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Breaking barriers: An assessment of the feasibility of long-haul electric flights

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ABSTRACT

This study is a response to the current long-term policy effort aimed at reducing greenhouse gas emissions from aviation. It explores the short-term feasibility of servicing medium and long-haul commercial air routes with fully electric, zero-emission aircraft. The focus on long-haul flights reflects our understanding of the high levels of emissions associated with these routes. The analysis applies technical details of current electric aircraft development to the conditions faced by 183 long-haul over-water inter-city air routes. It also investigates the effect of future technical developments in battery power. Three scenarios of battery development illustrate how new electric aviation routes might evolve over time. Results show that, as expected, with current electric aircraft technology, most of the routes are more complex, slower, and more expensive than today's services. However, a significant number of simulated routes appear to be competitive in terms of fares with the current non-stop services. Furthermore, the simulations reflect conditions that existed in the early development of aviation and show that the expected evolution of batteries could increase the number of long-haul routes potentially served with electric aircraft. The study concludes that the immediate future of electric aviation might lie in selected, long-haul routes with low geophysical complexity and suggests that the methodology developed here could be used to evaluate proposals for services, some of which could be directed at smaller and remote locations.

1. Introduction

The need to consider the future of air transport was highlighted in the conclusions of the 2021 Glasgow Climate Change Conference (Buzzo et al., 2023), which emphasised the urgency of addressing the world's excessive greenhouse gas emissions (GHG) without delay. Recent advancements in engine technology have led to a reduction in GHG emissions per passenger-mile, but the substantial increase in passenger traffic has outweighed any benefits, resulting in a steady rise in absolute emissions (Budd and Suau-Sanchez, 2016). This phenomenon is known as the Jevons paradox. In response to this paradox, major European aviation industry groups signed "Destination 2050" in 2021, outlining a decarbonisation roadmap to achieve net-zero aviation emissions by 2050 while maintaining an average annual passenger growth of 1.4% (Royal Netherlands Aerospace Centre and SEO Amsterdam Economics, 2021).

Nonetheless, in its Net Zero by 2050 scenario trajectory (IEA, 2021), the International Energy Agency's Tracking Clean Energy Progress categorises aviation as 'Not on track'. The latest Aviation Tracking Report (IEA, 2023) *underscores* the challenges in scaling up sustainable aviation fuel production and emphasises the necessity for increased pressure applied through fuel taxes, low-carbon fuel standards, and mandatory blending.

While both industry and scholars acknowledge that most of the decarbonisation technologies and related aviation infrastructure (including energy storage, airframes, and propulsion engines) will take decades to develop (ICAO, 2022), there is a growing demand for immediate alternatives. Many analysts suggest that electric aircraft could play a role in addressing this challenge, albeit primarily for short distances (Baumeister et al., 2020; Monjon and Freire, 2020).

According to Eurocontrol, while long-haul passenger services account for only 6% of total flights, they are responsible for 51% of the industry's carbon emissions (Eurocontrol, 2021). Epstein and O'Flarity (2019) show that if mid-haul flights are included, 98% of the world's

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aviation greenhouse gas emissions are generated by airliners with >25 metric tons of take-off weight per flight. Park and O'Kelly (2014) demonstrate that for flight-stage distances of 5000 to 6500 nautical miles (9260 km to 12,308 km), airplanes begin to significantly increase fuel burn per kilometre by more than approximately 20% to 70% compared to the most efficient range distances. In more recent research, Dobruszkes et al. (2022) confirm that long-haul journeys need to be the major focus to manage the environmental impact of air transport and affirm that 82% of the fuel burned is on flight sectors longer than 1000 km, even though 44% of the passengers fly short-haul routes. Furthermore, for longer flights, the inherent need for more fuel is compounded by their lower fuel efficiency, primarily attributable to reduced seat density.

Therefore, the fact that current scholars and industry associate electric aviation only with the short-haul segment seems to imply that the decarbonisation of the overall industry is decades away, contradicting the urgency to meet the 2050 goals. The underlying assumption in the literature is that electric flights should be expected to meet the same criteria as current non-stop, long-haul flights to be considered a viable solution. This includes accommodating a similar number of passengers and achieving comparable distances and flight times as traditional jet fuel aircraft. Consequently, it is worth considering whether electric aircraft could reshape long-haul flights by challenging some of the current travel patterns.

We address this research gap by applying current knowledge of electric flight operations to long-haul segments in two steps. First, we develop an Intermediate Stop Operations (ISO) approach to analyse the economics and operating constraints of electric aircraft on long-haul missions. Second, we apply this approach to assess their potential substitution for current flights. The analysis is conducted on 183 simulated flights within the long-haul range. We run these simulations separately for three scenarios of current and future battery technology development. The results of the simulations are also applicable to the medium-haul segment.

We have structured this paper as follows. Following an overview of current thinking in this area in the Literature Review chapter, we continue with a Data and Methods and a Results section and conclude with Discussion and Further Research.

2. Literature review

The foundation for the analysis and subsequent simulations of long-haul routes is based on four primary sources in the literature: the current technical capabilities of low or zero-emission passenger aircraft; the cost and operational analysis of short-haul, point-to-point zero-emission commercial flights; the projected advancements in rechargeable electric batteries and their impact on electric air travel; and insights from the evolution of early long-haul aviation routes.

Within the literature exploring the current technical capabilities of aircraft, two main categories of studies have been identified: those focused on technologies that marginally reduce emissions, such as Sustainable Aviation Fuels, SAF (Emmanouilidou et al., 2023; Ng et al., 2021) or hybrid propulsion systems (Cardone et al., 2023; Arat et al., 2023); and those focused on technologies that aim to fully eliminate the carbon footprint of flights. This research has primarily focused on the second category of ideas.

An array of researchers has concluded that Electric Aircraft Propulsion (EAP) with rechargeable batteries is the most readily available technology to achieve zero-emission aviation in passenger and cargo air transportation in the next few years (Eissele et al., 2023; Gnadt et al., 2019; Otto et al., 2022;). Throughout this paper, the concept of "zero emissions" refers solely to tailpipe emissions during flight, not to the full life cycle GHG emissions originating from electricity generation for battery charging. These emissions are highly dependent on energy production emissions and battery manufacturing processes (Barke et al., 2022; Johanning and Scholz, 2015). In reality, ensuring a consistent supply of emissions-free electricity is highly challenging, particularly if numerous airports are used for refuelling the aircraft batteries.

While electric, zero-emission transport technologies are already in place or foreseeable in the near future for ground and sea transportation, two key hurdles make a transition to fully electrified aviation with rechargeable batteries a challenging task. First, current electric batteries store much less energy per kilogram than jet fuel does (Kuhn et al., 2011). Second, electrifying aviation will require significant aircraft redesign, which could render today's models redundant (Brelje and Martins, 2019). These new designs will undergo a lengthy certification process to demonstrate their ability to safely carry passengers.

The key issue with batteries is related to their Gravimetric Energy Density (GED), measured in watt-hours per kilogram (W·h/kg). This represents the amount of available energy per kilogram of weight, a critical dimension when considering the operation of an aircraft. In other transportation systems, such as ground or water, the vehicles can typically carry their battery weight, albeit with some loss of speed or acceleration. In contrast, aircraft must lift all their load into the air and sustain it throughout a journey. In undertaking this task, jet fuel provides 12,700 W·h/kg, whereas the GED of currently used batteries ranges from 260 to 270 W·h/kg. This significant difference severely limits the feasibility of battery-powered aircraft (Barheim et al., 2023).

In terms of safety, although incidents involving fires with rechargeable batteries have been reported in various types of currently operational electric vehicles, particularly cars, the battery technology has been shown to offer much higher safety standards than comparable combustion engine vehicles (Larsson et al., 2014). However, safety is a central focus in the certification of electric aircraft (Sripad et al., 2021).

Despite these challenges, there is growing motivation and interest from aircraft designers, airlines, governments, and investors to electrify the aviation industry by utilising rechargeable batteries (Adu-Gyamfi and Good, 2022; Greenwood et al., 2022), with airlines like SAS planning to launch electric flights over the next decade (Scandinavian Airlines, 2023). Various public and private organisations worldwide are leading this movement, endorsing projects related to different aspects of the value chain for electrified flights (Tom et al., 2021; Zhang et al., 2022).

One of the breakthroughs expected to address the battery density problem in the longer run is the utilisation of hydrogen fuel cells to power the engines, as an alternative to traditional batteries (Janic, 2014). These hydrogen-powered aircraft have the potential to offer larger passenger capacity and greater range than battery-powered aircraft (Verstraete, 2009). However, hydrogen technology still faces significant technical challenges that will likely take over a decade to overcome (Hoelzen et al., 2021). Therefore, attention has returned to batteries.

While battery technology in its current state limits electric aviation from completely replacing jet fuel operations, in the longer term, batteries could provide the GED required to compete with existing aircraft models and operations. In April 2023, CATL, one of Tesla's leading battery suppliers, announced the introduction of a lithium-ion battery with a remarkable GED of 500 W·h/kg. Mass production of this battery is anticipated to commence in the first half of 2024 (CATL, 2023). Furthermore, in March 2023, researchers successfully developed a rechargeable lithium-based battery with an even higher GED of 711 W·h/kg (Li et al., 2023). These technological advances are in line with previous research indicating that GED has tripled over the last decade (Cao et al., 2020; Placke et al., 2017; Song et al., 2017). Other recent studies (Gil-González et al., 2022; Wang et al., 2022; Xiong et al., 2023) envision even faster battery evolution, expected to surpass the 1000 W·h/kg GED mark in the short term. When these batteries become available, they could enable electric aircraft to cover longer distances and enhance their safety and reliability.

Consistent with the focus on short-haul, point-to-point routes, studies on the operational costs of existing electric aircraft models have primarily cantered around this segment. Witte et al. (2013) provide cost estimates for six potential short-haul Scandinavian routes and compare the operating costs of two existing jet fuel aircraft, the Beechcraft 1900D and the Jetstream JS31, with a similarly sized electric aircraft, Heart Aerospace's ES-19. A noteworthy finding of this study is that the operating costs for the electric prototype consistently range from 15% to 22% lower than those of similar-sized, fuel-powered aircraft. This outcome aligns with previous comparative cost analyses, such as Ploetner et al. (2013), and is supported by more recent studies (Apanasevic et al., 2021; Monjon and Freire, 2020). These studies suggest that an ES-19 could reduce operational costs by up to 40% and energy costs by up to 80% when compared to a similar fuel-powered aircraft. In our analysis, we adopt a cost structure similar to that of Apanasevic et al. to generate cost estimates for the simulated long-haul routes.

Finally, to establish a spatial framework for our simulations, we draw upon an analysis of the evolution of early commercial aviation, a time when engine technology limitations restricted capacities and ranges. We adopt a four-stage model of airport route development originally formulated by O'Connor (1995), revisited by Derudder and Witlox (2014), and illustrated in the aviation history of the Asia Pacific region (O'Connor, 2019) and the US (Bowen, 2010). The first stage represents the initial route configuration when technology only allows short-range flights. In the second stage, as technology improves, both range and cruise speed increase, leading to the bypassing of some intermediate airports and enabling more optimal routes based on geographic convenience and airport importance. Stages Three and Four correspond to hub development and a principal axis shift. This representation of technological development helps us envision a role for short-haul links within long-haul services. Additionally, it provides insight into the role that cities along the routes play in the operation of air services and suggests that electric aircraft operations could return us to an earlier configuration of cities and airports.

To our knowledge, this paper represents the first attempt to assess the feasibility of pure electric long-haul commercial services based on an alternative travel pattern.

3. Data and methods

3.1. Data and city-pair selection

The analysis is conducted on the 200 most populated non-stop flights within the long-haul range (>3000 km or 1620 nautical miles) using OAG data from 2019 (OAG, 2019). Subsequently, we simulate alternative ISO electric routes based on real stopover airports. This simulation is carried out for three scenarios of battery development. The first scenario reflects the currently available battery capabilities, while the other two represent future scenarios with advanced batteries.

To explore the impact of geographic complexity on the electric routes, we categorise all the simulated routes into three groups based on their geophysiographic complexity, measured as the percentage of detour from the theoretical Great Circle Line (GCL). The first group consists of routes where potential recharging airports could be found, resulting in less than a 1% detour from the GCL. In the second group, detours range from 1% to 20%, while the third group includes routes with detours exceeding 20%. It must be noted that actual detours between electric flights and real flights might be smaller. This assertion is supported by the findings of Dobruszkes and Peeters (2019), which reveal that real long-haul flights tend to deviate an average of 4.8% from the Great Circle Distance (GCD). Taking into account this correction to double-check the route groupings, our analysis confirms that the defined route groups remain unchanged.

From the total database of 200 routes, we exclude 17 routes belonging to the third group, the most complex, due to their destinations being remote islands that are inaccessible to electric planes requiring recharging stopovers. In total, we create 549 simulations, which include the remaining 183 routes for the three battery scenarios.

Additionally, OAG data provided us with detailed route-specific real ticket fares and actual flight times, allowing for a granular comparison of the potential of pure electric long-haul flights. In the following sections, we present detailed maps for three examples from each of the route groups with varying levels of geophysiographic complexity: Frankfurt-Dubai, Sydney-Singapore, and London-New York.

The Frankfurt-Dubai example falls into the first group of city pairs, characterised by a dispersion of cities along the route with appropriate airport infrastructure, enabling the simulated routes to closely align with a GCL. The Sydney-Singapore pair belongs to the second group of city pairs, presenting some alignment with a GCL but also facing challenges in locating usable airports in sparsely populated areas and navigating open-ocean crossings. Lastly, the city pair London-New York exemplifies the third group of routes, featuring significant geographic and airport infrastructure challenges.

3.2. Selection of an electric aircraft based on 2023 technology

The conceptual electric aircraft used in the simulations incorporates information from existing aircraft projects awaiting certification and data from the current state of electric battery technology, with a particular focus on GED achieved as of 2023. Table 1 displays aircraft with recent maiden flights with low or zero direct (Scope1) emissions as of mid-2023. Only Eviation has released detailed performance specifications for the Alice model flights using 100% zero-emission technologies (Eviation, 2023). With the currently installed 375 W·h/kg battery, Alice has a range of 250 nautical miles, taking into account regulatory reserves at Maximum Take-Off Weight (MTOW). The manufacturer has recently announced plans to install a 500 W·h/kg battery or higher when it becomes available. The other three prototypes have operated in hybrid mode, meaning they generate power using a combination of fuel and hydrogen cells or hydrogen combustion (Ampaire, 2022; Universal Hydrogen, 2023; ZeroAvia, 2023).

For our simulations, we define a conceptual aircraft model similar to Eviation's Alice. We also assume the use of a rechargeable battery with a GED of up to 500 W·h/kg, which is currently available and can be readily incorporated into the production of this conceptual aircraft.

Based on this information, we envision an all-electric, 9-seater aircraft with a range of 420 nautical miles at MTOW, inclusive of regulatory reserves, and a cruise speed of 250 knots. The published specifications of the Alice prototype in 2023 indicate a required MTOW runway length of 2750 ft. Although the cruise flight level is not explicitly specified, most turbo propellers similar to this aircraft typically operate at altitudes around 15,000 ft (Habermann et al., 2023). Consequently, the necessary runway length and flight ceiling suggest that these planes will be well-suited for use at smaller, less-utilised airports and along less congested, low-altitude air routes (Doctor et al., 2022).

3.3. Selection of airports en-route: re-charging and stop-over facilities

Another crucial consideration in our simulations is identifying airports that could facilitate battery recharging and accommodate passengers as needed. Whenever possible, we select airports with an ICAO code that meet specific criteria, including a minimum runway length of 2750 ft and proximity to electrical substations. These chosen airports are conveniently located near quality accommodation facilities, allowing for overnight stops if required. The distance between each stop falls within the maximum range of the aircraft, also considering safety reserves. Our analysis intentionally excludes political or conflict-related factors when assessing route feasibility. However, it is essential to acknowledge that in practical application, geopolitics can render several routes longer or even infeasible during specific periods.

We assess multiple route options for each city pair and ultimately choose routes that minimise the total distance flown. Considering that the ten longest real non-stop routes from our OAG data range from 12 to 15 h, we assume that a maximum day's trip duration of approximately 15–16 h is reasonable, even though some major airlines are planning

Table 1
Summary of features of low-emission aircraft with recent maiden flights (Source: Producer Websites).

Name	Producer	Maiden Flight	Engine Technology	Range (nm)	Speed (Ktas)	Passengers	Orders
Alice	Eviation	Sept 2022	100% Electric battery	250	260	9	330
Dornier 228	ZeroAvia	Jan 2023	Hybrid/Hydrogen Cell	300	n.a	19	50
Eco Caravan	Ampaire	Nov 2022	Hybrid Hydrogen/Fuel	1000	n.a	8	100+
Dash 300	Universal Hydrogen	Feb 2023	Hybrid/Hydrogen Combustion	600	n.a	40	n.a.

non-stop services lasting >18 h (Grimme et al., 2020).

3.4. Scenarios of the evolution of electric battery power

We explore three battery power scenarios, one based on the current technology associated with our selected aircraft, and two representing future increases in battery GED. The three scenarios are as follows: (1) the baseline 500 W·h/kg GED value, (2) 1000 W·h/kg, and (3) 1500 W·h/kg. We assume that the enhanced GED will be utilised to extend the aircraft's range from 420 nautical miles in scenario one to 840 nautical miles and 1280 nautical miles in the second and third scenarios.

For our purposes, we assume that the additional battery power will be used to increase the aircraft's range. We acknowledge that higher battery power could alternatively be used to increase speed or capacity, but the latter involves complex calculations related to aircraft operation, including speed-induced drag and lift-induced drag considerations.

3.5. Operational costs

We calculate the cost per mile for each of the 183 routes in each of the three battery scenarios to assess the financial implications of long-haul operations. Our estimates of operational costs are derived from technical and industry sources provided in Appendix 1.

4. Results: electrical aviation on long-haul routes

4.1. Scenario 1: Current battery technology

The 183 routes have been categorised into three groups based on geographic complexity, as previously discussed. These groupings are employed in the simulations to investigate the impact of geo-physiography on the results.

In the simulations, we use the conceptual aircraft model, with each leg of the trip limited to a maximum of 420 nautical miles. The cruise speed is assumed to be 250 knots, and the total travel time incorporates a 50-min stopover at each recharging airport (30 min for battery recharging and 20 min for the approach, descent, taxi, take-off, and climb phases). Figs. 1, 2, and 3 illustrate three selected examples from the entire database of routes.

Frankfurt-Dubai in Fig. 1 is an example of the first group of routes -low geophysiographic complexity-. It has a relatively short sea crossing and plenty of cities with airports with established runway capacity along the route to allow a route that closely follows a GCL between the origin and destination. Table 2 shows that the Frankfurt-Dubai city-pair has a total travel time of 16:19 h and could practically be completed without overnight stops.

In Fig. 2, the Sydney-Singapore route exemplifies the second group of routes, characterised by medium geophysiographic complexity. On the route between Sydney and Singapore, there is some deviation from the GCL due to the absence of airports in certain areas and the necessity to cross the sea. Table 3 provides details for the Sydney-Singapore route, consisting of ten legs and totalling 22 h and 44 min of travel time. An

Fig. 1. Route Frankfurt - Dubai in Scenario 1. Detour from the GCL = 0.6%.

Fig. 2. Route Sydney-Singapore in Scenario 1. Detour from GCL of 5.9%.

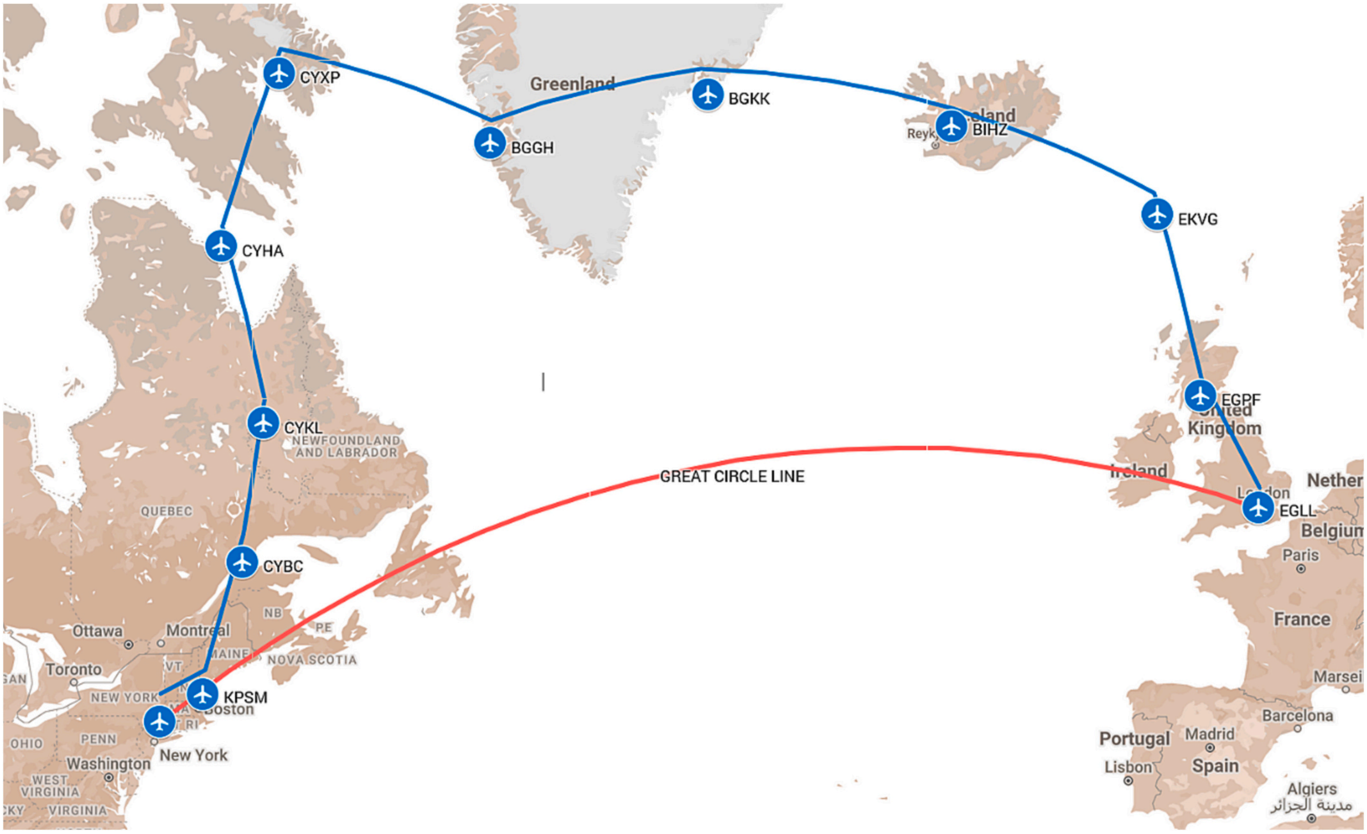

Fig. 3. Route London-New York in Scenario 1. Detour from the GCL = 29.5%.

overnight stop is required for this duration, adding the equivalent of a night's sleep to the total trip time. The scarcity of suitable airports in the Outback regions of Australia necessitates a detour from the GCL of nearly 6%, and the most suitable overnight stop is Darwin, located approximately 11 h from Sydney.

The London to New York flight serves as an example of the third group of routes, characterised by a complex physiography that poses challenges for the limited range of the aircraft. This complexity results in a substantial deviation from the direct great-circle line connecting the origin and destination, as depicted in Fig. 3. This added complexity increases the duration of the journey, and with stops for recharging, the total travel time, excluding sleep-over, amounts to 24 h and 39 min (See Table 4). The schedule necessitates one night stopover at Nuuk, which is approximately 11 h away from London. Nuuk is a city that offers decent

Table 2
Times and distances for the route Frankfurt - Dubai in Scenario 1.

	FRANKFURT-DUBAI			
Leg	**City**	**ICAO code**	**NM/Leg**	**Time* (h)**
0	Frankfurt, Germany	EDDF	–	–
1	Gyor, Hungary	LHPR	392	2:24
2	Bucharest, Romania	LROP	391	2:23
3	Kastamonu, Turkey	LTAL	391	2:23
4	Mardin, Turkey	LTCR	401	2:26
5	Al Kut, Iraq	ORUB	381	2:21
6	Bushehr, Iran	OIBB	338	2:11
7	Dubai, UAE	OMDB	328	2:08
Total			2621	16:19

Table 3
Route Sydney – Singapore in Scenario 1.

	SYDNEY-SINGAPORE			
Leg	**City**	**ICAO code**	**NM/Leg**	**Time* (h)**
0	Sydney, Australia	YSSY	–	–
1	Bourke, Australia	YBKE	355	2:15
2	Longreach, Australia	YLRE	407	2:27
3	Mount Isa, Australia	YBMA	314	2:05
4	Borroloola, Australia	YBRL	330	2:09
5	Darwin, Australia (sleep)	YPDN	384	2:22
6	Suai, East Timor	WPDB	379	2:20
7	Makassar, Indonesia	WAAA	404	2:26
8	Banjarmasin, Indonesia	WAOO	317	2:06
9	Ketapang, Indonesia	WIOC	304	2:02
10	Singapore	WSSS	406	2:27
Total			3600	22:44

Table 4
Route London-New York in Scenario 1.

	LONDON-NEW YORK			
Leg	**City**	**ICAO code**	**NM/Leg**	**Time* (h)**
0	London, United Kingdom	EGLL	–	–
1	Glasgow, United Kingdom	EGPF	299	2:01
2	Vagar, Norway	EKVG	382	2:21
3	Husafell, Iceland	BIHZ	398	2:25
4	Kulusuk, Greenland	BGKK	413	2:29
5	Nuuk, Greenland (sleep)	BGGH	379	2:20
6	Pangnirtung, Canada	CYXP	372	2:19
7	Quaqtaq, Canada	CYHA	323	2:07
8	Schefferville, Canada	CYKL	385	2:22
9	Baie Comeau, Canada	CYBC	344	2:12
10	Portsmouth, USA	KPSM	380	2:21
11	New York, USA	KJFK	197	1:37
Total			3871	24:39

services and has several quality hotels. Having established the geography and the times of these routes, attention now turns to their costs. Table 5 presents details of the estimated costs for the operation of the three example routes.

Table 5 illustrates that the total travel times for the three selected examples of long-haul city pairs, including stopovers and recharging time, span between 16 and 24 h. The overall cost, which encompasses variable and fixed expenses, ranges from approximately USD 1000 to 2000 per trip per passenger, with energy accounting for over 50% in all instances. In two of these cases, the cost per passenger is lower than the actual business class fare of the respective non-stop services in 2019.

We conduct a similar cost and trip time analysis for all 183 routes sourced from the OAG database. Figs. 4 and 5 present the findings for the three distinct groups of geographic complexity.

In Scenario 1, the majority of the simulated routes result in a per-passenger trip cost that exceeds the business class fare as of 2019. However, there are 69 exceptions to this pattern, primarily involving city pairs within Group 1 characterised by low geophysiographic complexity and, across all groups, where the GCL distance does not exceed 6000 km. Beyond this distance, the need for additional recharging stopovers adversely affects both trip duration and cost.

Table 5
Route Operation Costs estimate for the concept 9-seat electric aircraft one-way and real (OAG, 2019) non-stop services data.

Summary table one-way trip cost per passenger in USD			
	Fankfurt/ Dubai	Sydney/ Singap.	London/ NYC
Trip Total Time (h)	15:30	21:54	23:48
Energy cost	613	1093	1265
Maintenance cost	52	72	77
Pilot cost	266	366	393
Depreciation	72	99	107
Airport/aeronautical charges	100	163	184
Catering & sleepover	200	200	200
Total cost/pax in USD	**1305**	**1993**	**2227**
Average OAG flight time	6:20	8:20	7:55
Average OAG Bus Class Fare, USD	2198	1601	3129

Table 6 provides a list of electric routes for city pairs that, in Scenario 1, not only have lower costs than the business class fare, but also do not require overnight stays due to a total trip time below 16 h.

For all routes, the energy cost constitutes approximately 40% of the total cost, and, notably, GHG emissions are zero with electric aircraft. This percentage is not significantly higher than the average fuel cost of the global airline industry in 2022 and 2020, which was 30% and 19%, respectively, of the operating expenses (IATA, 2022).

4.2. Scenario 2 and 3: improved battery performance

The revised route configurations for scenario 2 highlight a reduction in the number of stops. In scenario 3, many cities are bypassed, aligning more closely with the GCL, which is most noticeable in the London-New York route. The overall effect of battery development on the previously mentioned example routes is summarised in Table 7. The lengthy and costly journey in scenario one appears vastly different from what we expect today. However, what initially seems like a primitive, multi-stop, and time-consuming journey, gradually evolves, and improves with more robust battery power. Travel times decrease significantly (almost half the duration for London-New York), costs decrease (reducing by a third to a quarter), and routes become less complex (requiring just one or two stopovers, making it possible to fly these example routes without overnight stays). One implication of this change is the impact on bypassing cities, which could further stimulate the development of hubs on major routes, as passengers in bypassed cities will now need to connect with services at these hubs.

The changes observed as battery power improves suggest a greater potential for electric aviation on long-haul routes. This impression is reinforced by how the changes seen in scenarios 2 and 3 in Fig. 6 correspond to the transition from piston-engine to jet aircraft, as depicted in the O'Connor (1995) model. A future breakthrough in battery or aircraft design could usher in a similar shift towards electric aircraft. However, it is important to consider some of the additional challenges that this transition must overcome, as outlined in the Discussion Section.

Figs. 7 and 8 present the comprehensive results of the 183 simulations in scenarios 2 and 3. Fig. 7 reveals that in both scenarios, the majority of city pairs from group 1, enjoy a lower trip cost compared to the corresponding current business class fare. Approximately half of the routes from groups 2 and 3 also exhibit a lower electric trip cost than the corresponding business class fare.

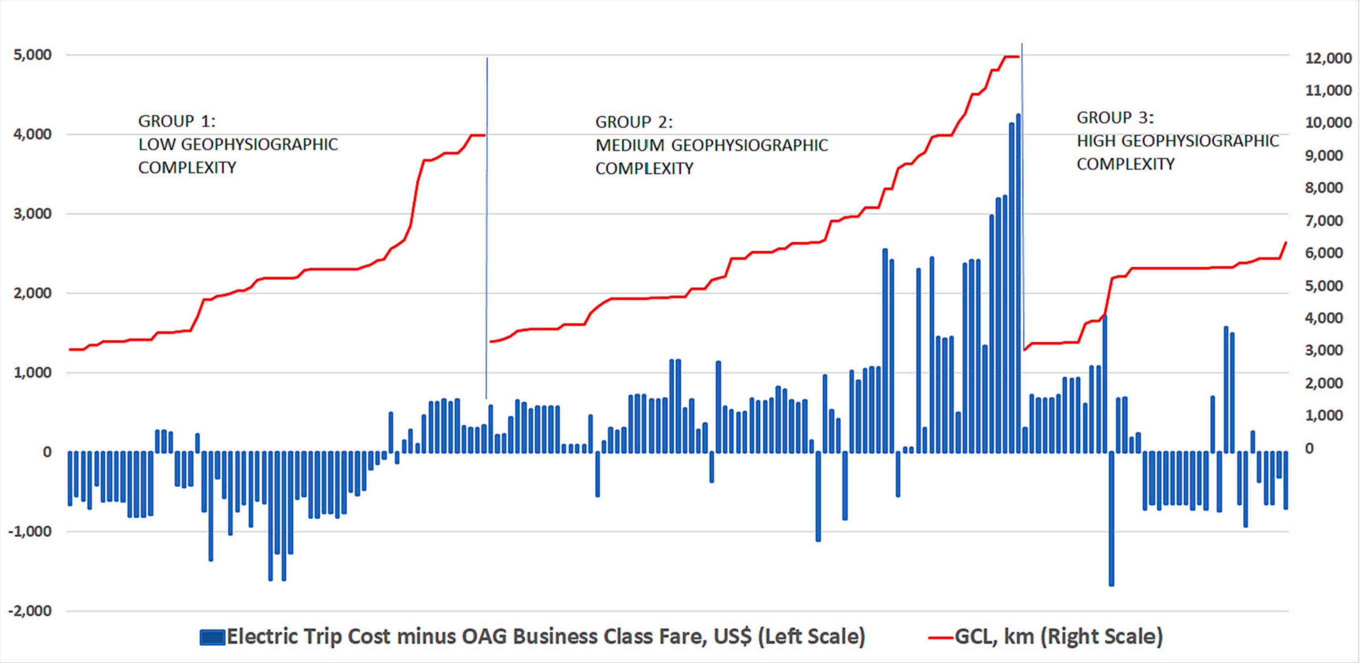

Fig. 4. Simulation results for the 183 routes in Scenario 1. The bars represent the disparity between the electric trip cost per passenger and the actual business class fare for each route. Additionally, the chart displays the GCL distance in kilometres for each city pair.

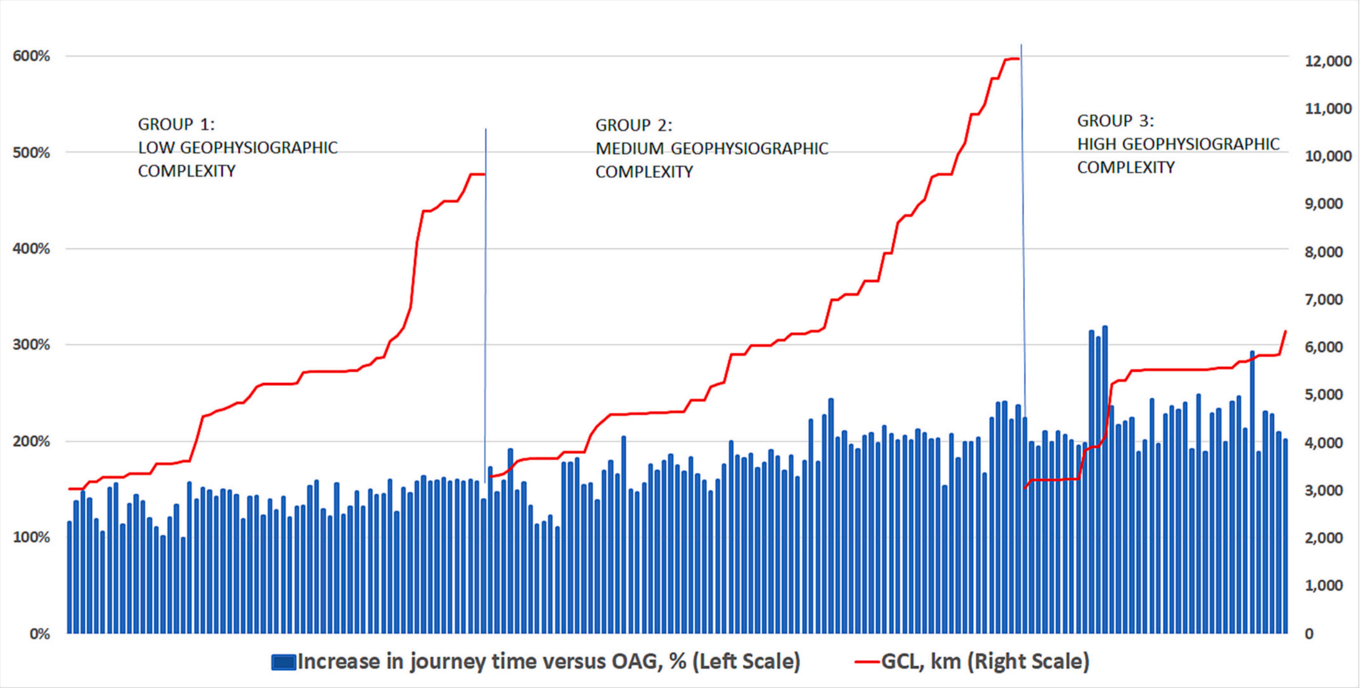

Fig. 5. Simulation results for the 183 routes in Scenario 1. The bars illustrate the additional trip time of the electric simulation as a percentage compared to the current non-stop service. Additionally, the chart displays the GCL distance in kilometres for each city pair.

In Fig. 8, scenario 2 demonstrates that the electric trip time for nearly all city pairs more than doubles, compared to the real non-stop current service. However, in scenario 3, we observe many routes with a time increase lower than 100%, and some routes even experience only a 50% increase in travel time.

5. Discussion and further research

Current technical development of zero-emission passenger aircraft has advanced to the point where fully electric short-range flights are becoming a reality. However, most emissions in the air transportation industry are generated by mid and long-haul flights. In fact, the current long-haul business model, which uses direct, point-to-point services, now extending into ultra-long stages, is the antithesis of a zero-emission

Table 6

City pairs where simulated electric routes have a trip cost per passenger lower than the OAG 2019 real business class fare and do not exceed a total trip time of 16 h.

Departure Airport	Arrival Airport	Seats (FY 2019)	GCL, km	GCL, nm	Electric route, nm	OAG Trip Time	Electric Trip Time	Stops	Avr Bus Class Fare, USD	Electric Trip Cost/pax, USD
Istambul	Dubai	204,424	3026	1634	1639	04:35	6:33	4	1417	748
Dubai	Male	207,404	3038	1640	1646	04:10	6:35	4	1305	751
Male	Dubai	204,454	3038	1640	1646	04:00	6:35	4	1365	751
Paris (CDG)	Beirut	204,304	3185	1720	1725	04:15	6:54	4	1496	783
Beirut	Paris (CDG)	203,890	3185	1720	1725	04:40	6:54	4	1205	783
Sydney	Perth	561,827	3275	1768	1784	05:05	7:08	4	1424	808
Perth	Sydney	469,274	3275	1768	1784	04:10	7:08	4	1415	808
Perth	Sydney	281,102	3275	1768	1784	04:05	7:08	4	1415	808
Sydney	Perth	248,699	3275	1768	1784	04:55	7:08	4	1424	808
Vancouver	Toronto	386,657	3344	1806	1811	04:30	7:14	4	1631	819
Vancouver	Toronto	350,202	3344	1806	1811	04:20	7:14	4	1631	819
Vancouver	Toronto	270,659	3344	1806	1811	04:27	7:14	4	1631	819
Toronto	Vancouver	245,800	3344	1806	1811	04:49	7:14	4	1612	819
London (HR)	Tel-Aviv	208,050	3586	1936	1942	04:45	7:46	4	1288	873
Brisbane	Perth	195,871	3605	1947	1953	05:35	7:48	4	1323	877
Perth	Brisbane	195,457	3605	1947	1953	04:20	7:48	4	1294	877
Rome	Abu Dhabi	258,196	4339	2343	2383	06:05	9:52	6	1893	1337
Munich	Dubai	246,814	4561	2463	2470	05:55	9:55	6	2125	1378
Frankfurt	Doha	269,192	4583	2475	2482	06:00	10:07	6	2752	1384
London (HR)	Kuwait	190,541	4672	2523	2531	06:15	10:11	6	1733	1406
Milan	Dubai	296,334	4704	2540	2548	06:05	10:19	6	1987	1414
Zurich	Dubai	204,198	4765	2573	2581	06:10	10:29	6	2466	1430
Frankfurt	Dubai	271,757	4839	2613	2621	06:20	10:29	6	2198	1449
Dubai	Frankfurt	224,206	4839	2613	2621	07:05	10:45	6	2102	1449
Paris (CDG)	Doha	206,967	4966	2681	2690	06:30	11:11	6	2417	1481
Amsterdam	Dubai	191,718	5166	2789	2798	06:40	11:20	6	2145	1531
Dubai	Barcelona	204,262	5172	2793	2989	07:10	11:20	7	2082	1706
Dubai	Paris (CDG)	200,607	5235	2827	2835	07:20	11:20	6	2195	1549
London (HR)	Doha	323,227	5237	2828	2837	06:50	11:20	6	3157	1550
Doha	London (HR)	272,269	5237	2828	2837	07:10	11:20	6	2821	1550
London (HR)	Doha	243,006	5237	2828	2837	06:45	11:22	6	3157	1550
Doha	London (HR)	212,598	5237	2828	2837	07:25	11:50	6	2821	1550
Boston	London (HR)	242,659	5238	2828	3663	06:35	11:54	9	3930	2248
Abu Dhabi	Paris (CDG)	207,612	5251	2835	2844	07:25	11:54	7	2220	1634
Dubai	London (GW)	198,717	5469	2953	2962	07:35	11:54	7	2251	1692
London (HR)	Dubai	397,590	5493	2966	2975	07:00	11:54	7	2526	1699
London (HR)	Dubai	304,006	5493	2966	2975	06:50	11:54	7	2526	1699
Dubai	London (HR)	270,687	5493	2966	2975	07:45	11:54	7	2461	1699
Dubai	London (HR)	245,376	5493	2966	2975	08:00	11:56	7	2461	1699
London (HR)	Dubai	231,806	5493	2966	2975	06:55	11:56	7	2526	1699
Dubai	London (HR)	195,876	5493	2966	2975	07:55	12:07	7	2461	1699
Abu Dhabi	London (HR)	383,636	5514	2977	2987	07:40	12:14	7	2208	1705
London (HR)	Abu Dhabi	240,690	5514	2977	2987	07:10	12:30	7	2242	1705
Dubai	Birmingham	204,327	5599	3023	3033	07:45	12:33	7	2205	1727
Manchester	Dubai	269,710	5650	3051	3060	07:15	13:30	7	1956	1741
Lisbon	Luanda	250,216	5774	3118	3127	07:30	9:32	7	1922	1774
Moscow	Beijing	284,919	5794	3129	3138	07:30	11:57	7	1862	1779
Doha	Johannesburg	226,165	6238	3368	3379	08:55	14:39	8	2129	1995

flight. Hence, the simulations were developed to focus the research lens on electric aircraft and long-haul routes. They showed that electric aircraft could serve certain routes with a comparable cost to existing business class fares but significantly more than today's average ticket. The total trip times, however, would be double or more than double. For the remaining routes, EAP technology would initially take considerable time, involve many stops and have even higher costs. Nonetheless, the simulations also suggest that ongoing improvements in battery energy density and aircraft frame design will eventually make it feasible to expand the reach of electric aircraft to more long-haul routes.

However, transitioning from simulation to effective operation entails engaging various stakeholders and encountering numerous challenges, aside from considering the technology readiness level (TRL) of high-density electric batteries.

Initially, for electric aviation to make a more substantial contribution towards achieving zero emissions, a significant challenge revolves around its current demand potential. Firstly, the higher cost associated with electric flights would limit their suitability to a specific niche of premium travellers who can afford this elevated expense. Premium fares and long-haul routes exhibit lower elasticity compared to economy fares (Njegovan, 2006).

Second, the intermediate stops and low speeds mean travellers would need to accept a considerable increase in travel time and reduction in comfort. Several studies highlight the importance of speed, time-lapse, and direct connectivity in passengers' decisions concerning air services (Sismanidou et al., 2013; Veldhuis, 1997). Alternatively, an increasing number of people, particularly among younger generations, are becoming more conscious of their carbon footprint, and seem to be happy to trade comfort and convenience with a lower carbon footprint. Recent behavioural studies based on surveys indicate that an increasing number of people are avoiding air travel for environmental reasons (Budd et al., 2021) in the context of the rising "flight shame" phenomenon (Gössling et al., 2020). Recent post-Covid surveys indicate that environmental concerns might be among the reasons prompting individuals to refrain from long-haul travel (Roland Berger, 2023). However, Magdolen et al. (2022) reveal conflicting attitudes and behaviours towards sustainable mobility, particularly among young urbanites. Who see their sustainable behaviour in daily travel as compensation for their air travel. While "flight shame" is not a prevailing trend, as per Ullström et al. (2023), "there are signs that it has begun to destabilise

Table 7
Key route parameters for each Scenario and for the three examples from the database, including the Current (OAG, 2019) data for real non-stop flights.

Trip Total Time (h)	**Frankfurt-Dubai**	**Sydney-Singapore**	**London-NYC**
Scenario 1	15:30	21:54	23:48
Scenario 2	13:00	17:00	16:30
Scenario 3	11:44	16:07	14:55
Current	6:20	8:20	7:55
Recharging Stops	**Frankfurt-Dubai**	**Sydney-Singapore**	**London-NYC**
Scenario 1	6	9	10
Scenario 2	3	4	4
Scenario 3	1	2	2
Current	0	0	0
Cost/Passenger (USD)	**Frankfurt-Dubai**	**Sydney-Singapore**	**London-NYC**
Scenario 1	1305	1993	2227
Scenario 2	1104	1467	1416
Scenario 3	968	1285	1232
Current (Avg. Bus. Cl. Fare)	2198	1601	3129

contemporary cultures of aeromobility," implying that only a few may be willing to revert to past practices involving multiple stops to achieve environmental benefits. In the contemporary landscape, a substantial portion of time-sensitive travellers often prioritise urgency over cost considerations. Conversely, many cost-sensitive passengers might not be particularly time-sensitive. This scenario underscores the necessity for stringent regulatory measures or a significant transformation in individual behaviour concerning long-haul electric flights. This requirement extends far beyond the nascent "flight shame" movement and the sentiments expressed by a segment of younger individuals opting against air travel.

Developments on the policy side could also have an impact on the demand side. Several initiatives are already under consideration, including the introduction of additional green taxes or the implementation of a carbon footprint passport (Larsson et al., 2019). While governments are presently cautious about curbing the demand for aviation, given the pressing concerns about environmental degradation and mounting pressure from advocacy groups, it is not inconceivable that such measures may be adopted in the future, thereby promoting the demand for low-emission flights. Furthermore, policymakers could accelerate the implementation of electric technologies by streamlining the currently lengthy certification process, making it more efficient and effective (Buzzo et al., 2023).

A further practical issue affecting feasibility, is the very limited capacity provided by the small electric aircraft used in the simulations. At present, OAG (2022) report 2.848 million seats available annually on the London-New York route, and BITRE (2022) show 0.5 million passengers on the Sydney-Singapore route. Even a 30-passenger model development by Heart Aerospace (The Economist, 2023:56), using much-advanced battery technology, and multiplied by many carriers with high frequencies, will struggle to meet demand at that scale. The substitution of large aircraft with multiple smaller aircraft may also affect congestion, even when the suggested routes primarily utilise secondary airports and low-altitude airways. In reality, not all major cities are equipped with regional or secondary airports. In some cases, passengers may require connecting flights, necessitating service at larger airports. Moreover, it is widely acknowledged that airport congestion incentivises airlines to utilise larger aircraft.

Finally, aircraft manufacturers, airports, airlines, and their supply chains must be convinced of the business potential, financial viability, and operational feasibility of EAP. Understandably, industry players tend to favour policy options that align with their existing business models and operations, as continuing with business as usual is considered less risky. The prime illustration is SAF, which, despite significant production challenges (as noted by Becken et al., 2023 and Rutherford et al., 2021), currently stands as the preferred technology according to the roadmaps established for the aviation industry (Federal Aviation Administration, 2021; ICAO, 2022; European Commission, 2021; World Economic Forum, 2020).

While the study primarily focused on long-haul routes, the results can also be applied to mid-haul routes with a more specific use case. Recent research has identified approximately 5000 underutilised regional airports in the US (NASA, 2021). Electric aircraft could potentially operate from some of these locations, supporting the growth of the regional air mobility (RAM) market. This approach may have relevance in providing services to smaller cities, particularly those in predominantly rural areas worldwide. In this manner, electric aircraft could make a significant, geographically targeted contribution to a more environmentally friendly aviation industry.

The paradigm shift proposed in this paper deviates from the

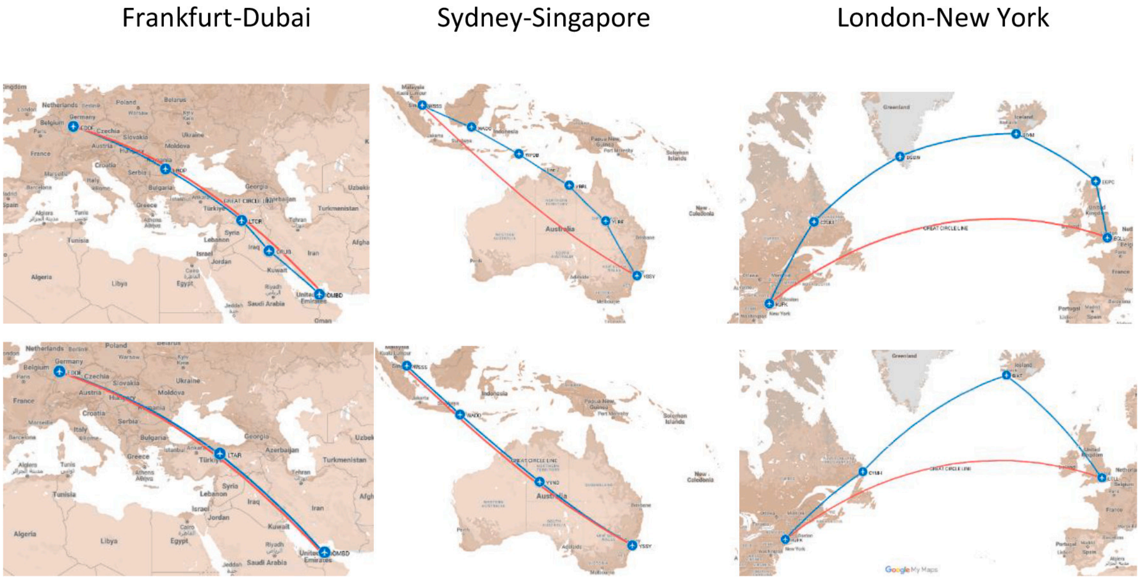

Fig. 6. Scenarios 2 (first row) and 3 (second row) of battery development for the three example routes of groups 1,2 and 3 of increasing geophysiographic complexity.

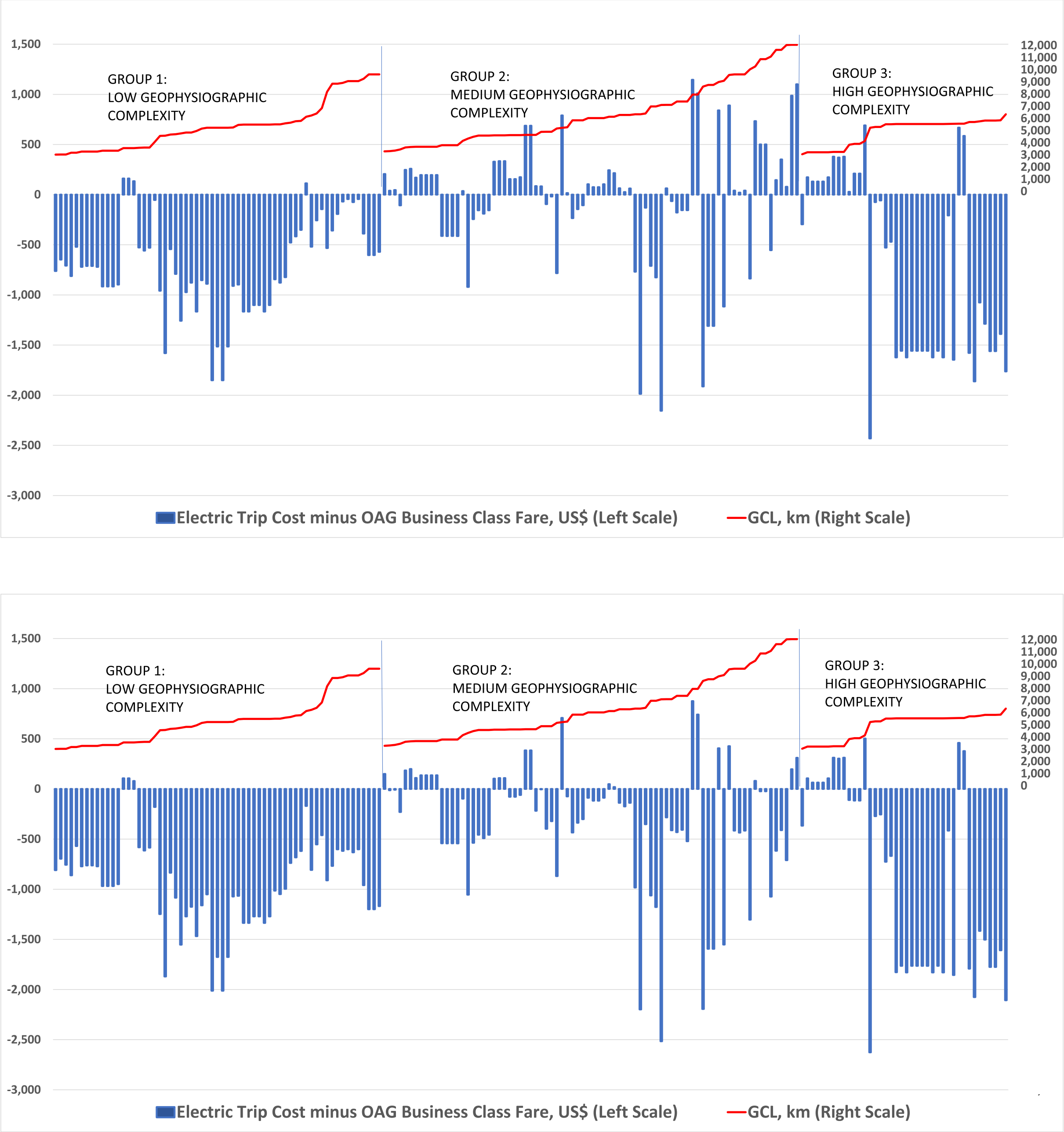

Fig. 7. Simulation results for the 183 routes in Scenarios 2 (top chart) and 3 (down chart) of battery development are displayed. The bars illustrate the difference between the electric trip cost per passenger and the real business class fare for each route. The chart also provides information on the GCL in kilometres for each city pair.

prevailing business model of longer, faster, and cheaper non-stop long-haul flights and therefore "may upset the established order" (Gössling and Cohen, 2014). Nevertheless, promoting alternative travel patterns (Peeters and Dubois, 2010) could also trigger new consumer, business, and policy dynamics aimed at accelerating the transition towards decarbonised aviation.

Author statement

During the preparation of this work the author(s) used ChatGPT in order to CHECK GRAMMAR AND LANGUAGE ERRORS. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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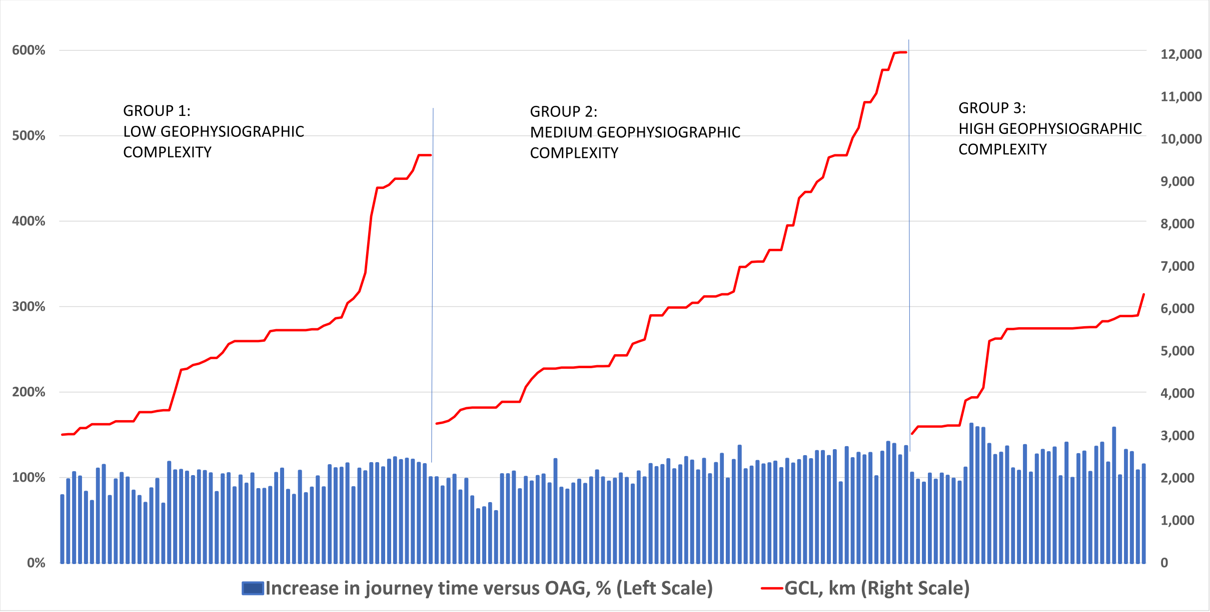

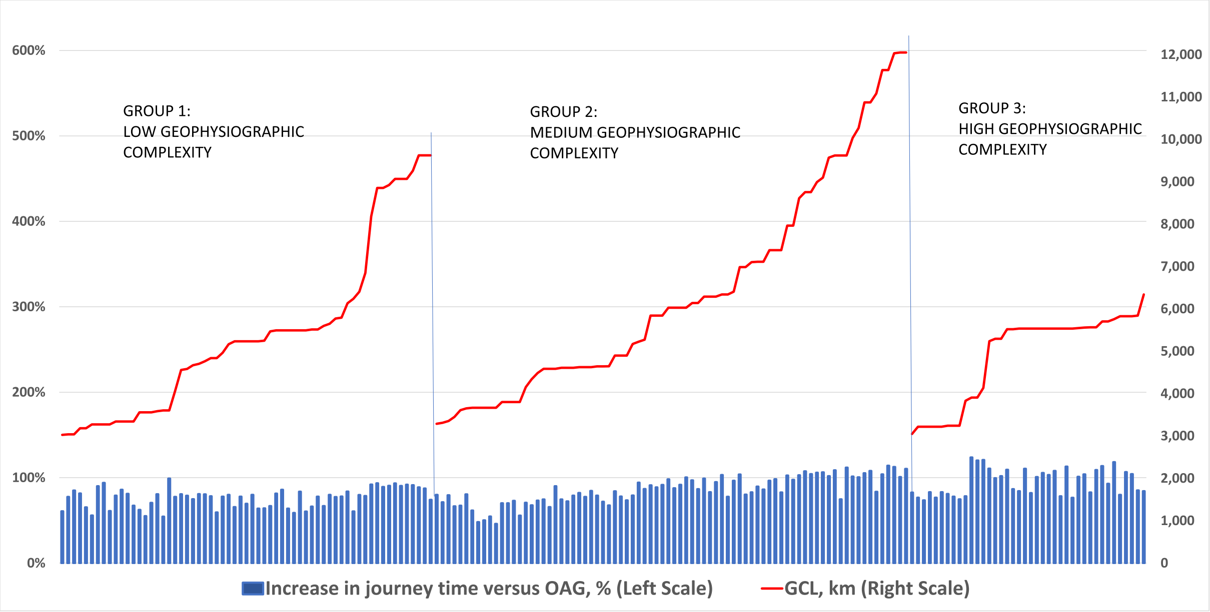

Fig. 8. Simulation results for the 187 routes in Scenarios 2 (top chart) and 3 (down chart) of battery development are presented. The bars represent the additional trip time of the electric simulation compared to the current non-stop service, expressed as a percentage. The chart also provides information on the GCL in kilometres for each city pair.

CRediT authorship contribution statement

Athina Sismanidou: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. **Joan Tarradellas:** Formal analysis, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Pere Suau-Sanchez:** Data curation, Validation, Writing – original draft, Writing – review & editing. **Kevin O'Connor:** Conceptualization, Data curation, Validation, Writing – original draft, Writing – review & editing.

Data availability

Data will be made available on request.

Appendix 1. Cost Analysis Assumptions the three example routes on a concept 9-seat electric aircraft in Simulation 1

Concept	Fra/Dub	Syd/Sin	Lon/NY	Notes
Main Assumptions				
Distance (one way/in nm)	2621	3600	3871	*Sum of the legs' distances*
Number of Stops	6	9	10	*Simulation 1*
Total in-flight time (in hours)	10.48	14.40	15.48	*Total distance / Speed*
Extra time per stop (in minutes)	50	50	50	*Approach, landing, taxi, charging and take off.*
Total route time (in hours)	15.5	21.9	23.8	*Flight time plus extra time for the stopovers (50′)*
Speed in ktas (knots of true air speed)	250	250	250	*Eviation, Alice aircraft specifications*
# of takeoffs	7	10	11	*Simulation 1*
# of landings	7	10	11	*Simulation 1*
# of taxis	7	10	11	*Simulation 1*
Number of seats	9	9	9	*Eviation, Alice aircraft passenger capacity*
Load factor	90%	90%	90%	*Assumption*
Passengers	8	8	8	*As per the load factor assumption*
Maximum Take-off Weight (in kg)	8346	8346	8346	*Eviation, Alice aircraft MTOW specifications*
1. Energy consumption				
Per takeoff & climb (in Kwh)	1494	2052	2206	*13.3% of cruise consumption (OAG)*
Per approach/landing (in Kwh)	674	926	995	*6% of cruise consumption (OAG)*
Per taxi in and out (in Kwh)	1483	2037	2190	*13.20%*
Takeoff/Landing/Taxi total (in Kwh)	25,555	45,129	53,918	*Take off and climb + taxi + aproach and landing*
Cruise enregy (in Kwh)	11,233	15,429	16,590	*Capacity 1800 Kwh /* max. *Range 420 nm x distance*
Energy consumption route	36,788	60,557	70,508	*Total*
Cost Kwh (in USD)	0.15	0.15	0.15	*Vijayagopal, R.; Rousseau, A. (2021) and Amol Phadke* et al. *(2019)*
Total energy cost per trip (USD)	5518	9084	10,576	*USD 3009/# block hours*
2- Maintenance				
Cruise speed (in ktas)	250	250	250	*Eviation, Alice cruise speed specifications*
Block hours (one way)	10.48	14.40	15.48	*Assumed equal to in-flight hours*
Maintenance cost (per block hour/in USD)	45	45	45	*50% of Piaggio I maintenance cost per flight hour*
Total maintenance cost (USD)	472	648	697	*Calculation*
3. Crew				
Captain Salary and benefits (in USD)	137,200	137,200	137,200	*Yearly salary 98,000 USD + 40% benefits*
Hours flown/pilot/year	900	900	900	*Eurocockpit*
Hourly rate (per block hour/in USD)	152	152	152	*Calculation*
CoPilot Salary and benefits (in USD)	68,600	68,600	68,600	*https://egnatia-aviation.aero/pilot-salary-guide/*
Hours flown	900	900	900	*Eurocockpit*
Hourly rate (per block hour/in USD)	76	76	76	*Calculation*
Pilots cost (total one way/in USD)	2397	3293	3541	*Calculation*
4- Depreciation/ Ownership cost				
Aircraft price (in USD-without battery)	2,160,000	2,160,000	2,160,000	*Assume 80% aircraft cost 2,7 mio USD*
Battery cost (in USD)	540,000	540,000	540,000	*Assume 20% aircraft cost*
Life expectancy aircraft (in years)	25	25	25	*EASA* 2019
Life expectancy battery (in years)	10	10	10	*similar to cars*
Yearly depreciation cost frame	86,400	86,400	86,400	*Straight line depreciation*
Yearly depreciation cost battery	54,000	54,000	54,000	*Straight line depreciation*
Aircraft yearly utilisation in block hours	2263	2263	2263	*Regional Jet < 60 passengers:*
Depreciation cost per block hour (in USD)	62.0	62.0	62.0	*Calculation*
Total Depreciation cost per trip (USD)	650	893	961	*Calculation*
5- Route Navigation fee				
Navigation fee (in USD)	0	0	0	*Assumed to be levied: see Thessaloniki Forum of Airport Charges, 2021*
Total Operating Costs (Variable and Fixed)	9038	14,670	16,583	*Calculation*
6. Airport and aeronautical fees	904	1467	1658	*Assumption based on many government reports*
7. Catering & sleepover	1800	1800	1800	*Own Estimate (One sleepover per trip)*
Total Costs Per Route (one way. USD)	11,741	17,973	20,041	*Calculation*
One way trip cost per passenger (USD)	1305	1993	2227	*Calculation*

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