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Emissions reduction potentials in business aviation with electric aircraft

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A R T I C L E I N F O

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A B S T R A C T

Under the looming climate crisis, public concerns have been raised regarding the environmental impacts of private jet flights. Electric aircraft are currently considered one of the most encouraging technological keys to significantly reducing the environmental impacts of aviation. This research aims to study the replacement of currently used business jets with fully electric aircraft. This study is based on actual flight data of a European business carrier. The carbon dioxide emissions reduction potential for different aircraft ranges was estimated. Obtained results showed that with fully electric aircraft the studied business carrier could significantly reduce its annual emissions by up to 93%. On a per-passenger basis, the emissions could decrease from 6,787 g of carbon dioxide equivalent per passenger kilometre to 449 g. However, as electric aircraft will operate at a slower speed than business jets, flight times would increase by 10–41 min, depending on the distance.

1. Introduction

Aviation is considered the most rapidly growing transport sector and experts in the field project an average yearly increase of 4.3 % in air transport demand within the upcoming 2 decades (ICAO, 2023). According to the new European Environmental Report, 9.3 million flights were operated from the European Union airports in 2019, 15 % more compared to 2005, while, for the same period, passenger kilometres showed a nearly twofold increase. Flights departing from the same airports in 2019 generated about 147 million tonnes of carbon dioxide (CO_2) emissions, which is a 34 % increase in comparison to 2005 CO_2 figures (EASA, EEA and EUROCONTROL, 2022).

Besides the overall positive effect of the sector's growth, awareness of the negative effect that air transport imposes on the quality of life (noise, emission generation, climate change), and of the necessity for actions towards more sustainable aviation is rising. Accordingly, the European Green Deal objectives, set towards climate neutrality by 2050, are referred to transport-related greenhouse gases (GHG) emissions reduction by 90 %, compared to 1990 levels. Dealing with emissions of pollutants from airport operations has become an important issue, as well (EASA, EEA and EUROCONTROL, 2022). Similarly, the International Civil Aviation Organization is targeting long-term worldwide net zero carbon emissions until 2050 (ICAO, 2022a). To achieve these goals, various measures have been assumed, one of which is aircraft electrification.

Namely, the electrification of aircraft is deemed to be an important element in meeting the environmental-related goals set out by

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the leading entities in the area and their strategies. Major aircraft systems that currently use non-electric power (e.g. engine start) will be replaced with new electrical systems, with the aim to enhance manifold aircraft characteristics, not just those related to emissions, but to efficiency, reliability and maintenance costs, as well (Sarlioglu and Morris, 2015). However, up-to-date battery technology is prompting the sector to investigate hybrid electric aircraft as a viable medium-term answer for reducing global emissions (Jain and Crossley, 2020).

Business aviation accounts for 2 % of the aviation sector's total CO_2 emissions (ICAO, 2022b), which equal to 0.04 % of the global man-made carbon emissions (ICAO, 2019). Besides the low contribution to the aviation sector's carbon emissions, business aviation is recognized as one of the particularly "environmentally critical activities" due to high fuel consumption and emissions per passenger-kilometre travelled. The term "business aviation" refers to the use of private aircraft for business-related travels by companies, executives, and private citizens. It includes a range of aircraft, from small jets to long-range aircraft, which are usually leased or owned by companies to meet their particular travel requirements. As such, business aviation differs from conventional passenger airlines primarily in its flexibility such as time of flight, origin and destination airports (e.g. there are about 3,000 airports in Europe, but only 300 are served by airlines (Aeroaffaires, 2024)), efficiency (time savings) and privacy. Business aviation sector was obligated (in 2021) to expand the commitments made ten years ago, in order to reach net zero CO_2 emissions by 2050 (IBAC and GAMA, 2021). Namely, private flights generate very high emissions per passenger: e.g., 50 times more polluting than trains or up to 14 times more compared to commercial flights, and generate 2 tonnes of CO_2 per hour, whereas the carbon footprint of European citizens was 6.8 tonnes per person in 2019 (Faber and Raphaël, 2023).

Although the Covid-19 pandemic had severe negative impact on air traffic demand in general, in the case of business aviation there was an opposite impact. According to the European Business Aviation Association's report (European Business Aviation Association, 2022), which uses EUROCONTROL data, there was a 6 % increase in business aviation activity in terms of the number of flights in 2021 compared to 2019. This increase in business aviation during and after the COVID-19 pandemic can be attributed to several factors. Due to greater flexibility and control over travel schedules compared to commercial airlines, during the pandemic, when commercial flights were reduced or cancelled, business aviation became a reliable alternative for executives and businesses needing to travel. Furthermore, business aviation offered a potentially lower risk of Covid-19 transmission and less exposure to large crowds compared to commercial aviation. This became particularly crucial during the pandemic when concerns about safety and health increased. Additionally, private aviation became more popular after the COVID-19 pandemic (a large number of first-time private flyers were observed during the pandemic), resulting in the number of flights in 2022 being over 1.5 times higher compared to those in 2021 (Faber and Raphaël, 2023).

In this paper, we will take a look at how electric aircraft could revolutionise business aviation emissions. We study the replacement of business jets with fully electric aircraft on routes of different lengths, in accordance with the current electric aircraft range and range expected in the foreseeable future. In addition to analysing the potentials of electric aircraft in terms of cutting the emissions down, the difference in flight time was also considered in this research. One of the primary goals is to demonstrate how carbon-intensive business jet flights are.

This research is structured as follows. Section 2 provides an overview of related research. The proposed methodology for emissions reduction potentials arising from electric aircraft introduction, i.e., replacement of business jets with electric aircraft, is described through its application in the chosen study case (one European business carrier) in Section 3. The main findings for the given case study are presented in Section 4, followed by further discussion of results within Section 5. Finally, Section 6 contains concluding remarks and suggestions for future research.

2. Literature review

More than 20 years ago authors discussed the concept of more-electric aircraft (MEA) and all-electric aircraft (AEA), as an over-20-year-old idea, emphasizing that studies related to required technologies and equipment were almost continual, but without operational realization (Jones, 1999). The questions asked then are similar to the ones posed today: Will the electric aircraft remain a concept for the future or is its adoption imminent? What has changed to make its adoption more likely in the near future? What is the way forward?

A large number of studies deal with technological issues of electric aircraft, and a majority of those especially emphasize issues related to battery performances. Aircraft performances largely depend on the specific energy of batteries, so concepts including smaller aircraft with shorter ranges are more optimistic. Furthermore, unit costs of batteries and electronics need to be factored in when considering aircraft purchase costs (Brelje and Martins, 2019).

Sarlioglu and Morris (2015) offer a thorough review of the system changes that have been or will be made towards the electric aircraft introduction, e.g., future features like gas-electric propulsion and electric taxiing are considered. Brelje and Martins (2019) discuss the existing research on fixed-wing electric aircraft, including all-electric, hybrid electric and turboelectric variants. The authors also specify the expected advantages and drawbacks of electric propulsion and discuss anticipated benefits. Different hybrid configurations with a generator for conversion of the gas turbine power to additional electric power are considered by Ansell and Haran (2020). Barzkar and Ghassemi (2020) go into detail on MEA and AEA electric power systems (EPS) by covering topics that include distributed propulsion systems, electric propulsion, power sources, and EPS voltage levels and architectures. The idea of MEA and the impacts of aviation on the environment are discussed by Thapa et al. (2021), with an overview of hybrid and AEA. The authors conclude that there has been significant progress in technology issues, which resultantly enables progress in converting conventional aircraft into electric ones. By reviewing various electric aircraft design concepts, prototypes, and currently available products, Adu-Gyamfi and Good (2022) identify the current state, regulatory frameworks, future projections and challenges of the main technological areas of electric aviation that may delay the implementation of electric aircraft.

Besides technological topics, a number of authors are dealing with possible reduction of aviation's CO_2 through electric aircraft introduction, as well as further potentials, including generated noise and cost reduction. While hybrid aircraft and the use of biofuels may result in lower emissions, only AEA could achieve zero emissions in the long term (Gnadt et al., 2019). Some of the authors nevertheless emphasize technological limitations, while others are more optimistic.

Lukasik and Wisniowski (2017) show that flying AEA instead of conventional mid-light business jet aircraft could lead to a considerable decrease not only in operating costs (as jet fuel is more expensive than electricity), but also in negative impacts on the environment (nitrogen oxide (NOx) and CO_2 emissions reduction). Due to challenging energy demands, turboelectric and hybrid aircrafts could be a viable solution enabling the sector to apply all electric propulsion benefits.

As an important step towards the net zero emissions transport sector, Norway is planning to electrify its entire aircraft fleet (Bills et al., 2020). Furthermore, Jain and Crossley (2020) focus on the potential effects of introducing a narrow-body hybrid electric aircraft into an airline fleet in the future, for flights up to 900 nautical miles. It is forecasted that, within 30 years of operations, this could lead to an approximately 15.9 % reduction in CO_2 emissions, compared to emissions of a conventional aircraft airline fleet. In a hybrid aircraft concept, a gas turbine is used together with a generator in order to be able to meet the endurance requirements (i.e. to generate additional energy) for the instrument flight rules operations (Jung and Grimme, 2022). These authors analyse actual 2019 data related to airport pairs operated by ATR42/72 and Dash 8–400 (regional turboprop aircraft) and the obtained results show that the majority of routes were not constrained by the alternate airports availability. While, in the short term, introduction of electric aircraft has limited contribution to the net-zero 2050 goals, in the long term, electric and hydrogen powered aircraft are the best options for ensuring the sustainability of the aviation industry. Electric propulsion will significantly reduce water vapor and nitrogen oxides emissions, responsible for increased radiative forcing, as well as noise around airports and the noise perceived by passengers (Avogadro and Redondi, 2024).

On the other hand, Epstein and O'Flarity (2019) emphasize that since the majority of CO_2 is generated by larger aircraft flying long distances, requiring "no known battery technology" and additional electric energy production, the economic and environmental viability of the AEA concept is questionable. The analysis conducted by Schäfer et al. also shows that batteries with much greater specific energy and lower prices are required (Schäfer et al., 2019) in order to fully benefit from AEA. A battery with specific energy of 800 W hours (Wh) per kilogram (kg) or more, enabling a range of 1,111 km with an A320-sized aircraft, has been identified as a potential solution resulting in fuel consumption and direct CO_2 emissions reduction of 15 %, as well as airport area NO_x emissions reduction of 40 %. A more efficient battery technology, enabling twice the above range, could result in higher reduction of negative effects: fuel consumption and direct CO_2 emissions by around 40 % and NO_x emissions by more than 60 %. The mentioned energy requirement (800 Wh per kg) is 4 to 5 times higher than the specific energy empowered by the latest battery technology (Viswanathan and Knapp, 2019). The limitations of electrification have also been demonstrated in Staack, Sobron and Krus (2021), where the operation of a small full-electric commuter plane is assessed. It is shown therein that, even if all short-range (500 km (km)) operations were carried out by fully electric aircraft powered by renewable sources, the change would affect less than 5 % of the energy used by commercial aviation. However, new types of lithium-sulfur batteries were developed in 2023, with energy densities of up to 500–700 Wh/kg and improved charging and discharging times, and further performance enhancements are expected (Avogadro and Redondi, 2024).

The characteristics of novel electric aircraft technologies also raise the question of their integration into the current airport infrastructure (Doctor et al., 2022). Key considerations are related to aircraft battery recharging time, as well as preconditions for installation of electric charging facilities on the ground.

Environmental impacts are focal points in most sustainability analyses of electric aircraft, while equally essential socio-economic aspects are often disregarded (Barke et al., 2020). These authors develop a conceptual framework to assess socio-economic aspects, based on the Life Cycle Sustainability Assessment (LCSA), and apply it to analyse the impacts of electric propulsion and sustainable aviation fuels (SAFs). Their findings indicate that both aircraft power solutions could contribute to the short-term and long-term Flightpath 2050 reduction goals. SAFs could come as an effective interim solution, which allows for the use of conventional aircraft, while the electric propulsion provides a major potential to reduce environmental impacts. Nevertheless, along the life cycle, both alternatives could induce some negative effects, both environmental and socio-economic.

Several studies dealing with quantification of the small aircraft electrification (potential) environmental effects, which are of greater importance for this research, are presented below.

In terms of future challenges, such as the introduction of a more seamless passenger journey, as well as reduction of aviation-related emissions, an electric 19-seater aircraft with a range extender could be a proper choice (Paul et al., 2019). Fully electric operations, with a range of about 190 km (the assumed specific battery pack energy is 230 Wh/kg and the effective specific battery pack energy is 160 Wh/kg; technical specifications are detailed in Atanasov et al. (2019)), could cover more than 50 % of movements of 19-seater aircraft used in scheduled passenger transport, while using 50 % electric power (with a range extender using hydro-carbon fuels) increases the range to 445 km, covering more than 80 % of operations (according to data for 2000 and 2018), which would all result in significant emissions reduction. For example, replacing all scheduled passenger flights with 19-seater aircraft in 2018 with electric aircraft would result in a total CO_2 reduction of 45.2 % (with the assumed values of CO_2 intensity for electricity generation and efficiency loss in batteries charging). This reduction could potentially increase to 73.3 %, if all electricity is generated from carbon-neutral sources (Paul et al., 2019).

The study by Baumeister et al. (2020) addresses the potentials of First Generation Electric Aircraft (FGEA) to decrease emissions at distances up to 1,046 km in Finland. It appraises CO_2 equivalent emissions and door-to-door real travel times (RTT) of FGEA compared to the current air, train, and car modes, and to the high-speed trains and electric vehicles that the paper puts forward to be introduced. All existing aircraft and cars on routes longer than 170 km could be replaced with FGEA, both resulting in CO_2 equivalent emissions and RTT reduction; however, the current energy mix does not favour using FGEA instead of the existing trains.

Mukhopadhaya and Graver (2022) analyze the performance of 3 types of electric aircraft: the 9Bolt, 19Bolt, and 90Bolt (carrying 9, 19 and 90 passengers, respectively), for different specific energy of the battery (250 to 500 Wh/kg) and empty mass fraction of the aircraft (the ratio of the aircraft's operating empty weight without batteries to its maximum take-off mass). Besides the significant decrease in carbon intensity per Revenue Passenger Kilometres (RPK) achieved with electric aircraft (49 % – 57 %, compared to aircraft using conventional fossil fuel, reaching 82 % – 88 % of reduction if batteries are charged by renewable energy), the contribution to overall CO_2 emission reduction is limited. Due to electric aircraft limitation to short-range small passenger aircraft, the aviation's emissions could be reduced annually by 3.7 million tonnes of CO_2 equivalent emissions by 2050, which represents 0.2 % of the expected aviation's emissions in 2050.

Also interesting for this research is a thorough overview of private flights and their emissions across Europe given in the CE Delft report (Faber and Raphaël, 2023). Different statistics are presented in the report, such as the total private aviation CO_2 emissions, the most frequently used private aviation routes, the highest CO_2 emission routes, etc.

Based on data for intra-European flights operated in 2019, Avogadro and Redondi (2024) quantify the potential GHG emissions savings with the electric aircraft introduction on regional routes under 400 km, currently served by aircraft with less than 20 seats and assumed to be taken over by FGEA (0.9 % of intra-European flights in 2019), and on routes served by middle-sized aircraft (30–50 seats) assumed to be replaced with Second Generation Electric Aircraft – SGEA (2.5 % – 3.8 % of intra-European flights). The replacement of small conventional aircraft with FGEA would result in an annual GHG emissions reduction of approximately 0.1 % of GHG emissions from intra-European flights, while SGEA introduction would enable a more significant reduction of 0.2 % and 0.4 % of emissions (based on SGEA size).

Eaton et al. (2024) analyze the potential of future AEA for emissions reduction, by comparing conventional fuel consumption and related emissions with the projected AEA energy consumption and emissions, for nearly 9.2 million United States domestic commercial flights. While AEA offer limited potential for CO_2-eq. emissions reduction of around 1.2 % on the national level in 2050, the identified airports and flight routes with the highest potential for emission reduction show a clear potential for more significant environmental benefits. The obtained results in this research assume batteries with a specific energy of more than 900 Wh/kg. In their previous research (Eaton et al., 2023), these authors show that, for the same market, AEA could reach 46.6 % of the domestic passenger share, which corresponds to 20.9 % of revenue passenger kilometers (RPK) by 2050, resulting in a 1.02 % – 19.8 % net CO_2-equivalent emissions reduction for the assumed emerging battery technology, namely lithium-air cells with a specific energy of 915 Wh/kg.

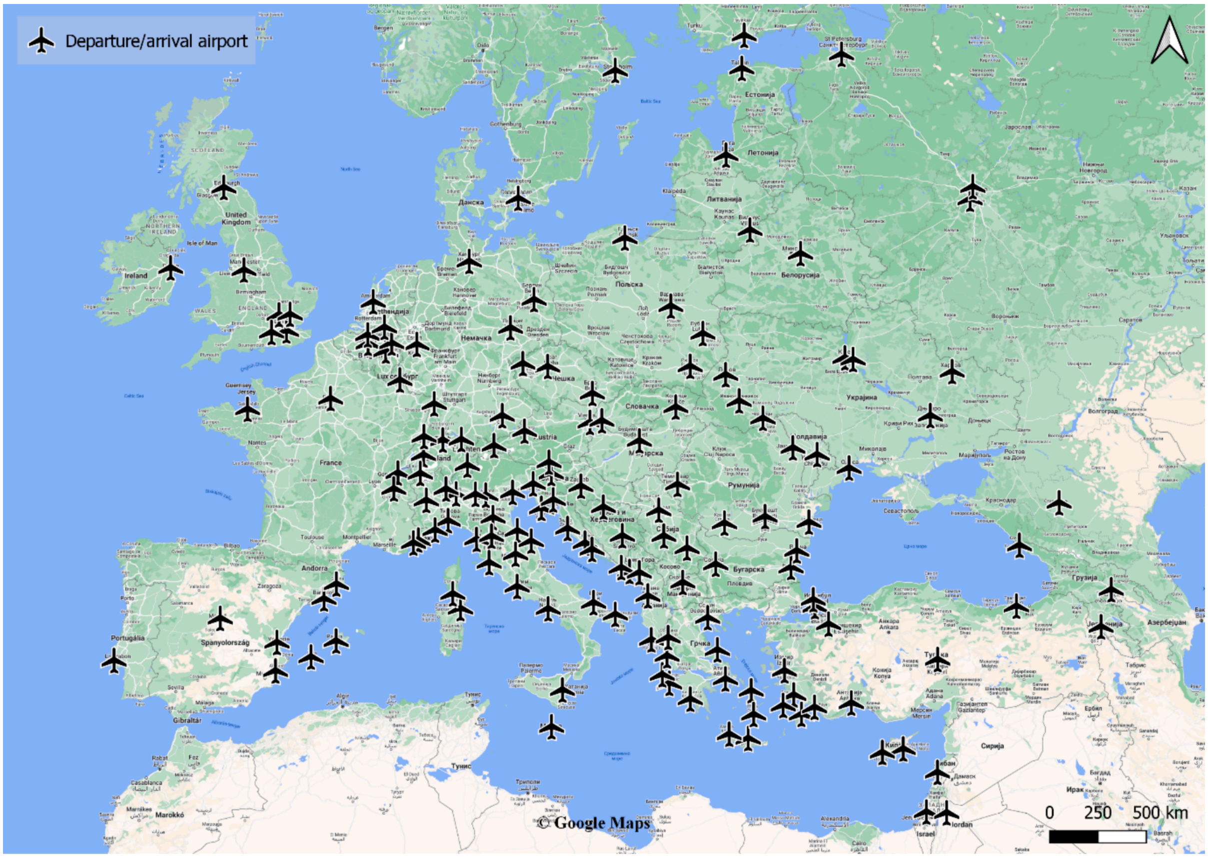

Fig. 1. Departure and/or arrival airports of the considered flights.

The literature review in the field shows the promising potential of electric aircraft. Nevertheless, there is a number of open questions related to their impact on the environment and required advancements in technologies and infrastructural development, in order to make this new regime of air transport viable and to meet aviation's goals related to environmental impact. This research contributes to the existing academic literature in the field, focusing on the quantification of potential benefits of introducing electric aircraft in business aviation.

3. Methods and data

In order to examine the effects of electric aircraft introduction, i.e. business jets replacement with electric aircraft, the methodology consisting of the following steps is proposed:

1) Select the relevant case (airline/specific routes/time frame) to study;
2) Chose the type of electric aircraft to introduce;
3) Define an approach for flight times (durations), fuel consumption and gas emission calculation for business jets, as well as for electric aircraft (appropriate for the selected case study – the approach could be chosen after the case study selection);
4) Calculate flight times, fuel and energy consumption and gas emission for the case study; and
5) Analyse the obtained (comparative) results, in order to investigate the effects of business jets replacement with electric aircraft.

3.1. Case studied

The chosen study is based on actual flight data of a European business carrier that operates two different aircraft types, the 5-seater Cessna 525 Citation Jet and the larger 9-seater Cessna 560XL.

The study year was 2021, because a comprehensive dataset required for this research was available for this year.

In total, we studied 1,076 flights on 548 different city pairs, where the flight distance was up to 1,000 km. The considered flights were performed from 156 different departure and/or arrival airports, located in 44 different countries, as shown in Fig. 1.

Although many business jets are hired also for longer flights, due to the limited range of electric aircraft, which at the current point in time are the only feasible alternative to business jets, we had to limit our study to the given range of 1,000 km. Namely, First Generation Electric Aircraft (FGEA) will not be able to operate on longer routes in the foreseeable future. So, flights (operated by the observed business carrier) beyond 1,000 km, have been excluded from our study.

Table 1 shows the collected data in terms of the number of flights and the number of passengers per each aircraft type, divided into ten different categories according to flight distance. There is almost equal flight distribution between the two aircraft types, going slightly in favour of Cessna 560XL (52.2 % of all flights). In terms of the distance flown, flights between city pairs within the 200–300 km range were most dominant (178 flights or 16.5 %), followed by flights within the 800–900 km range (176 flights or 16.4 %), while all other categories, according to flight distance, had less than 13 % of flights. Table 1 also provides data about Available Seat Kilometres (ASK) and Revenue Passenger Kilometres (RPK). ASK is a measure commonly used by airlines to describe their supply through passenger carrying capacity. It is determined by multiplying the available seats on any given aircraft by the number of kilometres flown on a given flight. On the other hand, RPK is an airline industry metric to measure actual demand shown as the number of kilometres travelled by paying passengers. It is computed by multiplying the number of revenue passengers by the total distance travelled.

In terms of the electric aircraft, Eviation's Alice was found to be a suitable replacement for the currently used Cessna 525 Citation and Cessna 560XL business jets. Eviation Alice can (currently) carry 9 passengers over a distance of up to 250 nautical miles (Nm), which is around 450 km (Eviation, 2023). Initially, the range was announced to be 1,046 km based on a 900 kW hour (kWh) battery, but in 2021 Eviation unveiled the production version of its aircraft with the range reduced to 440 Nm (around 800 km), (Electrek, 2022), with 820 kWh battery energy (Hemmerdinger, 2021), which is still viable for plenty of short routes. However, the company is

Table 1
Number of flights and passengers per aircraft type and distance.

Distance (km)	Number of flights		Number of passengers		ASK		RPK	
	C525	**C56X**	**C525**	**C56X**	**C525**	**C56X**	**C525**	**C56X**
up to 100	5	6	0	0	1124	3927	0	0
100–200	19	19	23	1	17,616	26,573	4303	176
200–300	103	75	173	71	147,236	186,481	49,184	20,915
300–400	47	51	70	13	79,255	157,955	23,847	4,704
up to 400 km	**174**	**151**	**266**	**85**	**245,231**	**374,935**	**77,333**	**25,795**
400–500	70	61	35	33	160,937	251,365	16,011	15,395
500–600	64	50	64	36	174,916	251,166	35,098	20,487
600–700	41	48	41	11	131,602	277,133	26,459	6,845
700–800	42	67	49	46	156,734	454,849	36,112	34,955
up to 800 km	**377**	**391**	**455**	**211**	**869,420**	**1,609,448**	**191,013**	**103,477**
800–900	68	108	76	102	286,845	819,478	64,557	86,285
900–1000	55	77	75	59	262,716	662,226	71,996	56,959
Total (up to 1,000 km)	**514**	**562**	**606**	**372**	**1,418,981**	**3,091,152**	**327,566**	**246,721**

planning to improve its battery technology, which will result in higher energy density and electric aircraft with a longer range (Electrek, 2022). This fully electric aircraft, still under development, made its first flight on September 27, 2022, and should be certified for commercial use by 2025 (Eviation, 2023).

Due to the uncertainty regarding the maximum range of electric aircraft, in this research, we used three different scenarios: 400 km, 800 km and 1,000 km.

3.2. Flight times, fuel and energy consumption and gas emission calculation

For business jets, fuel consumption is assessed with the help of the EMEP/EEA Air Pollutant Emissions Inventory Guidebook (EASA, 2022; Electrek, 2022; International Business Aviation Council (IBAC), 2021; UK Government, 2019; Winther, 2019). CO_2 emissions are determined from the fuel burned, by multiplying this value by a factor of 3.169 (Baumeister and Leung, 2021). In addition to that, non-CO_2 effects of aviation (such as water vapour, nitrogen oxides, sulphate and soot aerosols, contrails and cirrus clouds) were also taken into account, as recommended by the EASA, 2022; Electrek, 2022; International Business Aviation Council (IBAC), 2021; UK Government (2019), adding a factor of 1.9 to the CO_2 emissions. Methan (CH_4) and nitrous oxide (N_2O) emissions were also determined, referring to the fuel burn by assuming 0.0005 g per megajoule (MJ) for CH_4 and 0.002 g per MJ for N_2O, whereas the heat value was considered as 43 MJ/kg following Baumeister and Leung (2021). CO_2, CH_4 and N_2O emissions per flight for conventional aircraft were calculated by using the following equations (1)–(3):

$$CO_2 = \text{Fuel Burn} * 3.169 * \text{Non-}CO_2 \text{ effects} \quad (1)$$

$$CH_4 = \text{Fuel Burn} * \text{Heat Value} * 0.0000005 \quad (2)$$

$$N_2O = \text{Fuel Burn} * \text{Heat Value} * 0.000002 \quad (3)$$

Carbon dioxide emissions (CO_2-eq) per flight were calculated according to the Intergovernmental Panel on Climate Change's (IPCC) Report (IPCC, 2021) by using the following equation (4):

$$CO_2\text{-eq} = CO_2 + CH_4 * 29.8 + N_2O * 273 \quad (4)$$

The time period used for GWP (Global Warming Potential) is 100 years, which is the most commonly applied timeframe in policy making. Compared to the GWP20 and GWP50 timeframes, GWP100 provides a stronger focus on long-lived GHGs that have long-term warming effects such as CO_2.

The CO_2 emissions generated by production of the electricity required for the proposed Eviation Alice were obtained according to the methodology used by Baumeister et al. 2020, based on the aircraft range, battery energy and the existing energy mix of the country which the studied business carrier operates from. For different aircraft versions observed (different ranges and related battery energy), CO_2-eq emissions were calculated for the observed flights, up to distances of 400 km, 800 km and up to 1,000 km, by the following equation (5):

$$CO_2\text{-eq} = (\text{Battery energy} / \text{Aircraft range}) * CI * \text{Flight distance} \quad (5)$$

where:

CI is the carbon intensity, i.e. the grams of CO_2-eq emissions released to produce a kWh of electricity, according to the energy mix of the country which the studied business carrier operates from and it was obtained from Electricity Maps (2022).

For conventional aircraft, energy consumption directly relates to fuel burn, as shown in equation (6), where the specific energy of aviation fuel is 42.8 MJ/kg (ASTM American Society for Testing and Materials, 2017).

$$E(MWh) = 42.8MJ/kg*1kWh/3.6MJ*1MWh/1000kWh*F(kg) = 0.01189*F(kg) \quad (6)$$

where E is the energy consumption in MWh, and F is the fuel consumption in kg.

Energy consumption for Eviation Alice was calculated using a similar approach as for CO_2-eq emissions, for different aircraft versions observed (different ranges and related battery energy), for the observed flights, up to distances of 400 km, 800 km and up to 1,000 km, by using the following equation (7):

$$E = (\text{Battery energy}/\text{Aircraft range})*\text{Flight distance} \quad (7)$$

Flight times are assessed based on the above-mentioned EMEP/EEA Guidebook (Winther et al., 2019) which provided the exact flight times for both Cessna business jets. For Eviation Alice, maximum operating speed is 260 knots, which is similar to the speed of turboprop aircraft ATR72. Therefore, the flight times of the ATR72, obtained based on the same guidebook, were used as a reference model.

Some additional assumptions are introduced. Although not all flights were carrying passengers, all empty flights were allocated to the passengers carried, as these flights would not have taken place without those passengers e.g., empty flights to pick up passengers or to return to the base of operations.

Furthermore, the battery charging time was not considered, since it was seen as irrelevant, as the actual aircraft operations were not part of this study. Nevertheless, it has to be acknowledged that recharging of the batteries will take longer than refuelling an aircraft of a similar size and will affect the aircraft operations. Oosterom and Mitici (2023) estimate a full recharge of Eviation Alice's batteries to last for about 4 h. However, battery swapping as discussed by Mitici et al. (2022) could hereby also be seen as a feasible alternative.

4. Results

In 2021, the studied business carrier operated 1,076 flights at distances up to 1,000 km carrying in total 978 passengers. This resulted in an average load factor of just 12.7 % (RPK divided by ASK – see Table 1). Of those 1,076 flights, 325 flights carried 351 passengers at distances up to 400 km, with additional 443 flights with 315 passengers at distances from 400 km to 800 km, which resulted in 768 flights carrying 666 passengers at distances up to 800 km. Although the business carrier uses mainly small jets (5 and 9 seaters), many flights carry only 1–2 passengers, which explains the low load factor in addition to the fact that many flights were flown empty due to operational reasons, such as picking up passengers or empty return flights to the home base.

Table 2 shows the results obtained for the total and average CO_2 equivalent emissions for the observed aircraft types and related number of flights at different flight distances, with the emission reduction for different electric aircraft ranges. For example, the carbon dioxide equivalent emissions for all 1,076 operated flights within the range of 1,000 km resulted in a total of 4,257 tCO_2-eq, which translates into 4,353 $kgCO_2$-eq per passenger. When dividing the total carbon dioxide emissions from all 1,076 operated flights by the total distance flown during the calendar year 2021 (627,258 km), the per passenger-km (pkm) emissions resulted in 6,787 gCO_2-eq/pkm.

By replacing the currently used aircraft types Cessna 525 Citation and Cessna 560XL with Eviation Alice on all 1,076 flights (routes up to 1,000 km), the studied business carrier could reduce its annual total carbon dioxide equivalent emissions by 3,975 tCO_2-eq or 93.38 %. Flying on Eviation Alice instead of a Cessna business jet would result in only 288 $kgCO_2$-eq per passenger and cut down emissions per passenger-km to 449 gCO_2-eq/pkm. For the lower electric aircraft ranges (up to 800 km and up to 400 km), the obtained values of CO_2 equivalent emissions per passenger-km are slightly higher − around 535 gCO_2-eq/pkm.

The CO_2 emissions reduction for the lower electric aircraft ranges would also be significant − by 93.38 %, compared to emissions generated by flights operated at the corresponding distances: up to 400 km or up to 800 km. Compared to all operated flights observed (up to 1,000 km), the electric aircraft introduction on flights up to 800 km or up to 400 km, would result in CO_2-equivalent emissions reduction by around 56.95 % and 18.56 %, respectively.

However, by replacing the currently used Cessna business jets with Eviation Alice, the flight times would increase, depending on the distance flown, due to the fact that Eviation Alice operates at a lower speed (similar to those of turboprop aircraft). For example, as shown in Fig. 2, on longer flights, close to the maximum range of FGEA (1,000 km), flight times increase by 41 min compared to Cessna 560XL and by 35 min compared to the smaller Cessna 525 Citation. With decreasing flight distance, the difference in flight times also decreases. For example, for a flight distance of 250 km, the FGEA would take only 10 min longer.

Fig. 3 shows the relationship between distance and CO_2-eq emission for both types of aircraft (obtained using the chosen methodology described in Section 3.2). The difference between CO_2-eq emission per kilometre (flight distance) generated by conventional and electric aircraft is very significant. In addition, Fig. 4 shows the relationship between distance and energy consumption. The displayed curves are the same as in Fig. 3, since energy consumption and CO_2-eq emission are both directly calculated from the fuel burnt. (Note: it is assumed that electric energy consumption (and therefore CO_2 emission) per kilometre flown is equal for the 400 km and 800 km range scenarios).

5. Discussion

The findings clearly highlight the immense environmental impact of flying on business jets compared to the already high impacts of flying on regular commercial flights. The high impacts can be explained by the nature of business jet operations, which often carry only few passengers and require many empty flights to pick up passengers or to return to the business carrier's home base. This becomes quite obvious by the low load factor, which in the case of our study yielded only 12.7 % (for all observed flights, on the routes up to 1,000 km). While regular commercial flights operate according to pre-set timetables, bundling large streams of passengers on both outbound and inbound flights with the clear aim to sell as many seats as possible (in order to yield high load factors in the range of 80–90 % or above), business carriers operate more on an on-demand basis depending on the individual needs of single passengers or small groups of passengers. These flight services are often point-to-point and, as already mentioned, in many cases only in one direction. Although the aircraft used by business carriers are rather small, the nature of these flights i.e. a very low load factor, makes the environmental impact of an individual air passenger grow far beyond that of a regular airline passenger. While the per passenger-km emission of an average short-haul European flight ($<$1,000 km) ranges at 285 gCO_2-eq, in the analysed case (in this paper) of the business carrier and its passengers, it accounts from 6,787 gCO_2-eq, as the average value for the flights on routes up to 1,000 km, to 9,248 gCO_2-eq per passenger-km for the observed flights up to 400 km. In comparison to that, travelling by car with a 1.5 passenger occupancy results in 158 gCO_2-eq, while travelling by electric train would emit only 14 gCO_2-eq per passenger-km (EEA, 2014).

Replacing currently used business jets with FGEA on routes up to 1,000 km would allow business carriers' operations to be rendered significantly more sustainable, cutting emissions over 93 %. For the lower electric aircraft ranges, up to 800 km or 400 km, the CO_2 equivalent emissions reduction would also be significant, by around 57 %, and 18.6 %, respectively, compared to all operated flights (up to 1,000 km) observed.

Also, from a passenger's point of view, flying electric would help close the gap between flying on a business carrier and travelling on regular commercial flights or even other land-based transport modes. Nevertheless, by emitting 449 or 535 gCO_2-eq per passenger-km, flying on a private FGEA would still exceed those emissions from flying on regular commercial flights. One of the downsides of flying electric would be the flight time, especially noticeable for longer flights, closer to 1,000 km. Here, a two-hour business jet flight would take 40 min longer when replaced with FGEA, while a one-hour flight would increase by 10 min. Although flying electric would significantly reduce emissions, it remains to see whether business jet travellers, with limited time available, would accept longer flight

Table 2
Emission reduction for different electric aircraft ranges.

				Cessna 525 and Cessna 560XL emission			Eviation Alice emission			Emission reduction	
	No of flights	No of pass.	Total distance (km)	Total tCO_2-eq	$kgCO_2$-eq/passenger	gCO_2-eq/pkm	Total tCO_2-eq	$kgCO_2$-eq/passenger	gCO_2-eq/pkm	Total tCO_2-eq	% compared to 1076 flights
Up to 400 km	325	351	90,706	838	2,390	9,248	48	138	535	790	18.56
Up to 800 km	768	666	352,712	2,613	3,924	7,409	189	283	535	2,424	56.95
Up to 1,000 km	1076	978	627,258	4,257	4,353	6,787	282	288	449	3,975	93.38

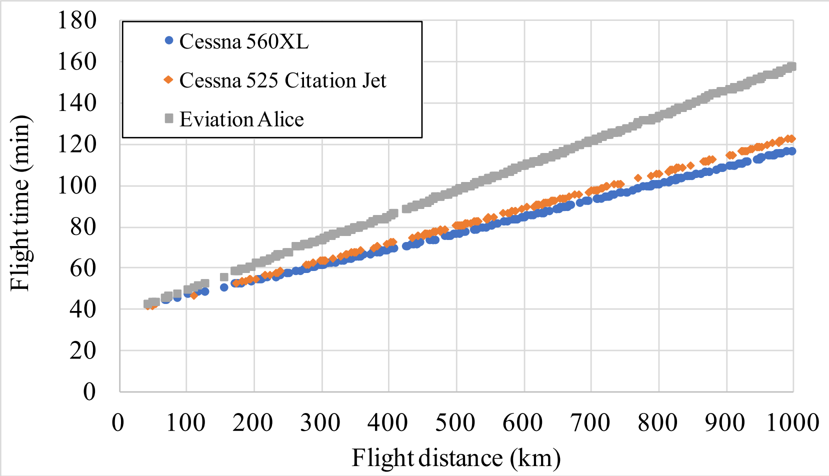

Fig. 2. Flight distance and time curves for business jets and FGEA.

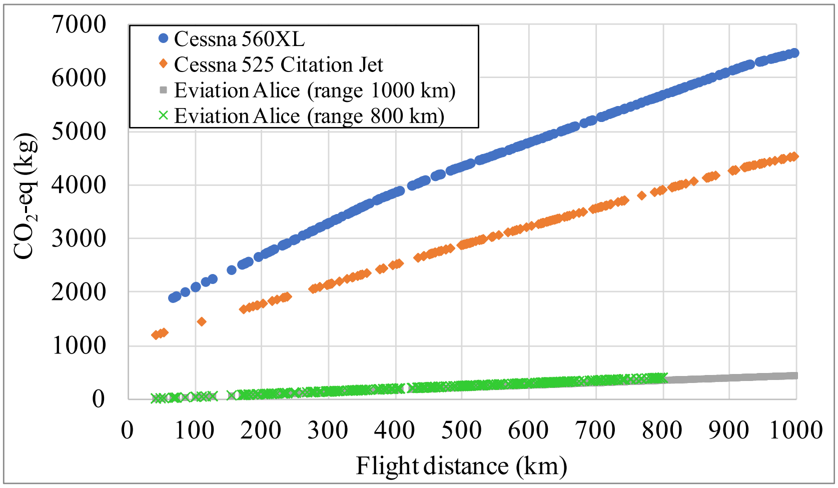

Fig. 3. Flight distance and CO_2-eq curves for business jets and FGEA.

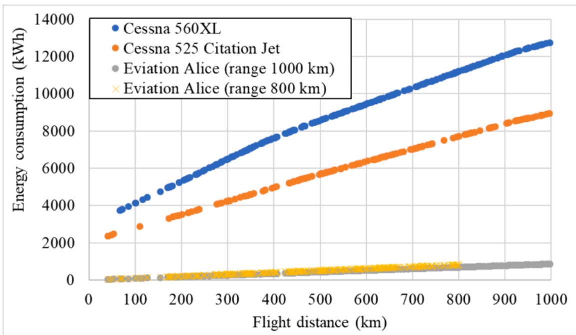

Fig. 4. Flight distance and energy consumption curves for business jets and FGEA.

times.

In terms of the total impact of replacing the currently used business jets with FGEA upon the aviation sector, their role might seem insignificant as business aviation contributes with only 2 % of CO_2 emissions to the entire sector (ICAO, 2022b). Nevertheless, from a passenger's point of view, the emissions reduction potentials are quite significant. Furthermore, as FGEA are limited to routes up to

1,000 km, this might seem like another limitation. However, according to the European Business Aviation Association (2024) only 5.7 % of business jet flights are currently Extra-European, while the vast majority of 58.2 % are European and 36.1 % were domestic. In 2021 the average stage length of the 30 busiest business aviation routes in Europe was 623 km, while only 5 of these routes exceeded the limit of 1,000 km (European Business Aviation Association, 2022). Although Eviation Alice would be limited to 1,000 km, it could cover a large share of business aviation routes currently operated in Europe. The National Business Aviation Association (2024) likewise states that in the United States the majority of business jets seat 6 passengers and operate on stage lengths of less than 1,000 miles.

6. Conclusion

This paper set out to study the replacement of business jets with FGEA, analysing the emissions reduction potentials of electric aircraft, as well as the differences in flight time. The low number of passengers and many empty flights make business carrier flights far less efficient compared to regular passenger flights. This clearly reflects in the significantly lower load factors and highlights the need for alternative solutions in order to justify the use of business carrier operations in the future as well.

FGEA could provide a viable alternative to currently used business jets on flights up to their maximum range, providing an alternative to a vast number of short routes currently operated by business jets. FGEA could help cut down emissions from a business carrier operator's perspective significantly and close the huge gap between individual per passenger-km emissions flying on business jets and the use of other transport modes. Actually, regular commercial flights or land-based transport modes could still be feasible alternatives at distances up to 1,000 km. FGEA does lack behind business jets only in terms of flight time. Nevertheless, the longer flight time could be acceptable given the significant decarbonisation potentials FGEAs offer.

In terms of limitations of this study, only a small number of flights were studied instead of looking at the entire business aviation sector as a whole, which certainly limits the generalizability of our findings. Furthermore, only small-sized business aircraft were studied and only one electric aircraft type (Eviation Alice) was considered for replacement of both Cessna 525 Citation and Cessna 560XL. While Eviation Alice has the same number of seats as the larger Cessna 560XL, it is significantly larger than Cessna 525 Citation, which is only a 5-seater. Replacing Cessna 525 Citation with a smaller FGEA might have yielded even higher emissions reduction potentials than assumed in our current study. Nevertheless, acquiring two different types of FGEA to cover flights of less than 1,000 km (or even flights at shorter distances) might economically not have been viable in the case of the studied business carrier, which is why only one FGEA was considered to replace both aircraft types currently in use.

In terms of future research, as discussed in the limitations, more FGEA models could be studied both in the 9-seater and 5-seater segments. In addition to that, aspects other than emissions reduction potentials and flight times could also be considered, such as operating costs, aircraft reliability or the effects of fleet diversification due to adding FGEA to existing fleets. Furthermore, the integration of FGEA into the current air traffic system and their impacts due to different aircraft performances could be a subject for further research. Last but not least, the effects of using various sustainable aviation fuels, other than fully electric aircraft, to power business jets could be studied.

It can be concluded that electric aircraft are a promising solution to reducing emissions in the business aviation sector. With their greater efficiency and near-zero emissions, these new technologies could be a major breakthrough in the fight against climate change. In addition to helping reduce carbon dioxide and other GHG pollution, electric aircraft will also provide cost savings by reducing reliance on costly fossil fuels. As this technology continues to develop and becomes more accessible to business aviation operators, it is likely that electric aircraft will become increasingly important components of the global effort to combat climate change.

CRediT authorship contribution statement

Stefan Baumeister: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Conceptualization. **Tatjana Krstić Simić:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis. **Emir Ganić:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Formal analysis, Conceptualization.

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References

Adu-Gyamfi, B.A., Good, C., 2022. Electric aviation: A review of concepts and enabling technologies. Transportation Engineering 9, 100134. https://doi.org/10.1016/j.treng.2022.100134.

Aeroaffaires, 2024. *Private aviation vs. commercial aviation: what are the differences?* Available at: https://aeroaffaires.com/.

Ansell, P.J., Haran, K.S., 2020. Electrified Airplanes: A Path to Zero-Emission Air Travel. IEEE Electrif. Mag. 8 (2), 18–26. https://doi.org/10.1109/MELE.2020.2985482.

European Business Aviation Association, 2022. *Business Aviation Traffic Tracker Europe December 2021*. Available at: https://www.ebaa.org/resources/european-business-aviation-traffic-tracker-december-2021/.

ASTM American Society for Testing and Materials, 2017. *D1655: Standard Specification for Aviation Turbine Fuel*. West Conshohocken, PA: ASTM International.

Atanasov, G., van Wensveen, J., Peter, F. and Zill, T., 2019. Electric Commuter Transport Concept Enabled by Combustion Engine Range Extender, in: Deutscher Luft- und Raumfahrtkongress 2019.
Avogadro, N., Redondi, R., 2024. Demystifying electric aircraft's role in aviation decarbonization: Are first-generation electric aircraft cost-effective? Transportation Research Part D - Transport and Environment 130, 104191. https://doi.org/10.1016/j.trd.2024.104191.
Barke, A., Thies, C., Melo, S.P., Cerdas, F., Herrmann, C., Spengler, T., 2020. Socio-economic life cycle assessment of future aircraft systems. Procedia CIRP 90, 262–267. https://doi.org/10.1016/j.procir.2020.01.096.
Barzkar, A., Ghassemi, M., 2020. Electric Power Systems in More and All Electric Aircraft: a Review. IEEE Access 8, 169314–169332. https://doi.org/10.1109/ACCESS.2020.3024168.
Baumeister, S., Leung, A., Ryley, T., 2020. The emission reduction potentials of First Generation Electric Aircraft (FGEA) in Finland. J. Transp. Geogr. 85, 102730 https://doi.org/10.1016/j.jtrangeo.2020.102730.
Baumeister, S., Leung, A., 2021. The emissions reduction potential of substituting short-haul flights with non-high-speed rail (NHSR): the case of Finland. Case Studies on Transport Policy 9, 40–50. https://doi.org/10.1016/j.cstp.2020.07.001.
Bills, A., Sripad, S., Fredericks, W., Singh, M., Viswanathan, V., 2020. Performance metrics required of next-generation batteries to electrify commercial aircraft. ACS Energy Lett. 5 (2), 663–668. https://doi.org/10.1021/acsenergylett.9b02574.
Brelje, B.J., Martins, J.R.R.A., 2019. Electric, hybrid, and turboelectric fixed-wing aircraft: a review of concepts, models, and design approaches. Prog. Aerosp. Sci. 104, 1–19. https://doi.org/10.1016/j.paerosci.2018.06.004.
Doctor, F., Budd, T., Williams, P., Prescott, M., Iqbal, R., 2022. Modelling the effect of electric aircraft on airport operations and infrastructure. Technol. Forecast. Soc. Chang. 177, 121553 https://doi.org/10.1016/j.techfore.2022.121553.
EASA, EEA and EUROCONTROL, 2022. *European Aviation Environmental Report 2022*. Doi: 10.2822/04357.
Eaton, J., Naraghi, M., Boyd, J. G., 2024. *Regional Pathways for All-Electric Aircraft to Reduce Aviation Sector Greenhouse Gas Emissions*. Available at: https://ssrn.com/abstract=4759156.
Eaton, J., Naraghi, M., Boyd, J.G., 2023. Market capabilities and environmental impact of all-electric aircraft. Transportation Research Part D - Transport and Environment 124, 103944. https://doi.org/10.1016/j.trd.2023.103944.
EEA, 2014. *Focusing on environmental pressures from long-distance transport;TERM 2 014: transport indicators tracking progress towards environmental targets in Europe,* EEA Report No 7/2014, Doi:10.2800/857401.
Epstein, A.H., O'Flarity, S.M., 2019. Considerations for Reducing Aviation's CO2 with aircraft electric propulsion. J. Propul. Power 35 (3), 572–582. https://doi.org/10.2514/1.B37015.
Electrek, 2022. *Watch Eviation's all-electric Alice aircraft first flight*. Available at: https://electrek.co/2022/09/27/eviation-all-electric-alice-aircraft-first-flight/.
European Business Aviation Association, 2024. *EBBA Yearbook 2023*. Available at: https://yearbook.ebaa.org.
Eviation, 2023. *Alice Commuter*. Available at: https://www.eviation.com/.
Faber, J., Raphaël, S., 2023. CO2 emissions of private aviation in Europe. Delft, Netherlands.
Gnadt, A.R., Speth, R.L., Sabnis, J.S., Barrett, S.R.H., 2019. Technical and environmental assessment of all-electric 180-passenger commercial aircraft. Prog. Aerosp. Sci. 105, 1–30. https://doi.org/10.1016/j.paerosci.2018.11.002.
Hemmerdinger, J., 2021. Eviation changes Alice design, performance specifications shift. Available at. https://www.flightglobal.com/airframers/eviation-changes-alice-design-performance-specifications-shift/144376.article.
Icao, 2023. Future of Aviation. Available at: https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx.
ICAO, 2019. *Business Aviation and Sustainability: An Industry with a Good Story to Tell*. Available at: https://www.icao.int/environmental-protection/Documents/Environmental Reports/2019/ENVReport2019_pg177-181.pdf.
ICAO, 2022a. *Doc 10184, Assembly Resolutions in Force (as of 7 October 2022)*.
ICAO, 2022b. *Contribution of the business aviation sector to environmental protection and in addressing the impact of climate change*. Available at: https://www.icao.int/Meetings/a41/ Documents/WP/wp_440_en.pdf.
International Business Aviation Council (IBAC) and General Aviation Manufacturers Association (GAMA), 2021. *Business Aviation Declaration on Net-Zero Carbon Emissions by 2050*. Available at: https://ibac.org/app/ibac/files-module/local/documents/Declaration on NZE 2050 210922 Final.pdf.
IPCC, 2021. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Edited by V. Masson-Delmotte et al. Cambridge University Press Cambridge, UK.
Jain, S., Crossley, W. A., 2020. Predicting Fleet-level Carbon Emission Reductions from Future Single-Aisle Hybrid Electric Aircraft. In: 2020 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS), pp. 1–15.
Jones, R. I., 1999. The More Electric Aircraft: the past and the future? In: IEE Colloquium. Electrical Machines and Systems for the More Electric Aircraft. IEE, pp. 1–1. Doi: 10.1049/ic:19990830.
Jung, M., Grimme, W., 2022. Availability of en-route alternate aerodromes as potential limitation in flight planning for hybrid-electric regional aircraft. Transp. Res. Procedia 65, 44–51. https://doi.org/10.1016/j.trpro.2022.11.006.
B. Lukasik W. Wisniowski All-electric propulsion for future business jet aircraft: A feasibility study Proceedings of the Institution of Mechanical Engineers, Part g: Journal of Aerospace Engineering 231 12 2017 2203 2213 10.1177/0954410017727027.
Electricity Maps, 2022. *Climate Impact by Area*. Available at: https://app.electricitymaps. com/map.
Mitici, M., Pereira, M., Oliviero, F., 2022. Electric flight scheduling with battery-charging and battery-swapping opportunities. EURO Journal on Transportation and Logistics 11, 100074. https://doi.org/10.1016/j.ejtl.2022.100074.
J. Mukhopadhaya B. Graver Performance analysis of regional electric aircraft 2022 International Council on Clean Transportation White paper 10.13140/RG.2.2.30087.16803.
National Business Aviation Association Business Aircraft https://nbaa.org/business-aviation/business-aircraft/ 2024 Available at.
Oosterom, S., Mitici, M., 2023. Optimizing the battery charging and swapping infrastructure for electric short-haul aircraft – The case of electric flight in Norway. Transp. Res. C 155, 104313. https://doi.org/10.1016/j.trc.2023.104313.
Paul, A., Grimme, W., Atanasov, G., van Wensveen, J., Peter, F., 2019. Evaluation of the Market Potential and Technical Requirements for Thin-haul Air Transport. Deutscher Luft- Und Raumfahrtkongress 2019. https://doi.org/10.25967/490206.
Sarlioglu, B., Morris, C.T., 2015. More Electric Aircraft: Review, challenges, and opportunities for commercial transport aircraft. IEEE Trans. Transp. Electrif. 1 (1), 54–64. https://doi.org/10.1109/TTE.2015.2426499.
Schäfer, A.W., Barrett, S.R.H., Doyme, K., Dray, L., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P., Torija, A.J., 2019. Technological, economic and environmental prospects of all-electric aircraft. Nat. Energy 4 (2), 160–166. https://doi.org/10.1038/s41560-018-0294-x.
Staack, I., Sobron, A., Krus, P., 2021. The potential of full-electric aircraft for civil transportation: from the Breguet range equation to operational aspects. CEAS Aeronaut. J. 12 (4), 803–819. https://doi.org/10.1007/s13272-021-00530-w.
Thapa, N., Ram, S., Kumar, S., Mehta, J., 2021. All electric aircraft: A reality on its way. Mater. Today:. Proc. 43, 175–182. https://doi.org/10.1016/j.matpr.2020.11.611.
UK Government, 2019. *2019 Government Greenhouse Gas Conversion Factors for Company Reporting – Methodology Paper for Emissions Factors*. Edited by N. Hill et al. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/904215/2019-ghg-conversion-factors-methodology-v01-02.pdf.
Viswanathan, V., Knapp, B.M., 2019. Potential for electric aircraft. Nat. Sustainability 2 (2), 88–89. https://doi.org/10.1038/s41893-019-0233-2.
Winther, M., 2019. *EMEP/EEA air pollutant emission inventory guidebook 2019 – 1.A.3.a, 1.A.5.b Aviation, Guidebook*. European Environment Agency. Available at: https://www.eea.europa.eu/ds_resolveuid/a59477d89ef04310a64f4a52aa9f4987.