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Prospective life cycle assessment of a short-haul hybrid-electric aircraft

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Abstract

Purpose The aviation sector faces increasing pressure to decarbonize with growing global demand for air travel. Hybrid-electric aircraft is emerging as a promising pathway towards low-emission regional aviation. This study aims to explore the prospective life-cycle environmental impacts of a hybrid-electric aircraft across different flight missions and comparing to conventional regional aviation.

Methods This study presents a cradle-to-grave prospective life cycle assessment of a 30-seater hybrid-electric aircraft, assumed to be produced in 2035 and operated until 2065, accounting for future changes over its lifetime. Industrial data were used for the modeling. Ten mission distances (100–700 km) were modeled to evaluate environmental performance across operational ranges.

Results and discussion Across all flight missions, the use phase dominates life-cycle impacts. Among the missions assessed, the 260 km flight performs best in terms of climate and the longer-term crustal scarcity indicator, while the 289 km flight mission performs best in terms of particulate matter impacts. Longer missions with hybrid operation exhibit higher climate, particulate matter impacts, as well as crustal scarcity indicator because the fuel combustion increases. In contrast, results for abiotic resource depletion show a decreasing trend with increasing mission distance, driven by less frequent battery replacement. Overall, the study indicates that regional hybrid-electric aviation has promising environmental performance. The results and the sensitivity analysis highlight the need for advances in battery-specific energy and cycle life, as well as electricity decarbonization.

Conclusion This study showed the promising environmental performance of hybrid-electric aviation, especially when operated in full-electric mode. Future research should focus on improving the battery performance to support the development of environmentally friendly hybrid-electric aviation. Supportive policy frameworks are also required for alternative aviation fuels to fully realize the environmental potential of regional hybrid-electric aviation.

Keywords Electric aviation · Climate change · Lithium-ion battery · Solid-state battery · Alternative aviation fuel

Abbreviations

GHGs Greenhouse gases
AAF Alternative aviation fuels
pLCA Prospective life cycle assessment

EoL End-of-life
Pkm Passenger kilometer
ADP Abiotic depletion potential indicator
CSI Crustal scarcity indicator
NO_x Nitrogen oxides
PM Particulate matter
SSP Shared Socioeconomic Pathway
NDC Nationally Determined Contributions
PEM Proton exchange membrane
SMR Steam-methane reforming

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1 Introduction

Air transport enhances connectivity and gives convenience by enabling fast long-distance mobility, maintaining access to remote regions. It supports time-sensitive mobility for work, education, tourism, and family when alternative modes are slow or unavailable. The sector has grown rapidly and expanded faster than rail, road, or shipping in recent years (Climate Action, 2025). Global air transport demand is expected to keep rising in the coming decades (Gnadt et al. 2019; Teo 2025). The IEA (2024b) projects a global annual growth rate of 3.8% in air traffic, adding more than 4.1 billion passenger journeys by 2043 compared to 2023. Meanwhile, conventional aircraft emits more greenhouse gases (GHGs) per passenger kilometer (130–300 g CO₂-eq) than rail (7–80 g CO₂-eq) and road transport (specifically for cars, 80–280 g CO₂-eq) (Trevisan and Bordignon 2020). Continued growth without additional GHG emission mitigation would therefore increase aviation's climate impact. Today, the aviation sector accounts for about 2.5% of global energy related CO₂ emissions (Teo 2025), and projections from the Öko-Institut indicate that aviation could contribute up to 22% of global climate impact by 2050 (Martin et al. 2015). Decarbonizing the aviation sector is particularly challenging due to its current dependence on energy-dense liquid hydrocarbons, the high fuel cost share in airline operation (typically 20–30%), and the higher cost of bio-based alternative aviation fuels (AAF) (Bergero et al. 2023; Dray et al. 2022; Johnathan et al. 2020; Klöwer et al. 2021). In response, governments and international organizations have issued targets and measures to mitigate aviation emissions (Mayer and Ding 2023). Examples include the incorporation of aviation in nationally determined contributions (NDCs) under the Paris Agreement (DESNZ, 2025; *The United States' Nationally Determined Contribution*, 2024), the European Union Emissions Trading System (Climate Action, 2025), the United States Aviation Climate Action Plan (EPA, 2024), and the International Civil Aviation Organization goal of net-zero carbon emissions by 2050 (ICAO, 2024).

Multiple technological options for GHG emission mitigation are under development, including novel aircraft designs (engines, airframes, etc.), operational improvements, shifting to low-carbon emission AAF and implementing new infrastructure (Lai et al. 2022; Xue et al. 2025; Zaporozhets et al. 2020). Among these options, battery powered all-electric and hybrid-electric aircraft are considered promising and attract growing interest from researchers and industry (IATA, 2021). In particular, hybrid electric aircraft provide a technically feasible intermediate step toward full electrification. However, limited efforts have yet been put into assessing the life-cycle environmental impacts of all-electric

and hybrid-electric aviation (cf. Section 2). Early-stage assessment of such technologies is valuable for evaluating environmental performance, and identifying hotspots and potential trade-offs before large-scale deployment. Electric aircraft are not yet commercial, and aircraft typically have a lifetime of about 30 years (Rupic et al. 2023). Their impacts should therefore be assessed given future changes in production, the energy system, battery technology, and fuel mix. In response, the aim of this study is to explore the prospective life-cycle environmental impacts of a hybrid-electric aircraft produced in 2035 and operated until 2065, across different flight missions, using industrial data and comparing to conventional regional aviation.

2 Literature review

Many studies have assessed the environmental impacts of conventional fossil-fuel aviation. Chester (2008) was among the first to calculate life cycle GHG emissions for three aircraft types: small-size Embraer 145, medium-size Boeing 737, and large-size Boeing 747. They used economic input-output life cycle assessment (LCA) and focused on the context of the United States of America. The analysis found that operations account for 75–81% of total GHGs. Lopes (2010) analyzed an Airbus A330-200 without the end-of-life (EoL) phase, and provided a detailed flight composition inventory that has been widely used in later studies. Lewis (2013) evaluated environmental impacts of three aircrafts (180-seat A320, 253-seat A330 and 525-seat A380) using LCA coupled with an aviation emissions model. The study reported that larger aircraft tend to have lower impacts per passenger kilometer (pkm). A recent study by Vivalda (2023) assessed cradle-to-grave environmental impacts of a 42-seat regional flight ATR 42, and attributed more than 98% of climate impacts, terrestrial acidification, and ozone formation to the use phase. At sector level, Pierrat et al. (2021) assessed the aircraft production impacts by analyzing 2213 aircrafts from 88 companies produced globally in 2017. The analyzed aircraft range from a 2-seat military jet to a large commercial flight A380. They highlighted the impacts of airframe and engine production, as well as the production of aluminium and titanium. Together, these studies agree that fuel combustion and upstream fuel production dominate life-cycle impacts. Looking forward, Schäfer et al. (2016) projected that the cruise phase CO₂ emissions for the domestic United States' narrow-body aircraft could fall below 50 g CO₂ per pkm by 2050 with next-generation aircraft technology (e.g., open-rotor engines, carbon-fibre airframes), air traffic management and airline operational improvements, plus the use of AAF.

Research on the environmental impacts of electric aviation remains comparatively limited and is often based on conceptual aircraft designs. Gnadt et al. (2019) evaluated use-phase GHG emissions for a conceptual 180-seat all-electric aircraft operated in the United States and considered prospective electricity mix changes. They concluded that all-electric aviation could outperform fossil-fuel aircraft as early as 2030 if the battery's specific energy reaches 2000 Wh/kg and given decarbonized electricity. Similar conclusions can be found in Schäfer et al. (2019), who estimated use-phase GHG emissions for a conceptual 180-seat all-electric aircraft on a 741-km mission and reported that the CO₂ emissions can be lower than for a conventional aircraft when cleaner electricity is used. Scholz et al. (2022) performed an LCA of a hybrid-electric aircraft based on secondary data and found that environmental impacts could be reduced by about 7% compared to conventional aircraft when the electricity source is renewable, although their single-score aggregation approach limits the results interpretation. Thonemann et al. (2024a, b) developed a life cycle inventory model for a 50-seat hybrid-electric aviation ATR42, which Thonemann et al. (2024a, b) applied it in a cradle-to-grave prospective LCA of regional aircraft in 2030–2050. Their results show that hybrid-electric aircraft can significantly reduce climate impacts, but may increase other environmental impacts, such as land use, water use, and toxicity. Arvidsson et al. (2024) carried out a cradle-to-grave LCA of a two-seat all-electric aircraft using primary composition and production data and found lower climate impacts but higher mineral resource impacts than a conventional counterpart under the same lifetime assumption. They also identified the airframe and battery pack as the main contributors for such a small electric aircraft. A review study by Zaporozhets et al. (2020) also suggests that adopting of electric propulsion for short-haul aircraft, together with substituting fossil jet fuels, has the potential to achieve 25–63% GHG emissions by 2050.

Two main gaps emerge from previous research. First, production and use occur at different points in time for an aircraft, yet this temporal aspect is rarely considered in the modeling. To the best of our knowledge, this issue has not previously been addressed at the level of an individual aircraft. Second, given that the use phase is often identified as the hotspot, few studies examine how impacts vary across different flight missions. These two gaps are addressed in the following work.

3 Materials and methods

A prospective life cycle assessment (pLCA) was performed for a 30-seat hybrid electric aircraft, modelled based on a real aircraft design by a collaborating aircraft development company. It is assumed that the aircraft will roll out of the assembly hangar in 2035 and reach its EoL in 2065 following 30 years of operation lifetime. The assumed entry into service year (2035) is based on the industrial partner's plan to obtain type certification in 2028. At the time of assessment, the aircraft had reached an advanced development stage, including finalized design and ongoing testing activities. The aircraft is assumed to be manufactured and operated in Europe, while raw materials are sourced globally where appropriate. The system boundary is cradle-to-grave, covering production, the use phase, and EoL. Results are presented per the functional unit of 1 pkm, and can be expressed as:

$$EI_{aircraft\ per\ FU} = \frac{EI_{aircraft\ over\ lifetime}}{Total\ lifetime\ passenger\ kilometer}$$

$$EI_{aircraft\ over\ lifetime} = EI_{production} + EI_{use\ phase} + EI_{EoL}$$

where EI stands for environmental (or resource) impact. The EF 3.1 package of life cycle impact assessment methods is applied, and the impact categories in focus are climate change (GWP100; unit: kg CO₂-eq), particulate matter (human-health impact; unit: disease incidence), and mineral resource depletion assessed using the abiotic depletion (AD, ultimate reserves; unit: kg Sb-eq). Given that the AD (ultimate reserves) can be sensitive to temporal variations in production and reserve estimates (Hauschild et al. 2013; van Oers et al. 2020), the crustal scarcity indicator (CSI, unit: kg Si-eq) is also included to reflect long-term material scarcity (Arvidsson et al. 2020).

When reporting climate impacts of aircraft, it is important to note that aviation can contribute to global warming not only through greenhouse gas emissions, but also through other short-lived climate forcers at high altitude, commonly referred to as “non-CO₂ effects” (Klenner et al. 2024; Neumann et al. 2025). These phenomena are not associated to every flight but occur only under specific atmospheric conditions in connection with combustion-based air traffic. Two main contributors are condensation trails which evolve into cirrus clouds, and emissions of nitrogen oxides (NO_x) (Keles et al. 2024). In the context of this study, non-CO₂ effects are expected to be limited, as they are generally lower for turboprop aircraft (Keles et al. 2024), especially at a cruising altitude of about 5 km for the modelled

hybrid-electric aircraft. For this reason, the reported climate impacts include only greenhouse gas emissions, including those during operation. The topic is further discussed in the sensitivity analysis.

The remainder of this section first describes the aircraft system and data sources regarding the composition and production of the hybrid-electric aircraft (Sect. 2.1), as well as the use phase and EoL (Sect. 2.2). Then follows the scenarios considered (Sect. 2.3). A sensitivity analysis was performed to evaluate how the operational location influences the results.

3.1 Hybrid-electric composition and production

The composition of studied aircraft can be divided into four subsystems: the aircraft structure, hybrid-electric powertrain components, operational system, and the interior. The total environmental impacts of the aircraft production can thus be expressed as:

$$EI_{production} = EI_{structure} + EI_{power\ train} + EI_{operational\ system} + EI_{interior} + EI_{assembly}$$

The aircraft structure includes the fuselage, wings, horizontal and vertical tails, fairings, paint, and landing gears (main landing gear and nose landing gear). LCI data for the aircraft structure were derived from Arvidsson et al. (2024) and Lopes (2010). The powertrain comprises all components that generate thrust for propelling an aircraft, including turboprop engines, electric motors, power inverters, nacelles, propellers, gearboxes, and the battery pack with its associated systems. The model considers a promising future battery technology as the power source: an all-solid-state battery (ASSB) with lithium-nickel-manganese-cobalt oxide (NMC811) as cathode, lithium foil as anode and lithium-lanthanum-zirconate oxide (LLZO) as electrolyte is considered as the power source in the model. Previous literature has identified this battery chemistry as a promising option (IEA, 2024a; Kristina et al. 2023; Pattanayak and Mavris 2025). Further details are provided in supplementary

information (SI) section S1.2. The battery system includes battery cells, a battery management system, a high voltage connector, as well as materials used in the battery module and pack materials. Given the fast development in the battery field, advancement in battery technology is considered for batteries produced after 2045, including the cell design, cell-to-pack ratio, and battery performance in terms of battery capacity. The battery pack composition is sourced from Arvidsson et al. (2024), and the battery cell composition and performance are calculated using the model developed by Zhang et al. (2025). Relevant technical battery data for the battery system are presented in Table 1. The inventory for the electric motor is based on Nordelöf et al. (2018), while that for the power inverter is taken from Nordelöf et al. (2019). The turboprop engine inventory is derived from Thonemann et al. 2024a, b; Brown et al. (2005). Detailed descriptions and inventory are provided in the SI Sect. 1.2.

The operational system covers the flight-control system, avionics, the electrical wiring interconnection system, the environmental control system, and other electric systems. The inventory of the operational system is based on Arvidsson et al. (2024) and Lopes (2010). The interior comprises the cockpit instrument panel, flooring, overhead bins, seats, sidewall panels, cabin insulation, and other interior elements. The inventory of the interior is derived from Orson (2022) and Arvidsson et al. (2024). The aircraft's subsystems are modeled based on the mass breakdown provided by the collaborating aircraft development company. It should be noted that the LCI data for material and energy requirements, which were derived from previous literature, were used with modifications based on information from our industrial collaborator. The assembly process accounts for electricity use, heating demand, cleaning water, construction of the assembly buildings, and kerosene required for turboprop engine testing. Detailed descriptions of the aircraft's composition and datasets for production of subsystems and components are provided in the SI Sect. 1.

3.2 Use phase and EoL

Over the 30-year of use phase (2035–2065), the hybrid-electric aircraft consumes electricity and liquid fuels. The fuel is modelled as a blend of kerosene and AAF, with blending ratios set according to ICAO's simulated trajectories (ICAO, 2022). AAF is modeled as comprising two main fuel categories: fuel produced from waste CO₂ (AAF-waste CO₂) and hydrogen; and fuel produced from biomass, and solid and liquid waste (AAF-biomass, liquid and solid waste). The later one is modeled as a market mixture of raw materials and production methods based on ICAO (2022) projections, and the market mixture is assumed to remain consistent over the aircraft lifetime (Table 2). The feedstock

Table 1 Technical information about the battery

Battery parameter	1st generation (before 2045)	2nd generation (after 2045)
Cell capacity (Wh)	136	147
Specific energy (cell level, Wh/kg)	446	510
Cell-to-pack efficiency	80%	90%
Specific energy (pack level, Wh/kg)	357	458
Battery capacity (pack level, kWh)	1784	2291
Flight distance that can be supported by battery capacity (km)	289	383

include used cooking oil, vegetable oil (such as soybean, rapeseed, and palm oil), municipal solid waste, forestry and crop residues, as well as crops used to produce ethanol as a starting material (e.g. maize, sugarcane, and rye). Detailed inventory is provided in SI Sect. 1.6. It should be noted that this study considers only a limited range of AAF feedstock and production pathways, whereas the future market composition may evolve differently and remains uncertain. To address this uncertainty, we conducted a sensitivity analysis using alternative AAF compositions.

In addition, several components require regular replacement because of wear, tear, and degradation. Batteries age, leading to capacity fade and performance decline, and landing gear components experience mechanical wear and potential damage. Accordingly, batteries, wheels and tires are replaced regularly. Industry engineers from the collaborating company suggest replacement frequencies of every 350 landings for the main landing gear and every 250 landings for the nose landing gear, which are applied in the model (Table S36).

New components need to be produced and transported, and the retired parts need to be treated at their EoL. These activities generate emissions and require resources, which lead to environmental impacts. In the model, the waste treatment of the replaced parts (other than batteries, wheels and tires) and their transportation are grouped as ‘others’. The use phase environmental impacts ($EI_{use\ phase}$) are therefore represented by the following equation:

$$EI_{use\ phase} = EI_{electricity} + EI_{fuel} + EI_{battery\ replacement} + EI_{wheels\ and\ tires\ replacement} + EI_{others}$$

EI_{fuel} includes the environmental impacts caused by the production and combustion of kerosene and AAF. Combustion emissions for kerosene were obtained from Lopes (2010), except that nitrogen oxides (NOx) emissions were

based on Neumann et al. (2025). For AAF, previous studies have reported 50–97% lower particulate matter (PM) emissions relative to kerosene (Durdina et al. 2021; Moore et al. 2017; Tran et al. 2020; Voigt et al. 2021). Accordingly, an average PM emission reduction of 73.5% was applied to AAF combustion in this study. Other emissions from AAF combustion were assumed to be the same as those of kerosene, except that CO₂ and CO were treated as biogenic. In addition, PM emissions were modeled as emissions to non-urban air or from high stacks, as most fuel combustion occurs at high altitude, far from human populations. A sensitivity analysis assuming no human-health effects from combustion-related PM emissions was also conducted.

To simplify the analysis, electricity is assumed to be used preferentially from the start of the mission, covering the taxi-out, take-off, climb, and cruise phases until the battery reaches its depth-of-discharge limit. If the mission distances required more energy than the usable battery capacity, fuel is used to supply the remaining phases. When the available battery capacity is just enough to cover the entire mission distance, a small amount of fuel is still consumed to keep the engine in idle mode during landing as a safety measure. Detailed assumption and calculation are in SI section S1.7.

Use-phase impacts are highly related to the aircraft operation, including the amount of electricity and fuel required, as well as the frequency of components replacement. To capture this, 10 mission distances were considered in this study: 100, 200, 260, 289, 300, 383, 400, 500, 600, and 700 km. Short missions target regions with geographic accessibility constraints where rail and other public transport are difficult to access, including households around fjords, lakes, and mountainous terrain (Löfving et al. 2023). The 260 km mission reflects the typical distance targeted for the original aircraft design. The 289 km and 383 km missions correspond to the theoretical maximum flight ranges that can be powered purely by battery capacity for the first- and the second-generation battery packs, respectively. The detailed

Table 2 Overview of the scenario elements used in the study

Time horizon	Background scenario	Mission (km)	Battery technology	Fuel composition	AAF-biomass, liquid and solid waste
2035 (production)	SSP2-NDC 2035	-	1st generation ASSB	-	-
2035–2045 (use phase)	SSP2-NDC 2040	100, 200, 260, 289, 300, 383, 400, 500, 600, 700	1st generation ASSB	11% AAF- waste CO ₂ + 13% AAF- biomass, liquid and solid waste + 76% kerosene	Market mix
2045–2055 (use phase)	SSP2-NDC 2050	700	2nd generation ASSB	17% AAF- waste CO ₂ + 40% AAF- biomass, liquid and solid waste + 43% kerosene	Market mix
2055–2065 (use phase)	SSP2-NDC 2060	-	2nd generation ASSB	18% AAF- waste CO ₂ + 57% AAF- biomass, liquid and solid waste + 25% kerosene	Market mix
2065 (EoL)	SSP2-NDC 2065	-	-	-	-

Table 3 Batteries replacement scheme during use phase

Flight missions (km)	1st generation battery required (2035–2045)	2nd generation battery required (2045–2065)
100	11 (original+10)	21
200	7 (original+6)	14
260	7 (original+6)	12
289	7 (original+6)	12
300	7 (original+6)	12
383	6 (original+5)	11
400	6 (original+5)	11
500	5 (original+4)	8
600	3 (original+2)	6
700	3 (original+2)	6

Table 4 Flight operating frequency and lifetime flight distance for different flight missions

Flight mission (km)	Flights per day	Lifetime flight distance (km)
100	12	1.26×10^7
200	7	1.47×10^7
260	5	1.37×10^7
289	5	1.52×10^7
300	5	1.58×10^7
383	4	1.61×10^7
400	4	1.68×10^7
500	3	1.58×10^7
600	2	1.26×10^7
700	2	1.47×10^7

fuel and electricity consumption is presented in Table S37–38. It should be noted that, for all mission distances, the aircraft carries sufficient reserve fuel for 30 min of extra flight to comply with EU safety regulations, but this fuel is not assumed to be used during normal operation.

The aircraft is assumed to operate 350 days per year. Per-flight electricity and fuel requirement were partly from the collaborating aircraft company, and the partly from estimates developed in this study (SI Section S1.7). The number of batteries required over the aircraft lifetime (Table 3) for each mission was estimated from the flight frequency (Table 4) and the battery lifetime in cycles (Table S8). The total battery cycle demand over the modeled period was therefore equal to the total number of flights. Dividing this demand by the battery cycle life yielded the total number of batteries required, with values rounded up to the nearest integer. The same procedure is applied for wheels and tires, using mission-specific flight frequency (the same as landing frequency) counts to determine replacements. Details are provided in the SI Sect. 1.7.

The total lifetime passenger kilometer can therefore be calculated as:

$$\text{Total lifetime passenger kilometer} = \text{passengers} \times \text{lifetime flight distance}$$

$$\text{Lifetime flight distance} = \text{mission kilometers} \times \text{flights per day} \times \text{operating days per year} \times \text{years in use}$$

The number of passengers is 30. The number of flights per day for different flight mission ranges and the calculated lifetime flight distances are provided in Table 4, the operating days per year are 350 and the years in use are 30. When reaching to its EoL in 2065, the aircraft is assumed to be dismantled and the materials sorted into the corresponding market process existing in the Ecoinvent database for waste/scrap handling. Detailed inventory is presented in the SI Sect. 1.7.

3.3 Scenario selection

This LCA study is evaluates different flight missions while accounting for changes in battery technologies, AAF blend ratio, and background-system changes over the aircraft's 30-year lifetime, as summarized in Table 2. This study is based on one background scenario pathway, named Shared Socioeconomic Pathway 2 (SSP2, “middle of the road”) combined with the Nationally Determined Contributions (NDC) climate target. SSP2 represents a continuation of historical trends in society, economy, and technology (Riahi et al. 2017), and under the SSP2-NDC narrative, the increase in global mean surface temperature is limited to about 2.5 °C by 2100. The integrated assessment model REMIND is used to project future energy and industrial system changes (Baumstark et al. 2021). REMIND outputs are then use to transform the Ecoinvent database using the Python package Premise (Sacchi et al. 2022), generating pLCA databases for the years 2035, 2040, 2050, 2060, and 2065. The production and end-of-life stages of the aircraft were modeled for 2035 and 2065, respectively. Electricity and all other inputs produced between 2035 and 2045 were modeled using the 2040 pLCA database, those produced between 2045 and 2055 using the 2050 pLCA database, and those produced between 2055 and 2065 using the 2060 pLCA database.

4 Results and discussion

Figure 1 shows cradle-to-grave life-cycle impacts of the studied electric aircraft for its 2035–2065 service period, per passenger kilometer, across mission distances of 100–700 km. It should be noted that there were no additional calculations performed for distances between the modeled

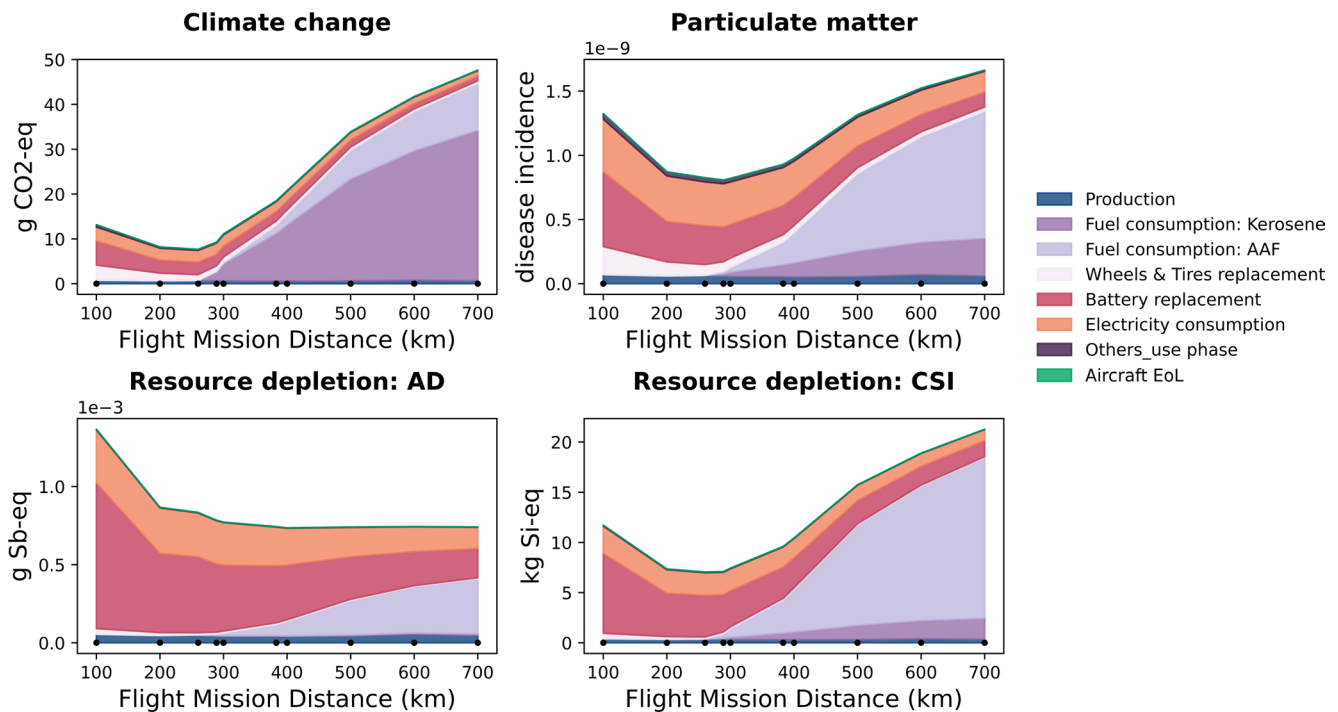


Fig. 1 Cradle-to-grave life-cycle impacts of the studied aircraft over the 2035–2065 period, with a functional unit of 1 passenger kilometer. Ten mission distances were modeled (black dots markers on horizontal axis). AD=abiotic depletion, CSI=crustal scarcity indicator

missions, so the connecting lines are linear interpolations to visualize trends. Different colors represent emission contributions from aircraft production, use-phase energy (i.e., kerosene/AAF combustion and electricity use) and maintenance (i.e., wheels and tires replacements, and battery replacements), and aircraft EoL. The following sections discuss the results for the focus impact categories (climate change, particulate matter, and mineral resource depletion). Detailed LCIA results are provided in the supplementary information. It needs to be noted that all results presented and discussed are calculated assuming 100% seat occupancy.

4.1 Climate impact from greenhouse gas emissions

The climate impacts of the hybrid aircraft vary with mission distance (Fig. 1). As distance increases from 100 to 700 km, climate impacts first decline from 13 to 8 g CO₂-eq/pkm up to 260 km, and then increase to 48 g CO₂-eq/pkm at 700 km. Across all flight missions, the use phase is the main contributor, accounting for 90–99% of the total climate impact. The aircraft production contributes 1–9%, while the EoL contributes negligibly (<0.12%). The decline from 100 to 260 km is mainly driven by reduced impacts from battery replacement and from wheels and tires. Battery replacement is mainly determined by the flight frequency and battery lifetime in cycles. In the model, the battery is recharged after each flight. This assumption is also applied

to 100 km mission, although the battery could theoretically support two flights per charge-discharge cycle. While the lower depth of discharge gives the 100 km mission a longer battery cycle life than the 200 km mission (Table S8), this advantage is not enough to offset the higher flight frequency (Tables 3 and 4). Consequently, battery replacement contributes both a larger absolute impact and a higher share of the total climate impacts in the 100 km mission, compared to the 200 km mission. The replacement frequency of wheels and tires correlates with the number of the landing cycles (Table S35-36), which increases with flight frequency. Longer mission distances are operated less often, so there are fewer landings per day and slower wheel and tire wear. Accordingly, as mission distance increases from 100 to 700 km, the wheels and tires impact drops from 3.37 to 0.48 g CO₂-eq/pkm, and their share of total climate impact falls from 26% to 1%.

Beyond the all-electric operating range, fuel use becomes the dominant driver of greenhouse gas emissions. In this study, the first-generation battery supports mission distances up to 289 km, and the second-generation battery (employed after 2045) extends this to 383 km. When flying at the battery-only maximum distances, turboprops remain idle during landing for safety, which explains the slight fuel consumption also for these flight missions. For longer missions, the aircraft operates in hybrid mode with propulsion from a mixture of electricity and liquid fuels. Between 289 and 700 km, kerosene and AAF account for 21–70% and 2–22%

of total climate impacts, respectively. This shift reflects the higher emission factors over 2035–2065 for kerosene production and combustion (about 334–336 g CO₂-eq/kWh) and for AAF production and combustion (about 122–129 g CO₂-eq/kWh) compared to European electricity (about 14–20 g CO₂-eq/kWh). The higher emission intensities of the two fuels explain the upward trend beyond 260 km and the dominance of the fuels for longer distances.

These results are consistent with other hybrid-electric studies and lower than those for conventional aircraft. Thonemann et al. (2024a, b) assessed a 50-seat regional aircraft under multiple flight design and background scenarios. After converting their results to the same functional unit as this study and applying the same SSP2-NDC background scenario, their hybrid-electric aircraft operating on a 370 km mission was estimated to cause 31 g CO₂-eq/pkm when produced and operated in 2030, 19 g CO₂-eq per pkm in 2040, and 10 g CO₂-eq/pkm in 2050. These values are consistent with the findings of this study, in which the 300 km and 383 km missions yield cradle-to-grave climate impacts of 11 and 19 g CO₂-eq/pkm, respectively. For conventional aircraft, Thonemann et al. (2024a, b) reported 127 g CO₂-eq/pkm for a 50-seat regional aviation (370 flight mission) in the European context. In the United States context, Chester (2008) reports 180 g CO₂-eq/pkm for the small flight (Embraer 145), 130 g CO₂-eq/pkm for the medium flight (Boeing 737), and 124 g CO₂-eq/pkm for the large flight (Boeing 747). Lopes (2010) reported 126 g CO₂-eq/pkm and Rupcic et al. (2023) reported 150 g CO₂-eq/pkm for conventional long-haul flights. However, these reference values predominantly represent operations at typical cruise altitudes, where non-CO₂ effects (e.g., NO_x) can contribute significantly to climate impacts but are not considered here. Accordingly, such comparisons may not fully capture differences in total climate impacts. Lai and Björklund (2025) assessed Swedish long-distance aviation in 2050 using a hydrogen-powered large narrow-body aircraft on a 2000 km route and reported life-cycle climate impacts of approximately 33–34 g CO₂-eq/pkm (values excluded airport operations). By comparison, the climate impacts caused by our aircraft in 2045–2055 range from about 6 to 41 g CO₂-eq/pkm across the different missions considered, with the 300 km mission (fully-electricity-powered distance) showing the lowest impact and the 700 km mission the highest. The results suggest that, for most mission distances considered in this study (100–500 km), our hybrid-electric aircraft shows a climate advantage relative to the hydrogen-powered aircraft assessed by Lai and Björklund (2025). However, this comparison should be interpreted with caution, as their study considered a much larger aircraft and a substantially longer mission distance, making direct comparison difficult. Bell et al. (2025) reported life-cycle climate impacts from

fuel production and combustion of 27–55 g CO₂-eq/RPK in 2050 for large medium-haul aircrafts using a 70% Power-to-Liquid AAF blend. The climate impacts caused by our aircraft in 2045–2055 are generally lower than this range, with the 500 km (27 g CO₂-eq/pkm), 600 km (34 g CO₂-eq/pkm), and 700 km (41 g CO₂-eq/pkm) missions falling within a comparable range.

The high contribution from the use phase found in this study also aligns with prior LCA works on conventional aviation (Lopes 2010; Thonemann et al. 2024a, b). Howe et al. (2013) and Lewis (2013) find that the use phase (including the impacts caused by fuel production) accounts for 96.5–99% of the total climate impacts. At the sector level, global aircraft manufacturing emission are about 1–2% of the global flight operation emissions (Pierrat et al. 2021; Trevisan and Bordignon 2020). It should be noted that these last values may better represent longer flight missions than those assessed here since most aircraft they considered carry more than 100 passengers and fly more than 1000 km.

4.2 Particulate matter

The particulate matter impacts exhibit the same mission distance dependency as observed for climate impacts. As the mission distance increases, total disease incidence decreases from $1.3 \cdot 10^{-9}$ at 100 km to $0.81 \cdot 10^{-9}$ at 289 km and then increases to $1.7 \cdot 10^{-9}$ at 700 km. Use-phase emissions are the dominant contributors across all flight missions, accounting for 92–96% of the total impact, while aircraft production contributes 4–8% and the EoL again negligibly (<0.02%).

Within the use phase, short-range flight mission impacts are driven primarily by battery replacements, electricity consumption, and wheels and tire replacements. At 100 km, these three parts account for 44%, 31%, and 16% of the particle matter impact, respectively. As the mission extends to 700 km, their shares fall to 7%, 10% and 2%, respectively. In contrast, fuel consumption becomes dominant as the mission distance grows. At 700 km, AAF and kerosene contribute 60% and 18% of the total impact, respectively.

For the battery replacement, key contributors are the battery cell precursors, such as nickel and cobalt sulfate for the cathode active material, as well as production of the solid-state electrolyte (i.e., LLZO). For the wheels and tires, the PM is driven mainly by aluminum production. For the AAF, it is mainly due to the feedstock production and processing. Feedstock include maize- and sugarcane-based ethanol, palm oil, rapeseed oil, soybean oil, forest residues, and used cooking oil. Hotspots are associated with emissions such as ammonia and nitrogen oxides from unit processes including palm fruit bunch production, palm oil mill operation, and ethanol fermentation. For kerosene, roughly one-third of the

PM impact comes from its combustion, and the remainder from its production.

PM impact in the use phase decreases over time when the flight mission distance is less than 400 km. For mission distances of 500 km and above, the use phase PM increases over time (Figure S2). The increase at longer range is driven by a rising AAF share in fuel consumption and by the increasing PM impact associated to the AAF supply chain. The latter is linked to the hydrogen used within AAF production. In this study, AAF is modeled using different feedstock with multiple technology pathways, and hydrogen serves as both an energy carrier and a process input. Based on the IAM outcome, European hydrogen supply shifts from 90% proton exchange membrane (PEM) electrolysis, 10% biomass gasification in 2040 to 97% PEM and 3% biomass gasification in 2060. Biomass gasification produced hydrogen causes much less PM (about 7.85×10^{-8} disease incidence per kg H_2 in 2030) than PEM-based hydrogen (around 2.4×10^{-7} disease incidence per kg H_2 in 2040). As the supply mix shifts toward PEM electrolysis, the PM intensity of hydrogen production rises, which increases the AAF's PM impact over time. Together with the growing AAF fraction on longer missions, this explains the upward trend of use-phase PM impacts for mission distances over 500 km.

The Ecoinvent activity “market for transport, passenger aircraft, very short haul”, which is based on inventory data generated by Cox et al. (2018), was used to benchmark the PM impact. Although Cox et al. (2018) provide mission-distance-specific modeling results, the corresponding Ecoinvent activity represents a weighted-average very-short-haul passenger transport dataset. In this activity, very-short-haul refers to flights below 800 km, with a mean distance of 504 km (Philippa et al. 2018). Under the same functional unit, LCIA method, and background scenario, this conventional aircraft shows a PM-impact of $1.4 \cdot 10^{-9}$ disease incidences (excluding the impact of airport construction). This value is higher than the PM impacts of the 100–500 km hybrid-electric missions, but lower than those of the 600 and 700 km missions.

Cox et al. (2018) show that conventional aircraft impacts decrease with increasing mission distance. Thus, using an average benchmark with a mean distance of 504 km may underestimate conventional aircraft impacts for missions shorter than 500 km, while overestimating them for missions longer than 500 km. Therefore, the comparison indicates that the PM-related advantage of the hybrid-electric aircraft is likely more robust for shorter missions. Overall, the results suggest that hybrid-electric aviation can potentially reduce PM-related impacts relative to conventional aviation when the mission profile allows sufficient use of

battery-electric operation. The PM impact of the conventional aircraft is mainly driven by kerosene production and combustion.

4.3 Mineral resource depletion

Overall, the AD results decline with mission distance, from $1.4 \cdot 10^{-3}$ g Sb-eq/pkm at 100 km to $7.4 \cdot 10^{-4}$ g Sb-eq/pkm at 700 km. The CSI results fall from 12 kg Si-eq at 100 km to 7 kg Si-eq at 260 km, and then increase to 21 kg Si-eq at 700 km.

In the AD results, the use phase is the main contributor across all missions. Within the use phase, battery replacement is the largest (25–68% of the AD results), and followed by electricity consumption (18–35%). AAF's contribution increase with the increase in mission distance, and reach to 48% at 700 km. While kerosene consumption is relatively small, accounting for 0.8–1.3% at longer mission distance (500–700 km). The aircraft production contributes 4–7%, while the EoL is again negligible (<0.002%). Within the battery production, more than half of the AD results is caused by the battery cell production, mainly driven by cathode precursors such as nickel and cobalt sulfate. Cobalt and nickel production are closely interconnected because cobalt is often a by-product of nickel ores (Schmidt et al. 2016). The battery management system is another hotspot due to the gold used in integrated circuit boards. For electricity supply, about one quarter of the AD results is linked to transmission network construction, especially copper and lead used in high-voltage direct current cables (Jorge et al. 2012). The remaining three quarters are mostly associated with photovoltaic production (for producing electricity), largely due to gold, silver, tin, and copper used in inverters and integrated-circuit production.

The CSI results also indicate that the use phase dominates across flight missions (95–98%). Battery replacement is the leading contributor at short-range missions, but its share decreases from 68 to 8% as the mission distance increases from 100 to 700 km. This decline reflects the increasing fuel requirement at longer range, for which the relative contribution rises to 75% for AAF and 10% for kerosene by 700 km. Electricity consumption remains important with 5–31% of the total CSI. Aircraft production contributes 2–5%, and EoL remains negligible (<0.004%). Upstream materials with high resource depletion according to the AD results also feature prominently in the CSI. In addition, kerosene shows higher share in the CSI because it accounts for the carbon and other elements in fossil resources, which the ADP does not.

Hydrogen supply contributes to the scarcity impact through electrolyser materials, most notably iridium. Hydrogen is used as both a reactant and an energy source

in AAF production, which increases the AAF share for the CSI. It is also used as an energy source in electricity production, affecting resource depletion directly and indirectly in the use phase. Iridium has the highest crustal scarcity potential of all elements due to its low crustal abundance of only 3×10^{-6} ppm (Arvidsson et al. 2020). There are discussions about whether iridium scarcity could constrain future hydrogen production (Fu et al. 2025; Minke et al. 2021). However, because iridium is not included in the ADP method, this potential constraint is not captured in the ADP-based resource depletion results.

Using theecoinvent activity “market for transport, passenger aircraft, very short haul” as modified based on Cox et al. (2018), as a benchmark, and applying the same functional unit, LCIA methods, and background scenario, the conventional aircraft shows an impact of $4 \cdot 10^{-5}$ g Sb-eq for the AD results (exclude the impact of airport constriction, with the range reflecting temporal differences), and approximately 10 kg Si-eq for the CSI. The AD results in this study are up to more than 30 times higher than those reported by Cox et al. (2018). In contrast, the CSI result from Cox et al. (2018) is higher than the impact of 200–383 km missions, but lower than those of the 100 km and 400–700 km missions. The differences in the comparison can be explained by the differences in the scope of the two methods. Unlike the CSI, the AD does not account for fossil resources. Consequently, resource use related to kerosene consumption is excluded, which makes the conventional aircraft appear less resource-intensive in this comparison. It also indicates that the hybrid-electric aviation caused more metal depletion due to the battery replacement in the use phase, while fossil fuel aviation causes higher mineral depletion due to the consumption of jet fuel.

5 Sensitivity analysis and future studies

5.1 Sensitivity analysis

Previous studies indicate that whether electric aircraft have the potential to outperform conventional aircraft in terms of environmental performance depends on the decarbonization level of the electricity mix (Gnadt et al. 2019; Scholz et al. 2022). In this sensitivity analysis, we modeled the environmental performance of the hybrid-electric aircraft when operated in different geographical contexts to assess how regional electricity mixes influence the results. The findings show that when the hybrid-electric aircraft operates in the United States, the climate impact of greenhouse gas emissions decrease by 1–8%, PM formation decreases by 3–11%, the AD result remains largely unchanged, while the CSI increases by 1–5%. In contrast, when operated in

China, the climate impact increases by 9–134%, PM formation increases by 12–61%, the AD result rises by 5–9%, and the CSI by 1–6%. More results are presented in SI Sect. 2. Despite these regional variations, the hybrid-electric aircraft still outperforms the conventional regional aircraft discussed above in terms of climate impacts, with values of 26–52 g CO₂-eq/pkm in China and 12–47 g CO₂-eq/pkm in the United States. Overall, the sensitivity analysis further highlights the importance of electricity grid decarbonization, although hybrid-electric aviation still shows lower impacts in certain categories regardless of region.

To assess the effect of high-altitude fuel-combustion emissions on the PM results, a sensitivity analysis was conducted in which all emissions from the fuel-combustion were assumed to have no human-health effects. Under this assumption, PM-related impacts reduced by up to 2.4% across the studied mission distances. No effect was observed for the 100, 200, and 260 km missions since fuel was not consumed in these mission distances, and the reduction increased gradually with mission distance, reaching 2.4% for the 700 km mission (Table S46).

To better understand the influence of the future AAF composition, a sensitivity analysis was also performed using an alternative market mix (Table S23) based on future AAF production projections reported by IATA (2025) (SI Sect. 1.6). The results (Tables S47–48) show that the climate impact is less sensitive, while PM, AD results, and the CSI can vary by up to 13%, particularly for longer flight missions, where AAF contributes a large share of power generation. This sensitivity analysis shows that changes in AAF market composition can affect the LCA results, indicating the limitation of considering only one AAF composition scenario. This uncertainty should be considered when interpreting the results.

To assess the influence of the background decarbonization pathway on the results, a sensitivity analysis was conducted using SSP2-PkBudg1150 as the background scenario. This scenario aims to limit global warming to approximately 2 °C above pre-industrial levels, with a global carbon budget of 1150 gigatonnes of CO₂ over this century. To simplify the simulation, the pLCA database generated under SSP2-PkBudg1150 for the year 2035 was applied to the entire life cycle of the aircraft, including production, use, and end-of-life. Other temporal developments in the model remained the same, including improvements in battery design and changes in the AAF blending ratio over time. The results show a significant increase in climate impacts (6–34%), especially for short-range missions powered entirely by electricity. PM impacts increased by 4–10%, while resource depletion-related impacts showed a reduction. The absolute and relative results are presented in Tables S49 - S50. This sensitivity analysis shows that

changes in background scenarios can affect the LCA results notably, highlighting the need to interpret the findings as scenario-dependent when considering them in specific decision-making contexts.

5.2 Future studies

Advances in battery technology are essential for sustainable regional aviation. Our results show that short-range missions outperform longer missions in terms of climate impact and PM because they can operate fully on electricity. Mineral resource depletion results also highlight the importance of long battery lifetime, as the high replacement frequency required for short-range missions is the dominant contributor to resource depletion. This highlights two research priorities in the battery field: higher specific energy (Wh/kg), volumetric energy density (Wh/L), and longer cycle life to extend the electric range and mitigate resource depletion. The longer cycle life can be pursued both through electrochemical improvements (e.g., materials and degradation mitigation) and operational strategies (e.g., charging protocols, depth-of-discharge management, and flight-planning that reduces stress on the pack). The frequency of battery replacement also highlights the need for future work to examine whether such a practice can be applied in a cost-effective way under real operating conditions. In this study, end-of-life batteries are modeled as being treated through hydrometallurgical processing. Future research could also explore second-life applications, in which retired batteries are repurposed for other uses. Such strategies may improve both environmental and economic performance. Moreover, the use of AAF can avoid conventional jet fuel, thereby lowering the CSI and use-phase climate impacts relative to kerosene combusting. However, to realize these benefits requires policy support: current AAF costs exceed those of conventional jet fuel, and certified blend limits (up to 50%) constrain its market deployment (Chireshe et al. 2025).

As pointed out in the method section, non-CO₂ effects can be relevant to consider when assessing the climate impact of an aircraft. Condensation trails, or contrails, NO_x, water vapor and sulfur emissions are specifically relevant. Contrails are short-lived and form only in cold, ice-saturated air. They occur predominantly at upper troposphere at 8–13 km and can produce substantial short-term radiative forcing (Kärcher 2018). However, given that our study focuses on regional aircraft that cruises at much low altitude, contrail effects are less relevant here. NO_x emissions occurring at high altitude affect the climate by two counteracting pathways: it increases ozone (O₃) on days-to-weekly timescales (a warming effect) and decreases methane (CH₄) on decadal timescales by enhancing hydroxyl radical (cooling effect) (Lee et al. 2021; Terrenoire et al. 2022).

The CH₄ decrease also reduces the long-term background O₃ (a further cooling). The net sign and magnitude depend strongly on emission altitude, latitude and season, and the background chemistry concentrations (Lee et al. 2021). In fact, Keles et al. (2024) even point to net-negative impacts of NO_x emissions below 6.5 km. Given this sensitivity, we consider NO_x relevant but presently too uncertain to characterize its effect in climate impacts in this study. We therefore report use-phase NO_x emissions per functional unit for each flight mission in SI Sect. 1.7 Table S33, and note that quantifying NO_x climate effects for regional, lower-altitude operations requires future, route- and altitude-resolved analysis. Regarding the effect of water vapor and sulfur emissions, their climate impacts depend strongly on emission altitude, route-specific atmospheric conditions, and background chemistry, and in the case of sulfur-related aerosol-cloud interactions, robust best estimates remain unavailable in the current literature, and would require more future studies (Lee et al. 2021).

Several aspects should be explored in greater detail in future studies. The composition of AAF is one important area, as it emerged as an environmental hotspot in this study and have significant effect on resource depletion potential. Hydrogen production is another key area for further investigation, since it also appears to be a major hotspot and can be associated with a wide range of feedstock, technologies, and energy sources. In addition, non-exhaust emissions, such as those from tire wear, were not included in the present assessment and should be considered in future work.

6 Conclusion

This study provides a detailed prospective LCA of a 30-seat hybrid-electric regional aircraft, integrating future energy-system projections and multiple mission profiles. The results show that the environmental performance of hybrid-electric aviation is strongly influenced by mission distance. In particular, hybrid-electric aircraft operating on short-range routes (200–400 km) can reduce climate impacts, particulate matter-related impacts, and long-term resource depletion compared with conventional aircraft. This is due to the high share of battery as power source and relatively low rate of battery replacement in these missions, indicating the importance of improving battery energy density to extend the all-electric range. At the same time, mineral resource depletion remains high due to battery replacement, highlighting the need to extend battery lifetime. Differences in operational region strongly influence the environmental performance of hybrid-electric aviation. Overall, the results suggest that hybrid-electric propulsion offers a promising pathway towards aviation with lower environmental

impacts, particularly for mission profiles that maximize the use of battery-powered flight.

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Data availability The data that supports the findings of this study is provided in the article and its supplementary information. Some data requires license to the Ecoinvent database for availability.

Declarations

Supplementary information Unit processes for the LCI modelling and detailed LCIA results are provided in the supplementary information.

Conflict of interest The authors declare that they have no conflicts of interest.

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