical improvements to airframe aerodynamic efficiency, as well as an increase in battery mass fraction.

## hybrid aircraft

Absent a truly radical breakthrough in battery and aircraft design, longer range flights will remain beyond the capabilities of battery electric aircraft for a long time to come. In the meantime the industry is developing hybrid systems which combine batteries, turbogenerators and electric propulsors to realise some of the benefits of electrification while overcoming the range limitations of batteries.

A key factor in terms of the carbon mitigation potential of hybrid aircraft will be the degree of hybridisation i.e. the proportion of an aircraft's operations which will be derived from low carbon electricity versus kerosene.

Aircraft manufacturers could opt for larger batteries that can handle a greater proportion of the aircraft's operations or larger fuel tanks which can deliver greater range. Opting for a smaller battery used predominantly for take-off and climb, with aviation fuel doing the heavy lifting for most of the flight will allow greater range but will generate more modest carbon mitigation.

Looking beyond kerosene, hybrid aircraft could potentially be fuelled by electrofuels (synthetic 'drop-in' fuels made using low carbon energy and ideally using carbon captured from the air which directly replace conventional fossil fuels)<sup>25</sup> or hydrogen.

Without knowing more about the degree of hybridisation that manufacturers will follow or the extent to which alternatives to fossil kerosene will be available, it is difficult to estimate the contribution to greenhouse gas mitigation that hybrid aircraft could present, but Siemens, who are developing hybrid electric systems for aircraft, see the potential for energy savings of between 4% and 20%<sup>26</sup>. This level of reduction would clearly be very useful but is not a game changer, particularly when compared against forecast growth in passenger numbers.




## conclusions

An enormous amount of research and development energy is being put into electric aircraft and the technology appears to be mature enough for electric aviation to make a start in the 2020s. However, in order for electric aircraft to have a meaningful impact on UK aviation CO<sub>2</sub> emissions, we will need to see aircraft manufacturers bringing aircraft to market with:

- radically more efficient airframe designs,
- powered by high energy density batteries,
- which take up a greater proportion of the aircraft's weight than fuel does now,
- driving wholly new electric propulsion systems.

Furthermore, if electric aircraft are constrained to small aircraft or if high battery mass fraction means that only low payload designs are feasible, then this would involve a fundamental shift in how airlines operate, with a large increase in the number of aircraft required to carry the same number of passengers and cargo.

All of these changes need to be brought about in a meaningful timescale in order for electric aviation to make a useful contribution to mitigating the climate change impacts of the industry, and to meeting the Paris Agreement goal to limit warming to well below 2°C by achieving 'net zero' global emissions by 2050. While it is encouraging to see attempts at electrification emerge, it is important to manage our expectations in line with the evidence.





Successful electrification of commercial aviation will entail completely new and radically improved airframe designs, new electric propulsion systems and megawatt-scale battery systems. Developing and testing these, so that regulators are satisfied with their performance and safety, will take time. Safety concerns have pushed the aviation industry towards being inherently conservative in its approach, and this has led to an incrementalist approach to technology adoption. As aircraft have become more complex, so product development times have increased. From the 1950s to the 1980s, it typically took Boeing and Airbus 5 or 6 years to move from product launch to first deliveries. In the 1990s this increased to 7 or 8 years and since the turn of the millennium, product development times have increased to around a decade on average.

Perhaps the new entrants to the aircraft manufacturing business will repeat what Tesla has managed to achieve in the automotive industry and produce a viable product which is attractive to airlines and, in doing so, push the incumbent manufacturers to launch their own electric vehicles. The incumbent manufacturers in the aviation sector, Airbus and Boeing, are so far investing very little in developing these first generation electric aircraft. Meanwhile Airbus has nearly 7,400 aircraft on order<sup>27</sup> and Boeing has 5,800 aircraft on order<sup>28</sup>, order books equivalent to half the current in-service fleet of 27,000 passenger aircraft<sup>29</sup>. More than 80% of these are short haul, single aisle aircraft, and all are models which burn fossil fuels.

Once built, an individual aircraft will then operate for decades and tens of thousands of flight cycles before they are retired, so many of the aircraft being delivered today will still be operating in 2050. If all we can expect from electric aviation in the 2020s is a number of small aircraft designs flying up to about 1,000km then it is difficult to avoid the conclusion that electric aviation will only contribute a modest amount to reducing emissions from the sector.

This is the context in which proposals such as a frequent flyer levy should be viewed. There is no realistic prospect - and there are no industry plans - for improvements in aircraft technology to bring about large overall reductions in greenhouse gas emissions from passenger flights within a timeframe

that is meaningful to averting catastrophic temperature rises. We welcome Transport & Environment's recent 'roadmap' paper commending accelerated development of synthetic electro-fuels to substitute for kerosene<sup>30</sup>. This is almost certainly necessary, but it will not be sufficient on its own to bring aviation emissions within safe limits; even if implemented in full, T&E's roadmap still sees demand growth significantly attenuated through increases in the cost of flying caused by switching to more expensive electro-fuels.

Growth in demand during the coming decades, both in the UK and globally, is set to far outstrip reductions in the carbon intensity of air travel in even the most technology-optimistic industry planning scenarios. The problems with reliance on carbon offsetting are beyond the scope of this paper, but have been well documented elsewhere. The inescapable conclusion is that governments need to enact policies to manage growth in demand for air travel if they intend to honour their commitments on climate change. Whatever technological hopes and dreams policymakers may share with the aviation industry, we must make provisions now to address the shortfall between where technology is able to get us and where science-based emissions targets tell us we need to be.

It is long past time that the UK government in particular began to take this challenge seriously, and to scope policy options for effective, socially just and politically deliverable air passenger demand management. We believe that a frequent flyer levy is the best option available.

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