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Demystifying electric aircraft's role in aviation decarbonization: Are first-generation electric aircraft cost-effective?

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ABSTRACT

This paper compares the operating costs of first-generation electric-powered aircraft with those of their conventional counterparts. We develop a cost model that incorporates both fixed and variable costs to evaluate the cost convenience of operating short-haul routes with electric aircraft. We find that first-generation electric aircraft have higher operating costs than conventional aircraft. However, reductions in aircraft price, maintenance requirements, and battery replacement costs, due to the consolidation of this technology, could soon make it convenient to deploy 19-seat electric aircraft on regional routes. Conversely, the most promising prospects for larger regional aircraft are anticipated in the medium-term with the advent of second-generation electric aircraft featuring significant technological enhancements. Substitution to electric aircraft is expected to have a limited contribution to aviation emissions reduction in the short-term – approximately 0.1% of emissions from intra-European flights – but this could increase substantially following upgrades in electric-powered aircraft technology expected in the medium-to-long term.

1. Introduction

The aviation industry is one of the fastest growing industries worldwide, doubling in size about every 15 years. This rapid growth has resulted in significant drawbacks and side effects, such as a huge environmental impact. In 2019, global commercial aviation emitted more than 920 Mt of CO_2 (85% from passenger flights) (Graver et al., 2020). This makes aviation responsible for approximately 2%–3% of global carbon emissions, and based on recent growth forecasts including the COVID-19 pandemic's severe effects on the industry, this figure is expected to increase significantly by 2050, in the absence of meaningful action (EASA, 2022). In response, policymakers and industry stakeholders have committed to achieving net-zero carbon emissions by 2050 (IATA, 2021b). To meet this ambitious decarbonization target, the aviation industry has, in recent years, intensified research and development of means and policies to reduce emissions. These include carbon pricing instruments, sustainable aviation fuels (SAFs), improvements in aircraft energy efficiency, new aircraft technologies, more efficient air traffic management procedures, and modal shift initiatives (Avogadro and Redondi, 2023; Scheelhaase et al., 2018; Schefer et al., 2020; Fukui and Miyoshi, 2017; Kousoulidou and Lonza, 2016).

Electric-powered aircraft are among the technologies with the most promising prospects to revolutionize the aviation industry in the short term and contribute to achieving climate goals in the medium to long term. Electric aircraft will drastically reduce atmospheric emissions (zero direct CO_2 emissions during operation) and will be significantly less noisy than conventional aircraft (Schefer et al., 2020; Pintos et al., 2023). However, despite strong research efforts, with more than 300 active aviation

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electrification projects worldwide and a target market entry year as early as 2025 for the first prototypes, first-generation electric aircraft (FGEA) are expected to face the major challenge of low battery density, resulting in shorter ranges, lower seating capacities, and lower speeds than their conventional fossil fuel-powered counterparts (Reimers, 2018; Baumeister et al., 2020). Therefore, at least in the short to medium term, electric aircraft are likely to be a viable option only for regional and short-haul markets, such as routes serving remote regions (Kinene et al., 2023).[1]

Regional routes have long been the focus of debates on their contribution to aviation emissions. Flights on regional routes have proven to be less fuel efficient due to the energy-intensive takeoff phase for a shorter flight duration (Grimme and Jung, 2018). However, although regional flights account for a significant number of movements, they only contribute a small fraction of total fuel consumption and emissions. For instance, Dobruszkes et al. (2022) estimate that flights shorter than 500 km account for 27.9% of departures but only 5.9% of the fuel that passenger flights in Europe burn. Nonetheless, regional flights account for a significant share of fuel consumption and emissions in some European countries, such as Norway (approximately 30%) and Sweden (20%). This is probably due to the specific peculiarities of those countries, which are characterized by difficult topography and concomitant challenges in building landside infrastructure, making air travel essential in providing adequate domestic and international connectivity. Additionally, regional routes are typically characterized by thin flows, necessitating the operation of small regional aircraft to achieve profitability.[2] The strong dependence on air transport owing to limited alternative land-based options, the low demand intensity, and the short distances to cover make regional routes an ideal environment in which to deploy electric aircraft. Doing so can contribute to reducing this travel segment's environmental impact. Furthermore, the economic case for aircraft electrification not only involves replacing existing air services but also encompasses the possibility of opening new (ultra-thin) markets, substituting business jet flights, and competing with land-based transportation modes (Brelje and Martins, 2019; Baumeister et al., 2020).

In addition to technical considerations, one of the determining factors for adopting electric-powered aircraft is their technological cost-effectiveness compared to conventional aircraft (Centracchio et al., 2018; EC, 2011). Although some information regarding FGEA costs is available–for instance, the purchase/leasing costs of electric aircraft are expected to be higher than those of conventional aircraft, whereas fuel and maintenance costs might be lower–a comprehensive analysis providing a holistic view of the economic effectiveness of FGEA from an operating cost perspective is lacking. Thus, in this study, we aim to estimate a cost model to evaluate FGEA's operating costs for comparison with those associated with their conventional counterparts. The estimated cost functions will allow for the identification of routes on which deploying electric-powered aircraft might incur lower costs than traditional aircraft. Further, we identify the key characteristics of FGEA that, due to technological development, can improve and substantially impact economic convenience in the medium term. Based on these potential evolutions, we appraise the potential environmental benefits of substituting regional flights with FGEA as well as those of subsequently introducing further upgraded electric aircraft models. Considering the above, the current research will help policymakers and practitioners better understand the role and potential of aircraft electrification in the short and medium terms regarding contributing to the aviation industry's net-zero transition.

The rest of the paper is structured as follows. In Section 2, we introduce the proposed operating cost model. In Section 3, we detail the data collection process and the main assumptions for model calibration. Section 4 presents the comparative cost model results. In Section 5, we conduct a sensitivity analysis of the main assumptions to evaluate the conclusions' robustness, and in Section 6, we estimate electric aircraft's potential to reduce aviation greenhouse gas (GHG) emissions. Finally, Section 7 summarizes the findings and suggests future research avenues.

2. Cost model

The cost model developed in this study focuses on operating costs, neglecting nonrecurring costs such as aircraft certification, crew training costs, and other general costs. The model incorporates both fixed and variable operating costs. The former includes ownership and insurance costs, and the latter covers per movement variable costs (airport charges and handling) and fully variable costs, such as maintenance, crew salary, and fuel consumption. More specifically, the cost of operating a particular route with aircraft type a and great-circle distance (GCD) φ can be formulated as follows:

$$C_a(\varphi) = C_a^{fix}(\varphi) + C_a^{mov} + C_a^{var}(\varphi) \tag{1}$$

where $C_a^{fix}(\varphi)$ denotes aircraft standing charges parameterized on a per block hour (BH) basis, C_a^{mov} denotes per movement variable costs, and $C_a^{var}(\varphi)$ represents fully variable operating costs.

Aircraft fixed costs ($C_a^{fix}(\varphi)$) capture aircraft ownership (depreciation and/or leasing) and insurance costs. Annual ownership and insurance costs mainly depend on the aircraft list price (p_a) and can be computed considering a fixed aircraft depreciation rate (η) and an insurance premium (μ). In turn, annual aircraft fixed costs can be allocated on a per flight basis, considering the BHs

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[1] Recently, Sismanidou et al. (2024) investigated the feasibility of operating long-haul commercial routes using fully electric aircraft, identifying suitable intermediate stop airports that could facilitate battery recharging. Results demonstrated the challenges in serving current long-haul routes with electric aircraft, including a strong increase in travel time (in most cases more than doubling) and a reduction in comfort (due to intermediate stops) for passengers. Moreover, the expected ticket cost would be higher than today's average ticket. Lastly, the limited seating capacity of current electric aircraft would cause a disproportionate increase in movements to maintain the same capacity, thus making the substitution challenging from an operational perspective in the short term.

[2] On very thin regional routes, other policies to reduce aviation emissions, such as modal shift to conventional or high-speed rail, cannot be an effective solution due to the significant costs as well as substantial indirect emissions emitted while building rail infrastructure (Avogadro et al., 2023).

allocated to operate each route with aircraft a ($BH_a(\varphi)$) and the annual utilization of the single aircraft model (τ_a).[3] Thus, aircraft fixed costs to operate a specific route with GCD φ can be computed as follows:

$$C_a^{fix}(\varphi) = \frac{(\eta + \mu)p_a}{\tau_a} \cdot BH_a(\varphi) \tag{2}$$

where the ratio represents the aircraft ownership and insurance costs parameterized per BH.

Per movement fixed costs (C_a^{mov}) include airport charges and handling services, which are typically specified as a function of aircraft weight (MTOW) and the number of passengers onboard.

Fully variable operating costs ($C_a^{var}(\varphi)$) include maintenance costs, crew salaries, and fuel (or electricity) costs. We compute these costs based on the following expression:

$$C_a^{var}(\varphi) = c_a^{maint} BH_a(\varphi) + c_a^{crew} BH_a(\varphi) + c_{fuel}\phi_a(\varphi) \tag{3}$$

The first term ($c_a^{maint} BH_a(\varphi)$) represents maintenance costs computed considering aircraft-specific maintenance costs per BH (c_a^{maint}). The second term represents crew costs. Similar to maintenance costs, crew costs are computed based on the aircraft-specific crew salary cost per BH (c_a^{crew}). We derive these costs by considering various crew members' (pilots and cabin attendants) average salary per BH and the typical composition of the crew onboard each aircraft model a. The last term in Eq. (3) accounts for fuel/electricity costs computed as the product of the specific fuel (jet fuel or electricity) price (c_{fuel}) and fuel consumption ($\phi_a(\varphi)$). For conventional aircraft, fuel consumption is estimated using the reduced order distance–fuel burn relationships Seymour et al. (2020) have calibrated, which provide practical yet accurate aircraft-specific functions to estimate the fuel burn on any given flight as a sole function of its GCD φ. The reduced order distance–fuel burn relationship adopts a quadratic form:

$$\phi_a(\varphi) = \alpha_a^0 + \alpha_a^1\varphi + \alpha_a^2\varphi^2 \tag{4}$$

where α_a^0, α_a^1, and α_a^2 are empirical coefficients calibrated for each aircraft type a. By utilizing a quadratic formulation instead of a simple linear relationship between mission distance and fuel burn, some nonlinearity in the fuel consumption of conventional aircraft can be incorporated. One of the most evident nonlinearities derives from fuel payload. To operate longer missions, a higher fuel mass is carried onboard, leading to increased fuel consumption during takeoff (due to basic energy balance) and cruise (due to lift-induced drag). Concerning electric aircraft, because their technology is in its infancy, similar reduced order models (but also more complex ones) are not yet available. Most existing economics studies assume fixed energy consumption per passenger km for FGEA (e.g., Baumeister et al., 2020; Reimers, 2018). However, although this assumption holds for the cruise phase, in which an electric aircraft, contrary to a conventional aircraft, does not benefit from weight loss (and therefore reduced drag) due to fuel consumption (Brelje and Martins, 2019), the same does not apply to takeoff, which is the most energy-intensive stage of flight for conventional aircraft. The same is expected to apply to FGEA, owing to the energy balance.[4] Following this pattern and consistent with Mitici et al. (2022) and van Oosterom and Mitici (2023), we assume that an FGEA's energy consumption depends linearly on the mission distance. Accordingly, we model electricity consumption using the following first-order functional form:

$$\phi_a(\varphi) = \beta_a^0 + \beta_a^1\varphi \tag{5}$$

where β_a^0 represents the electricity consumption needed for takeoff, and β_a^1 is the energy consumption per km during the cruise phase.

These distance–fuel burn relationships not only help estimate the fuel burned and consequently the fuel-related operating costs but can also be used to appraise GHG emissions. Let $k_f^{\mathrm{CO}_{2eq}}$ be the emission factor of fuel type f (jet fuel or electricity), which represents the amount of CO_{2eq} emissions per unit of fuel consumed. For jet fuel, this value depends solely on the type of fuel burned and is equal to 3.84 kg of CO_{2eq}/kg of fuel. Concerning FGEA, because electric aircraft eliminate direct GHG emissions during operation, we consider the carbon intensity for producing the electricity used. Then, the amount of GHG emissions for operating route r with aircraft a, K_{ar}, can be obtained by multiplying the fuel consumption with the fuel-specific emission factor, i.e., $K_{ar} = \phi_a(\varphi) \times k_f^{\mathrm{CO}_{2eq}}$.

For electric aircraft, in addition to the previously mentioned cost components, we also consider the battery replacement costs. Commercially available batteries do not provide a sufficient cycle life (i.e., the number of charge and discharge cycles a battery can complete before losing performance) to facilitate the use of a single battery pack during an aircraft's entire lifespan (Reimers, 2018; Schäfer et al., 2019; Wangsness et al., 2021). Therefore, it is expected that battery packs will be periodically replaced once their performance deteriorates. Accordingly, we compute battery replacement costs based on battery replacement frequency (considering commercially available batteries' expected cycle life) and the associated cost (i.e., the purchase cost of batteries per unit capacity). Owing to existing batteries' limited specific energy (energy storage per unit mass), FGEA's battery capacity is severely limited. This will inevitably reduce FGEA's operating range, implying that it is necessary to restrict operations to shorter routes and fully recharge aircraft batteries after each flight (Justin et al., 2020; Reimers, 2018). Accordingly, we assume that the battery depreciation cost is parameterized per flight (i.e., each flight requires one battery charge), and we add it to the per movement variable costs (C_a^{mov}).

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[3] Aircraft utilization is defined as the total number of BHs allocated to a specific aircraft model in a year. This measure primarily depends on the incidence of downtime caused by scheduled and unscheduled maintenance, as well as operation efficiency.

[4] Notice that, unlike conventional aircraft, electric aircraft engines do not suffer lower efficiency for operations at low altitudes. Thus, takeoff is expected to be more energy-intensive than cruise, albeit to a lesser degree, in a sense, than conventional aircraft.

Table 1
Descriptive statistics for selected conventional aircraft models.

Aircraft	Movements	Seating capacity	GCD (km)		
			25^{th}	50^{th}	75^{th}
De Havilland DHC-6T	10,817	19	60	108	224
Beechcraft 1900	12,904	19	369	418	483
De Havilland DHC-8-100	62,703	37	108	166	280

3. Data and assumptions

FGEA are currently under development, with a target entry-to-market year as early as 2025 (IATA, 2021a). However, state-of-the-art battery technology will constrain FGEA in terms of both seating capacity (<30 seats) and operating range (regional routes only). In the current study, we select three FGEA models expected to be commercially available shortly: (i) Alice, designed by the Israel-based company Eviation, with nine seats and a range of up to 1044 km; (ii) Heart Aerospace's ES-19, a 19-seat electric aircraft with an operating range of 400 km; and (iii) Heart Aerospace's ES-30, with a seating capacity of 30 and a 400 km fully-electric design range. For a fair comparison, we select conventional aircraft models with similar seating capacities that operate at comparable distances (regional distances). Specifically, based on historical data from the OAG Schedule Analyzer, we identified the (conventional) aircraft models with limited seating capacity (15–40 seats) that are the most commonly used on regional intra-European routes, as follows: (i) De Havilland DHC-6T (19 seats), (ii) Beechcraft 1900 (19 seats), and (iii) De Havilland DHC-8-100 (37 seats). Table 1 reports descriptive statistics on the utilization of these aircraft models on intra-European routes in 2019, based on OAG data. We obtained the parameters, specifics, and cost estimates used in the proposed cost model from aircraft manufacturers and other secondary sources. In the following subsections, we describe data sources and assumptions used for calibrating the cost model.

3.1. Conventional aircraft

We sourced the data on conventional aircraft seating capacity and maximum operating range from aircraft manufacturers[5] and validated these parameters using historical flight schedules from the OAG Schedule Analyzer. We retrieved the annual utilization rates (in terms of BHs) on a per model basis from Conklin and de Decker (2018). To ensure accuracy, we cross-checked the annual utilization statistics with FlightRadar data. Specifically, based on aircraft-tail level data from intra-European flights operating in May 2019, we have estimated the selected aircraft models' average weekly utilization for comparison with the declared values. Overall, for the selected aircraft models, we note an average daily utilization of between 4 h and 5.5 h, which is lower than the typical values for larger commercial aircraft models.[6] Furthermore, although all three conventional aircraft models have operating ranges of more than 1000 km, they are typically deployed on regional routes below 500 km (Table 1).

The number of pilots each aircraft model requires constitutes crucial data needed for estimating crew costs. We obtained these data from EASA type rating and license endorsement documents, which are part of the aircraft certification procedure.[7]

Considering the specific cost component estimates, we retrieved the aircraft list price required to infer ownership and insurance costs from Conklin and de Decker (2018) and compared the values to those estimated using the empirical model Lammering et al. (2012) proposed. We observe a slightly underestimated ownership cost compared with the empirical model which, however, has been calibrated considering larger aircraft models. We obtained maintenance costs per BH for turboprop aircraft (including labor, parts, engine allowances, and propeller/thrust reverser overhaul costs) from the FAA guidelines to perform a benefit–cost analysis.[8] The FAA provides the maintenance value per BH for given aircraft seating capacities. Thus, we adjusted the FAA values in proportion to the aircraft seating capacity to derive aircraft-specific values. This adjustment was necessary because maintenance costs increase with aircraft size (Vega et al., 2016). Finally, we estimated airport charges, including landing and takeoff, aircraft parking and handling fees, and per passenger charges, considering the average charges levied for the selected aircraft models in a set of representative airports used by regional aircraft. Specifically, we consider the charges associated with the top five EU airports by movements of regional aircraft in 2019, based on the OAG Schedule Analyzer database, namely Lyon, Glasgow, and three Scandinavian airports (Oslo-Gardermoen, Bodø, and Tromsø-Langnes). Airport charges mainly depend on the aircraft MTOW and the number of passengers onboard; for the selected aircraft models, they range between $250 and $540 per flight.

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[5] The referenced information is available on the De Havilland and Beechcraft websites.

[6] For comparison, US carriers reported an average daily BH utilization of over 10 h for their small narrow-body fleets (MIT Airline Data Project data).

[7] EASA Product Certification documents are available on the EASA website.

[8] Economic Values for Evaluation of FAA Investment and Regulatory Decisions — Section 4: Aircraft operating costs.

3.2. Electric aircraft

FGEA are still under development, and their specifics and performance are continuously evolving as technology improves. To estimate the proposed cost model, we obtained the FGEA models' specifics and characteristics from the manufacturers. For parameters that were not publicly available, we leveraged information from state-of-the-art scientific publications and recent reports. Owing to the high uncertainty surrounding FGEA characteristics due to their technological infancy, specific assumptions are required. Accordingly, to validate our findings and provide insights into the cost-effectiveness of the enhanced electric aircraft models expected to be available in the medium term, we will conduct a comprehensive sensitivity analysis of the key parameters (see Section 5). In the following paragraphs, we detail the main assumptions and data considered.

We obtained data on the selected FGEA models' operating range, seating capacity, and battery capacity from the manufacturers' websites.[9] As previously mentioned, FGEA are expected to have limited seating capacity (9–30 seats) and shorter ranges (<400 km) compared to their conventional counterparts. This is mainly due to current batteries' low specific energy, in the order of 200–250 Wh/kg, which is approximately 1.7% of the jet fuel energy content (Rheaume and Lents, 2016; Brelje and Martins, 2019; Schäfer et al., 2019; Doctor et al., 2022). As of 2023, new types of batteries (lithium-sulfur) with improved performance (energy densities of up to 500–700 Wh/kg), charging and discharging times, and profiles are being developed, and further improvements are expected in the next few years (Pintos et al., 2023; Sismanidou et al., 2024). Concerning crew composition, we consider the number of pilots based on the EASA regulations (CS-23 and CS-25) that the selected aircraft models must comply with during the certification process.

The mechanics of FGEA are simpler than those of conventional aircraft, with the former having fewer moving parts. This will likely reduce maintenance activities and associated costs (Reimers, 2018; Schäfer et al., 2019; Patterson et al., 2016). In the short term, 10%–15% less maintenance than conventional aircraft is foreseen for FGEA (Wangsness et al., 2021). These benefits are expected to increase in the medium term with the establishment of technology (Reimers, 2018). For the current study, as a baseline, we assume that an FGEA would require 15% less maintenance per BH than a conventional aircraft; however, we also propose a sensitivity analysis for this parameter.

Less maintenance and the opportunity to leverage predictive maintenance instead of reactive maintenance create medium-to-long term prospects for electric aircraft to benefit from higher availability and possibly higher utilization than conventional aircraft. These potential benefits are likely offset in the short run by less technological knowledge and the FGEA business model's high uncertainty concerning battery management, potentially affecting turnaround operations. To date, it is unclear whether battery charging, battery swapping, or a combination of both is the optimal solution for FGEA operation and will be adopted for commercial use (Mitici et al., 2022; Justin et al., 2020). Battery charging presents a more immediate solution and can benefit from fast-charging technology under development in the automotive industry. However, fast-charging standards for batteries demand high grid power levels and require the establishment of expensive infrastructure at airports (Brdnik et al., 2022). Moreover, the practice of constantly fast-charging batteries can lead to battery degradation, significantly reducing battery longevity (Rezvanizaniani et al., 2014). Finally, although increasingly rapid battery charging is technically possible, considering the available technologies, slightly higher turnaround times are necessary in the short run. However, battery swapping ensures a fixed time for battery pack interchange and allows recharging from the grid at relatively low power levels to preserve battery performance. Nonetheless, implementing battery swapping requires a modular aircraft design to facilitate the interchange of batteries and is likely to entail the acquisition of new specialized equipment to replace and move batteries across the airfield. This addition may complicate existing airport operations, raising potential safety concerns (Doctor et al., 2022). In summary, each approach has its advantages and disadvantages. Based on this, preliminary findings suggest that a modular design that allows for both plug-in recharge and battery swapping is the most promising approach for ensuring that turnaround times align with airport operators' (stand capacity) and airlines' (operational efficiency) requirements (Doctor et al., 2022; Mitici et al., 2022). More specifically, the battery swapping option can ensure limited increases in turnaround times, even in the event of slow development of fast-charging technologies in the next few years. This will allow air carriers to operate with a similar fleet size because a slightly longer turnaround can be accommodated in the current schedule for thin regional routes (routes targeted for FGEA). As mentioned above, aircraft utilization on these routes is relatively low (approximately 6 h per day), allowing for some flexibility in accommodating longer turnaround times. Based on these considerations, we assume that annual utilization of FGEA (in terms of BHs) will be similar to that of conventional aircraft.

The simplicity of electric engines also promises a lower aircraft list price (and, in turn, lower ownership costs). However, this benefit is currently counterbalanced by the high cost of batteries (Reimers, 2018). Furthermore, FGEA are little more than prototypes and thus do not yet leverage economies of scale in production. Accordingly, there is a common consensus that FGEA will be characterized by higher per seat ownership costs. We discuss the potential realignment of electric aircraft ownership costs in Section 5. Based on manufacturer data, FGEA will also be characterized by a lower cruise speed than conventional aircraft, implying longer flight duration allocated for flying the same distance. Together with a lower seating capacity, this will result in a higher crew cost per available seat km (ASK) than conventional aircraft (Wangsness et al., 2021).

Considering electricity consumption, as discussed in Section 2, we compute fixed energy consumption for takeoff and per km electricity consumption during the cruise phase (see Eq. (5)). Consistent with Mitici et al. (2022) and van Oosterom and Mitici (2023), we assume that approximately 8% of the battery capacity will be used for takeoff and that the rest will be fully used to fly a distance equal to the aircraft's maximum operating range.

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[9] The referenced information is available on the Eviation and Heart Aerospace websites.

FGEA batteries will also need to be replaced frequently owing to existing batteries' limited cycle life. Current lithium-ion batteries can ensure approximately 1000 full cycles before their capacity is reduced to 80% of that of a new battery (Reimers, 2018). Accordingly, we assume 1000 cycles as the cycle life of the FGEA battery pack and estimate the battery replacement cost by considering a per capacity cost of \$100/kWh (Schäfer et al., 2019; Neubauer et al., 2014; Justin et al., 2020).

Finally, we compute airport charges for the selected FGEA models based on the maximum number of passengers and the MTOW. We consider the airport charges of the same five airports considered for conventional aircraft. It should be noted that possible airport charge discounts may be applied to electric aircraft because of the lower overall noise and zero emissions during landing and takeoff. Indeed, in addition to zero local pollutant emissions owing to the absence of combustion (especially considering low-altitude NO_x emissions), a 50% takeoff noise contour area reduction and slightly increased landing noise (with an approximately 15% larger noise contour area) are expected (Schäfer et al., 2019; Pintos et al., 2023). At the same time, investments required to adapt airport infrastructure to handle electric aircraft, such as installing battery charging stations and providing spare batteries, coupled with potentially longer turnaround times, may contribute to increased airport charges for these aircraft.

3.3. *Common data and assumptions*

Together with conventional and electric aircraft data and specifications, common assumptions need to be formulated concerning the aircraft depreciation rate and insurance premium, the number of cabin attendants, crew salaries, and fuel prices.

Regarding the aircraft depreciation rate, we used Conklin and de Decker's (2018) market-based depreciation values, which assume that aircraft lose a fixed percentage of their original purchase price each year, with no residual value. The percentage varies based on the aircraft propulsion system; for turboprops (type of selected conventional aircraft models), it is equal to 6%. Because electric design is not expected to significantly impact aircraft life (Reimers, 2018), we use the same depreciation rate for FGEA. Moreover, similar to Zumegen et al. (2023), we assume that the yearly insurance premium is equal to 1% of the purchase price of both conventional and electric aircraft.

Unlike the number of pilots, the number of cabin attendants onboard is not specified in the aircraft certification. Thus, in line with most airlines' behavior and consistent with Zumegen et al. (2023), we assume no cabin attendants for aircraft with fewer than 20 seats and one cabin attendant for aircraft with up to 40 seats. Concerning crew salary, we estimate pilots' and cabin attendants' per BH wages considering average annual salaries and the number of monthly BHs flown per crew member, based on MIT Global Airline Industry Program data.[10]

To compute the fuel-related operating costs, we consider the average jet fuel and electricity prices for the period 2018–2023. We obtained the historical Jet-A1 fuel price from the IATA Jet Fuel Price Monitor and sourced the electricity price from Eurostat data.[11]

Lastly, to associate costs parameterized at the per-BH level (i.e., ownership and insurance, maintenance, and crew costs) with specific mission distances, aircraft-specific data regarding the number of BHs allocated to operate a flight with GCD φ are required. For conventional aircraft, we leverage aircraft-specific BHs–distance relationships, assuming the following formulation:

$$BH_a(\varphi) = \delta_a^0 + \delta_a^1 \varphi \tag{6}$$

where δ_a^0 and δ_a^1 are empirical coefficients calibrated by ordinary least squares regression for each aircraft type according to historical OAG Schedule Analyzer data on scheduled flight times for operating intra-European routes using the selected conventional aircraft models. Concerning FGEA, because no actual allocated BHs times are available, we adjust the BH–distance relationships calibrated for conventional aircraft to account for these aircraft models' lower expected cruise speed. Specifically, we rescale the first-order coefficient of Eq. (6) based on the ratio between conventional aircraft and FGEA cruise speeds.

4. Results

Figs. 1 and 2 depict the operating costs per ASK (CASK) for the selected aircraft models as functions of mission distance and seating capacity, respectively.[12]

Considering conventional aircraft, the cost model returns degressive costs in two dimensions: flight distance and seating capacity. The former is due to the impact of the fuel burn for takeoff and other per movement fixed costs (e.g., airport charges) distributed over a longer flight duration, and the latter is due to larger aircraft's higher efficiency as well as the presence of stepwise costs, such as pilot and crew costs, allocated to a higher number of seats. Overall, conventional aircraft exhibit CASK between \$0.45 and 0.20/ASK, based on mission distance. The figures align with the upper bound of CAPA estimates (\$0.20–0.07/ASK); however, those estimates consider commercial aviation and thus mainly include larger aircraft models that are more efficient per passenger.[13] Slightly higher costs were estimated using the model proposed by Janic (2000), which quantifies operating costs based on aircraft size and route length. Janic's model applied to the selected aircraft types returns a CASK between \$0.20 and 0.50/ASK. However, it

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[10] MIT Airline Data Project.

[11] Eurostat Electricity price statistics are available on the Eurostat website.

[12] Note that Fig. 1 only represents operating costs for mission distances below 600 km. No significant changes in the cost pattern are outlined for Eviation Alice (i.e., the only FGEA with an operating range higher than 400 km) for distances greater than 500 km.

[13] CAPA - Centre for Aviation CASK Database.

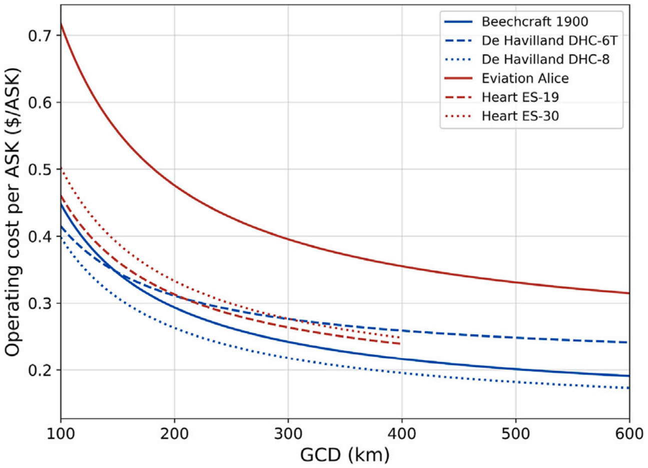

Fig. 1. Operating costs per ASK for conventional aircraft and FGEA by mission distance.

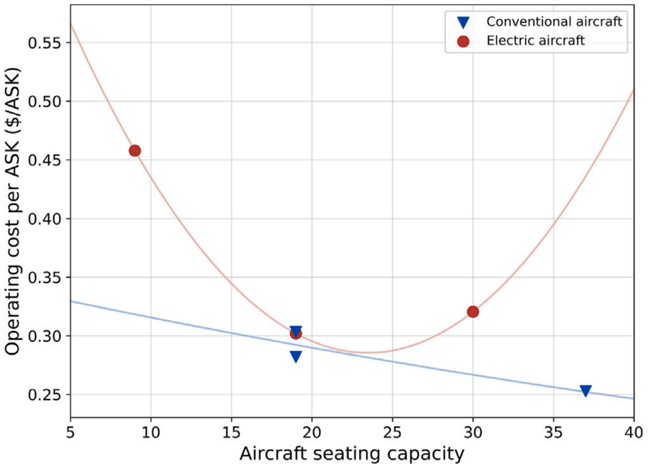

Fig. 2. Operating costs per ASK for conventional aircraft and FGEA with different seating capacities. Average operating costs per ASK for routes shorter than 400 km. Trend lines represent the trend in operating costs for the three selected aircraft models in each category.

is worth noting that Janic's model has been calibrated considering larger aircraft, and thus, it might slightly overestimate the cost of the small regional aircraft the current study considers. All three conventional aircraft models ensure an operating range of up to 1000 km. Considering specific aircraft models, the 19-seat DHC-6 is slightly more cost-effective for superregional flights (up to 150 km), whereas the Beechcraft 1900 is cheaper to deploy for longer flights. The 30-seat DHC-8 exhibits lower operating costs per ASK in the range of $0.40–0.20/ASK.

The FGEA, which are characterized by a limited operating range (400 km), except for the 9-seat Eviation Alice, show decreasing operating costs with increased GCD covered, for the same reason as conventional aircraft (Fig. 1). In contrast, when considering seating capacity, FGEA exhibit a U-shaped trend in operating costs (Fig. 2). This is a result of the inherently high operating costs associated with existing larger electric aircraft models (with more than 20 seats), stemming from their low technological readiness level, which offsets the benefits of distributing stepwise costs across a higher number of seats. Nevertheless, substantial improvements in these aircraft models' cost performance are anticipated in the next few years, promising a decreasing trend in operating costs with the increase in seating capacity also for electric-powered aircraft. Table 2 reports the operating costs per ASK for the selected FGEA in their specific operating ranges and the difference compared to their conventional counterparts.

Overall, FGEA have higher operating costs (CASK between $0.72 and 0.24/ASK) than their conventional counterparts. Eviation Alice, owing to its very limited seating capacity, is much more expensive per passenger than a conventional aircraft (+51% on average compared to the DHC-6). ES-19's operating costs are similar to those of comparable conventional aircraft (DHC-6 and Beechcraft), with lower operating costs for missions above 200 km than DHC-6 but higher operating costs for those missions than Beechcraft. On average, for flights that are shorter than 400 km, ES-19 exhibits lower operating costs than DHC-6 by approximately 1% and higher operating costs than Beechcraft by approximately 7.1%. In contrast, the ES-30 has significantly higher operating

Table 2
CASK for selected FGEA in their specific operating ranges.

Aircraft	Seats	CASK ($/ASK)			
		Max	Mean	Min	$\Delta_{vs conv.}$
Alice	9	0.72	0.46	0.36	+51%
ES-19	19	0.46	0.30	0.24	−1%/+7%
ES-30	30	0.50	0.32	0.25	+27%

Table 3
CASK difference between FGEA models and their conventional counterparts on routes shorter than 400 km under different scenarios of reduced electric aircraft list price.

FGEA list price	19-seat aircraft	30-seat aircraft
Base	7.1%	26.7%
−5%	5.8%	25.6%
−10%	4.4%	24.5%
−15%	3.1%	23.4%
−20%	1.8%	22.3%
−25%	0.5%	21.2%
−30%	−0.8%	20.1%

costs (by approximately one-third) than a 30-seat conventional aircraft (DHC-8). This is likely because of the relative infancy of electric technology in this market segment, particularly concerning battery energy density. However, significant improvements are expected in the next few years due to the expected continuation of the trend of batteries' energy density increasing between 3% and 4% annually since 2000 (Schäfer et al., 2019).

Regarding single-cost components, FGEA exhibit higher per seat ownership costs than their conventional counterparts by approximately 25%–30%. On average, FGEA crew costs are higher than those of conventional aircraft, with values ranging between +15% and +45% per seat (and +15% to +25% per flight). This is due to the longer flight durations (resulting from lower cruise speeds) and the smaller aircraft sizes. However, owing to electric engines' higher efficiency, fuel costs for FGEA are estimated to be approximately 75% lower than those of conventional aircraft.[14] Finally, regarding maintenance costs, the lower average speed of FGEA may offset the lower maintenance cost required per BH, leading to a cost differential with traditional aircraft ranging from −10% to +20% per seat.

5. Sensitivity analysis

Fully electric aviation is still in its infancy, and the industry is experiencing a highly dynamic development phase. Accordingly, frequent changes are occurring in electric aircraft concepts, design, and performance (Hammes and Johansson, 2023). In the following paragraphs, we conduct a sensitivity analysis of the key parameters affecting electric aircraft's operating costs. The aim is twofold: (i) to ensure the robustness of the results regarding FGEA cost-effectiveness and (ii) to address the uncertainty associated with the various potential development trajectories and provide insights into enhanced electric aircraft models' cost-effectiveness.

To conduct the sensitivity analysis, we compare ES-19's and ES-30's operating costs with those of the best-in-class conventional aircraft models with comparable seating capacities, namely Beechcraft 1900 and DHC-8, respectively, on routes shorter than 400 km. We explore the potential impacts of three cost components on the cost comparison: (i) aircraft list price, (ii) maintenance requirements, and (iii) battery replacement costs. All of these components are expected to evolve rapidly in the coming years.

As previously mentioned, considering the current estimated FGEA market prices, ownership costs are expected to be approximately 25%–30% higher per seat compared to fossil fuel-powered aircraft, mainly due to FGEA models' low technological readiness level and early production stage. However, the technological characteristics of electrically-powered aircraft (primarily, mechanical simplicity) promise a potential realignment of market prices with those of traditional aircraft owing to the establishment of economies of scale resulting from increased production volumes. Table 3 presents the average CASK difference between the FGEA models and their conventional counterparts on routes shorter than 400 km under different scenarios where the electric aircraft list price has been reduced. Fig. 3 depicts the cost comparison trends by mission distance.

Considering a 19-seat aircraft, potential alignment of FGEA market prices with those of conventional aircraft (approximately −25%/30%) would enable ES-19 to close the CASK gap with the best-in-class conventional aircraft under consideration (i.e., Beechcraft 1900). Specifically, a 25% reduction in the electric aircraft's list price would result in similar operating costs for the 19-seat electric aircraft and conventional aircraft. Alternatively, a 30% reduction would lower ES-19's CASK to 1% below that of Beechcraft. When considering the 30-seat aircraft model, a significant difference in operating CASK (20%) persists even after a 30% reduction of ES-30's market price.

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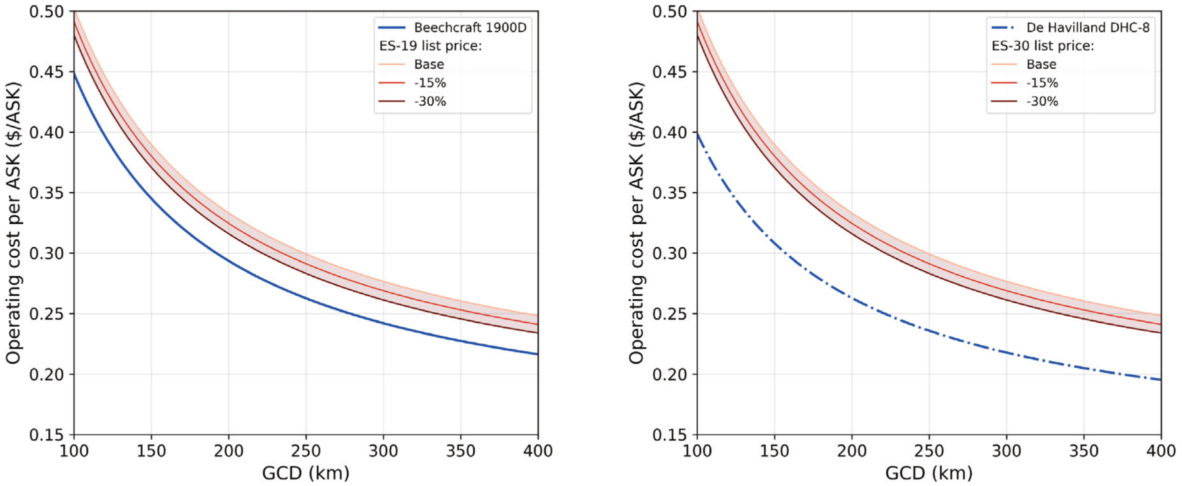
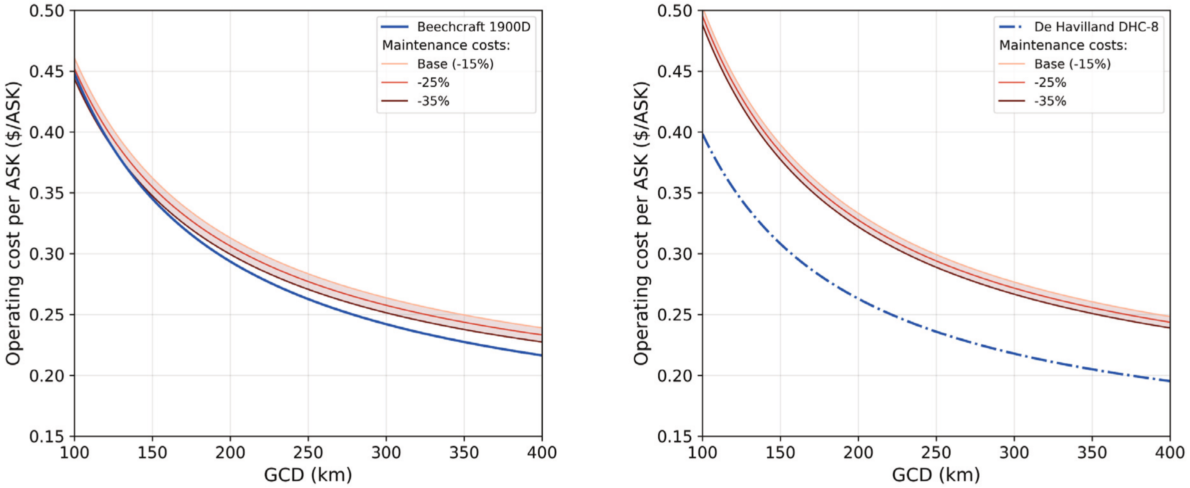
[14] For comparison, Reimers (2018) has estimated that energy consumption for a purely electric aircraft is roughly less than one-third that of traditional fossil fuel-powered aircraft.



(a) ES-19 (b) ES-30

Fig. 3. Electric aircraft list price sensitivity analysis results.



(a) ES-19 (b) ES-30

Fig. 4. Electric aircraft maintenance cost sensitivity analysis results.

Table 4
CASK difference between FGEA models and their conventional counterparts on routes shorter than 400 km under different electric aircraft maintenance requirements scenarios.

Maintenance requirements	19-seat aircraft	30-seat aircraft
−15% (base)	7.1%	26.7%
−20%	5.9%	25.7%
−25%	4.7%	24.6%
−30%	3.5%	23.5%
−35%	2.4%	22.4%

Similar to list price, the evolution of electric aircraft technology will likely lead to reduced electric-powered aircraft maintenance requirements per BH in the near future, owing to both engine simplicity and a shift toward predictive rather than reactive maintenance. To explore potential changes to the baseline cost comparison due to the maintenance cost assumption, we test different maintenance requirement thresholds for FGEA compared to their conventional counterparts, up to −35%. Table 4 and Fig. 4 present the results of the sensitivity analysis of the maintenance costs.

Table 5
CASK difference between FGEA models and conventional aircraft on routes shorter than 400 km under different battery replacement cost scenarios.

(a) ES-19

Battery cost ($/kWh)	Useful battery life (charging cycles)		
	1000 (base)	1500	2000
100 (base)	7.1%	5.4%	4.6%
75	5.8%	4.6%	4.0%
50	4.6%	3.8%	3.3%

(b) ES-30

Battery cost ($/kWh)	Useful battery life (charging cycles)		
	1000 (base)	1500	2000
100 (base)	26.7%	24.5%	23.4%
75	25.1%	23.4%	22.6%
50	23.4%	22.3%	21.7%

Concerning 19-seat aircraft, the reduced maintenance incidence (and thus associated costs) will narrow the cost gap between FGEA and traditional aircraft, albeit to a lesser extent than the impact of list price reductions. Conversely, when considering larger aircraft models (30 seats), FGEA will still be less cost-effective, even in the event of potentially reduced maintenance.

Overall, by jointly considering the two dimensions analyzed above, we conclude that concerning the 19-seat aircraft model, the potential benefits of large-scale production, such as reduced aircraft market prices and maintenance costs, might significantly contribute to bridging the cost difference with conventional aircraft. In fact, a slight reduction in aircraft list prices and maintenance costs can render FGEA cheaper to deploy on routes under 400 km. A realistic timescale for reaping these benefits is between 2030 and 2035, when large-scale commercialization of FGEA is expected. An optimistic scenario, with a 30% reduction in electric aircraft list prices and a 35% reduction in maintenance costs, reports lower operating costs for ES-19 compared to the Beechcraft 1900 by approximately 5.5%. In contrast, 30-seat electric aircraft models appear to be less cost-effective than their conventional counterparts, even when considering an optimistic scenario regarding the evolution of aircraft list prices and maintenance costs. For these larger aircraft, the best prospects for closing the cost gap with conventional aircraft lie in second-generation electric aircraft (SGEA), which will benefit from improved technological knowledge and new battery technology that is expected to be available in the medium to long term (after 2040).

Battery technology development is another potential factor that could impact battery replacement costs and thus the cost-effectiveness of operating regional routes with electric aircraft. Battery replacement cost depends on two main factors: battery cost per unit of storage capacity and battery cycle life. Table 5 presents the sensitivity analysis results for these two parameters. We find that both parameters significantly affect the cost-effectiveness of operating with FGEA. Nevertheless, the anticipated advancements in battery technology in the near future (up to 2040) are unlikely to completely bridge the operating cost gap compared to conventional aircraft. However, it is worth noting that this analysis does not consider potential developments in battery technology in terms of storage capacity per unit of mass, which are expected to significantly improve in the medium to long term. This parameter has the potential to radically enhance electric aircraft's operating performance and impact their operating costs.

Overall, by considering the various potential evolution patterns of key parameters impacting FGEA cost-effectiveness, we confirm that in the short run (2030–2035), FGEA will be cost-effective in the very small regional aircraft market segment (less than 20 seats). Conversely, in the near future, 30-seat electric aircraft operations will be more expensive than conventional aircraft operations (by approximately 20%), but the former has relevant potential in the medium to long run (2040–2045) thanks to the emergence of enhanced SGEA. These new aircraft models will fully exploit the benefits of new battery technology, reduce aircraft ownership costs, and lower the incidence of maintenance activities.

6. Expected impacts

In this section, based on the conclusions regarding FGEA's cost-effectiveness, we attempt to identify the impacts of the potential use of electric aircraft on routes currently operated using conventional aircraft.[15] Specifically, we investigate routes that can potentially be converted to electric aircraft operation in the coming years, with a focus on estimating the associated benefits in terms of GHG emissions reduction. Based on the cost model and sensitivity analysis results, we first concentrate on regional routes under 400 km currently served by aircraft with less than 20 seats that can soon (by 2030–2035) be converted to operation using FGEA. Next, we analyze routes serviced by middle-sized regional aircraft (30–50 seats), which are anticipated to benefit from the emergence of SGEA projected to become available in the medium term (2040–2045).

To quantify the potential benefits of electric aircraft takeovers, we consider data on intra-European flights operated in 2019, which we obtained from the OAG Schedule Analyzer database. Furthermore, we estimate the potential GHG emissions savings by considering the specific fuel consumption of aircraft models deployed on a single route (data retrieved from the OAG) and the expected electricity consumption to operate the route with an electric aircraft. In other words, we compute the potential GHG emissions reduction resulting from the hypothetical uptake of electric aircraft as the difference between the emissions operating flights with conventional aircraft generate and those produced by deploying electric aircraft along the route. To compute the emissions, we adopt a life cycle perspective considering well-to-wake emissions.[16] We report GHG emissions in units of carbon

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[15] Besides merely supplanting conventional aircraft, electric aircraft have the potential to attract passengers from other land-based transportation and serve new (ultra-thin) markets (Brelje and Martins, 2019; Baumeister et al., 2020; Avogadro et al., 2023). This aspect is not the focus of the current paper but could certainly constitute the basis for future research.

[16] Well-to-wake emissions encompass two primary components: (i) upstream or well-to-tank emissions, which arise from the extraction, generation, processing, transportation, and distribution of fuel, and (ii) downstream or tank-to-wake emissions, which comprise direct emissions resulting from fuel combustion.

Table 6
Aggregate statistics for intra-European routes potentially eligible for conversion to electric aircraft operations.

	FGEA	SGEA (40 seats)	SGEA (50 seats)
Movements	60,784 (0.9%)	176,524 (2.5%)	262,584 (3.8%)
km flown ('000)	9178 (0.1%)	32,037 (0.5%)	53,138 (0.8%)
GHG emissions reduction (CO_{2eq} tons)	51,345 (0.1%)	248,448 (0.2%)	425,187 (0.4%)

dioxide equivalents (kg CO_{2eq}). To account for the diverse impacts individual gases have on global warming, following the IPCC's guidelines, gases other than CO_2 are converted to CO_{2eq} by multiplying their global warming potential (GWP) relative to CO_2 over a 100-year time horizon (IPCC, 2014). For conventional aircraft, the fuel consumption is estimated using the reduced order distance–fuel burn relationships Seymour et al. (2020) have calibrated. Fuel consumption is then converted into CO_{2eq} emissions considering the ICAO conventional jet fuel well-to-wake carbon intensity of 89 g CO_{2eq}/MJ (ICAO, 2018), including emissions from crude oil recovery, transportation and refining, and jet fuel transportation and combustion. We assume a jet fuel heat value equal to 43.15 MJ/kg (Baumeister et al., 2020). Given electric aircraft's zero direct emissions during flight (no tank-to-wake emissions), we only consider emissions from electricity generation and distribution. Specifically, we consider the carbon intensity of electricity produced and used in European countries in 2019, as estimated by Scarlat et al. (2022), which is equal to 334 g CO_{2eq}/kWh of electricity.[17]

In 2019, movements on intra-European routes under 400 km accounted for about 1.46 million flights (21% of the total) and cumulatively covered a distance of 398 million km flown. Table 6 provides aggregate statistics on the intra-European routes on which conventional aircraft can potentially be replaced by FGEA and SGEA. The former account for approximately 60,800 movements (representing 0.9% of intra-European flights in 2019) and encompass 9.2 million km flown, whereas the latter account for approximately 176,500 and 262,500 movements (2.5% and 3.8% of intra-European flights) in the case of the advent of 40-seat and 50-seat SGEA, respectively. Under these scenarios, these flights account for approximately 32 million km flown and 53 million km flown per year, respectively.

Fig. 5 depicts the route network potentially eligible for conversion to electric aircraft. From a geographical perspective, the routes that can be quickly converted to FGEA operations mainly include domestic connections in Iceland and Great Britain as well as cross-border connections in the core of Europe (Italy, Germany, France, and Switzerland) and in the Balkan region. Routes eligible for conversion to SGEA primarily include domestic connections in the Scandinavian region and Great Britain and connections to and from minor islands (especially in Greece). From an environmental perspective, the contribution substituting conventional aircraft with electric aircraft can make to aviation emissions reduction is limited in the short run. This is mainly because of electric aircraft's potential short-term use in only a few niche markets of regional routes (representing a minor share of overall emissions from aviation). Specifically, the substitution of very small conventional aircraft (20 seats) with FGEA on regional routes would trigger an annual GHG emissions reduction of approximately 51,300 tons of CO_{2eq}, representing 0.1% of GHG emissions from intra-European aviation (0.3% of emissions on regional routes). The advent of SGEA, with their prospect of being competitive (from an operating cost perspective) for routes currently operated with larger regional aircraft, would provide more relevant emissions reductions, ranging, based on SGEA size (in terms of seats), between 248,448 tons and 425,187 tons of CO_{2eq} (representing 0.2% and 0.4% of emissions from intra-European aviation and 1.3% and 2.8% of emissions from regional routes, respectively).

7. Conclusion

This study proposes a cost model for comparatively evaluating the operating costs of deploying FGEA with respect to their conventional counterparts on regional routes. The cost model includes all the main operating cost components (i.e., ownership, fuel, crew salaries, airport charges, and maintenance) but does not consider other nonrecurring costs, such as aircraft certification and pilot training costs.

We find that although the per seat ownership costs (aircraft purchase or leasing) associated with FGEA are expected to be higher than those of conventional aircraft, other cost components such as fuel and maintenance are expected to be significantly lower. Additionally, we conclude that, in the near future, FGEA will have higher operating costs (per ASK) than conventional aircraft. However, the expected reductions in aircraft price, battery replacement cost, and maintenance costs owing to the consolidation of these technologies might significantly impact electric aircraft's cost-effectiveness. More specifically, we find that FGEA with up to 20 seats can potentially replace conventional aircraft on regional routes in the short run (by 2030–2035). Conversely, in the coming years, larger electric aircraft operations will be approximately 20% less cost-effective than those involving their conventional counterparts. Thus, we expect that electric aircraft will increasingly penetrate this market segment following relevant technological advancements. This is likely to occur with the advent of SGEA. Overall, in the short run, commercial electric aircraft operations will be confined to regional routes (shorter than 400 km) currently served by small regional aircraft, while their extensive use on regional routes will require relevant upgrades in electric-powered aircraft technology, which are anticipated in the medium term.

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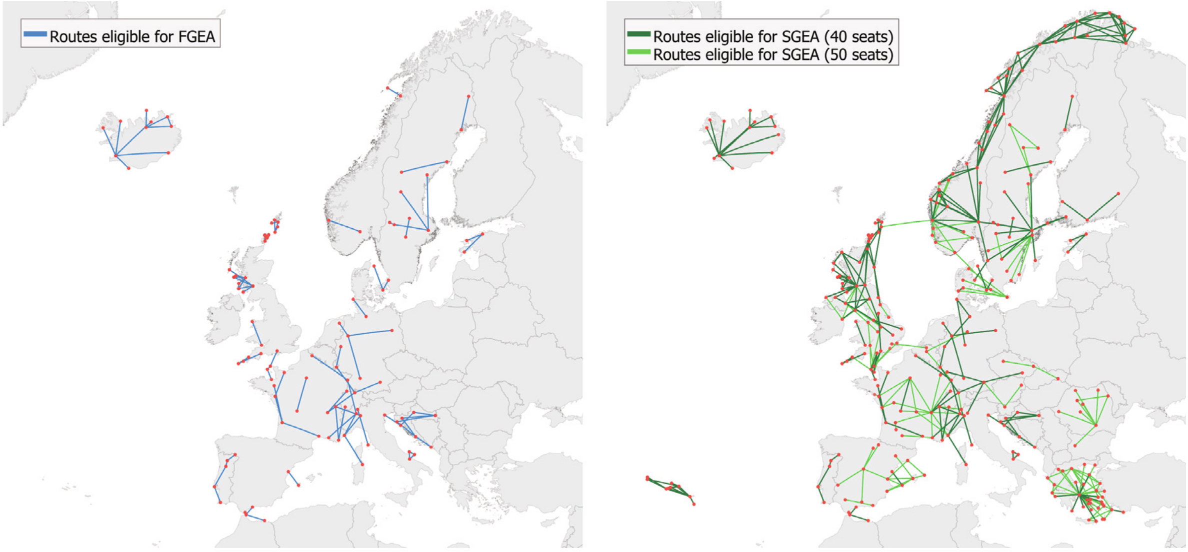
[17] This value includes GHG emissions from all the steps comprising the electricity pathway, namely upstream emissions for providing fuel to power plants; emissions from the construction, operation, and decommissioning of electricity generation facilities; emissions from fuel combustion to produce electricity; and transmission and distribution losses in the electricity grid.



(a) FGEA (b) SGEA

Fig. 5. Intra-European routes potentially eligible for electric aircraft substitution.

Finally, only the expected upscaling of electric technology to narrow-body aircraft with approximately 150 seats and an operating range of up to 1000 km by 2050, enabled by an increase in battery-specific energy to 800 Wh/kg, would permit full exploitation of aviation electrification potentialities (Nakano et al., 2022).

From an environmental perspective, the contribution replacing commercial flights currently operated by fossil-fueled aircraft with FGEA is expected to make to the decarbonization of aviation is relatively limited, and major reductions in GHG emissions are only expected with the advent of SGEA. However, it is worth mentioning that electric propulsion will drastically reduce water vapor and NO_x emissions, which are typically concentrated in the takeoff and climb phases and are responsible for increased radiative forcing. Furthermore, the use of electric engines would significantly reduce the noise around airports during aircraft climbing as well as the noise passengers perceive onboard; such noise is particularly intense in turboprop aircraft, and reducing it would improve passengers' overall comfort onboard. Considering these aspects, the expected environmental benefits exceed those quantified in the current study. Environmental benefits are also expected to be much greater in the long term, considering the potential upscaling of electric propulsion to the small narrow-body aircraft segment.

From a policy perspective, we show that in the short run, aviation electrification, initially targeting extremely niche regional markets, might contribute only marginally to the industry's net-zero transition. Consequently, policymakers should consider combining aircraft electrification with additional policies and measures aimed at curbing overall industry emissions to meet the ambitious climate goals for 2050. Conversely, electric and hydrogen-based aircraft constitute the best options for ensuring the long-term sustainability of the aviation industry.

The progressive transition toward deploying electric aircraft on regional routes also has major implications for passengers, airports, and airlines. For passengers, aircraft electrification will inevitably imply an increase in travel times (due to lower speeds), especially when considering longer trips (Sismanidou et al., 2024). Airports, particularly those with a high incidence of regional flights, need to progressively adapt their infrastructure, such as stands and charging facilities, to accommodate these innovative aircraft. Airlines grappling with the uncertainties surrounding electric aircraft technology will be called upon to strategically define these new aircraft models' role and contribution in their networks. This also involves planning the progressive integration of the new aircraft into the existing fleet. Regional airlines, characterized by extensive regional networks, are the best candidates for the initial adoption of electric aircraft in commercial operations. Conversely, larger airlines are more likely to consider (enhanced) SGEA models as a substitute for conventional aircraft in their networks or as a means to establish new connections. Short-term uncertainties may also lead airlines, other things being equal, to favor policy options such as the use of market-based measures or SAFs, which are more aligned with their existing business models and operations (Sismanidou et al., 2024).

The current study is not exempt from limitations. The main limitation lies in the infancy of electric aircraft technology, which is still in the prototype stage, with relatively little knowledge of the technology itself, its potentialities, and the associated costs. Accordingly, future research endeavors include fine-tuning the electric aircraft cost function considering anticipated technological developments (e.g., battery performance) and the business model that will be adopted for electric aircraft operations (slightly longer turnaround times vs. battery swapping). Furthermore, given that this study has analyzed electric aircraft's potential to replace conventional aircraft, future studies could extend the investigation by considering the potential use of electric aircraft as an alternative to land-based transportation modes, to capture new (ultra-thin) markets that were previously unserved or to substitute business jet flights. Such research would provide useful information about how electric-powered aircraft, which are characterized by specific peculiarities that are distinct from those of conventional aircraft, could present opportunities for airlines to restructure and redesign their networks. Moreover, an analysis of passengers' propensity to use electric aircraft may constitute the basis for future research. Additionally, from an environmental perspective, the present study's investigation of the potential impacts of aircraft electrification on GHG emissions might be extended to consider not only in-operation emissions but also those generated throughout an aircraft's entire life cycle.

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CRediT authorship contribution statement

Nicolò Avogadro: Conceptualization, Data curation, Methodology, Formal analysis, Writing – original draft, Writing – review & editing. **Renato Redondi:** Conceptualization, Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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