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Thoma, E., Zhao, X. (2026). Socioeconomic impact assessment of hybrid-electric aircraft introduction in Swedish air traffic. Transportation Research Part A: Policy and Practice, 209. http://dx.doi.org/10.1016/j.tra.2026.105022

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Transportation Research Part A 209 (2026) 105022

Contents lists available at ScienceDirect

Transportation Research Part A

journal homepage: www.elsevier.com/locate/tra

Socioeconomic impact assessment of hybrid-electric aircraft introduction in Swedish air traffic

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ARTICLE INFO

Keywords:
Hybrid-electric aircraft
Noise impact
Emissions reduction
Cost-benefit analysis
Air traffic modelling

ABSTRACT

In this study, the noise and emissions impact of introducing hybrid-electric aircraft into Sweden's domestic air traffic is assessed. As a case study, Stockholm Arlanda Airport is used, and, one baseline scenario for 2024, one intermediate scenario at 2035, and two development scenarios towards 2050 for the fleet and air traffic are presented. The results show that while hybrid-electric aircraft could potentially reduce noise emissions at the single event level, the increased flight frequency leads to larger cumulative noise areas. Although the noise affected areas are not directly proportional to the number of people affected by the noise due to the low population density surrounding the studied airport, a monetary assessment based on noise related health cost tables from three authorities indicates that the total noise related health cost with the hybrid-electric aircraft in the air traffic network is similar to that of a fleet composed of modern turbofan and turboprop aircraft. While the assessment is sensitive to the operational aspects of air traffic, the use of two historical runway usage data results in a consistent conclusion in total noise related health cost along with quite different noise footprint patterns. In terms of CO_2 emissions, the introduction of the target hybrid-electric aircraft into the domestic air traffic network could potentially reduce the emissions by 33%. The combined socioeconomic cost-benefit analysis reveals that the increased noise-related cost at scenario level will dominate the concern around local communities when the near-airport aircraft operations can be emissions-free from full electric landings and take-offs. For the studied case, the noise issue could result in a total health cost increase of 33 – 87% from scenario 2024 to 2050, depending on the authority-specific cost tables applied.

1. Introduction

The increasing need for the aviation industry to reduce greenhouse gas emissions has necessitated the development of new concepts and technologies (Wandelt et al., 2025). Among these concepts, electric and hybrid-electric aircraft are seen as one of the key solutions for improving the climate impact (Sahoo et al., 2020; Salem et al., 2023), and many concepts have been proposed and studied by industry and research institutes (ES-30, 2025; E-Fan X-Airbus, 2020; EcoPulse, 2024; Da-Ronch et al., 2024; Juretzko et al., 2020; Voskuijl et al., 2018; Shoukat and Redondi, 2025; Zumegen et al., 2022; Avogadro and Redondi, 2024; Baumeister et al., 2020). All these concepts show very promising results in reducing in-flight gas emissions, however, large uncertainties exist with regard to their impact on community noise.

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https://doi.org/10.1016/j.tra.2026.105022
Received 11 August 2025; Received in revised form 31 March 2026; Accepted 9 April 2026
Available online 25 April 2026
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Aircraft electrification is expected to significantly alter both the noise generation mechanisms and the resulting noise footprint compared to conventional aircraft. While, several propulsion noise sources, such as combustion noise, turbine noise and high speed jet noise, will be eliminated, fan and propeller noise will remain dominant. In addition, electrification could enable radical aircraft concepts, e.g. distributed propulsion, which could lead to either increases or decreases in overall noise level depending on the phase angle of the rotors as found in the studies by Zarri and de Prenter (Zarri and de Prenter, 2025) and Liu et al. (Liu et al., 2025). Therefore, careful consideration during the early design stage of novel concepts is required in order to avoid increase in noise emissions and to ensure that the potential acoustic benefits of electrification are fully realized. Geyer and Enghardt in their study (Geyer and Enghardt, 2023) investigated this aspect by comparing the noise generated by a conventional turboprop and turbofan with that generated by electrified engines. The comparison was performed using noise measurements taken at the certification points, which were then adapted to account for the absence of some propulsion noise sources, i.e. combustor, compressor, turbine, and core jet. An increase in the rotational speed of the fan and propeller was assumed to compensate for the loss of thrust caused by the absence of the core jet. They concluded that the electrification of engines alone will not lead to notable noise reduction, while in some cases, especially for the low bypass ratio engine, an increase of up to 7.2 EPNdB was observed. The maximum reduction was seen for the turboprop that showed a potential decrease of 1.3 EPNdB during take-off. On the contrary, Schäfer et al. (Schäfer et al., 2018) showed that if an all-electric aircraft with a conventional tube-and-wing configuration is assumed, a 50% reduction in the noise contour area of single event is expected during take-off, while during approach, an increase of 15% is estimated compared to existing best-in-class narrow body aircraft. Although, the study provides these relative contour area changes, it does not specify the corresponding absolute noise levels associated with these contours. However, based on Figure 1 in the supplementary material of the study (Schäfer et al., 2018), they are presumed to correspond to a sound exposure level of approximately 85 dB. Synodinos et al. (Synodinos et al., 2018) investigated the noise impact of a concept tube-and-wing aircraft based on an A320 with distributed electric propulsion. They used a method based on deriving noise-power-distance (NPD) curves for novel aircraft and showed that hybrid-electric aircraft have greater noise reduction potential than all-electric aircraft, assuming 2035 entry into service technology, while the amount of reduction is dependent on the number of propulsors, with 8 being the optimum for take-off with a reduction of about 4 dB in sound power level. In approach, the optimum was found at 10 propulsors with a reduction of only 2 dB. Bradley and Droney (Bradley and Droney, 2015) compared a high-span truss-braced tube-and-wing aircraft with a hybrid-electric tube-and-wing aircraft using component-based simulations and empirical predictions. They found only minimal improvement for the hybrid-electric configuration with a reduction of 1.4 EPNdB in cumulative noise level at the certification points.

These studies reveal that aircraft electrification alone is not expected to result in significant noise reduction. However, it is expected to lead to modifications in air traffic patterns, as the lower passenger capacities and shorter ranges, together with the increasing demand, will lead to more frequent flights. Although several studies are concerned with the impact of the introduction of electric aircraft on the air transport network, (Da-Ronch et al., 2024; Kinene and Birolini, 2024; Withanachchi, 2024; Mitici et al., 2022), the effect that this will have on community noise has not been studied. The present study focuses on the latter. Using the top-level requirements of an existing commercial hybrid-electric aircraft concept and projections for the development of domestic air traffic in Sweden, the noise footprint at the country's major airport, namely Arlanda airport in Stockholm, is assessed for two development scenarios. Due to current technology constraint and future projections on battery energy densities for hybrid-electric aircraft applications, the utilization of the aircraft is considered exclusively for domestic flights. While noise impact is inherently a cumulative effect, noise assessments of both domestic-only and all flights with simplifications are provided. Beyond noise impact, a cost-benefit analysis is conducted to weigh the trade-off between noise and CO_2 emissions for the different scenarios, providing insights into the interdependency between a major environmental concern and an often-overlooked public health issue within a realistic context. To ensure the robustness of the study results against the specific choice of key parameters, particularly the noise related cost, two sets of historical runway usage data and three noise related cost tables recommended by authorities from Europe are adopted and compared. The specific objectives of the study consist of:

- **Single event noise characterization:** Noise assessment of single event for the studied aircraft (modern commercial aircraft versus existing commercial hybrid-electric aircraft concept) to demonstrate the difference of noise impact from the modeled individual aircraft operation.
- **Traffic level noise mapping:** Noise assessment of traffic scenarios (conventional fleet versus electrified fleet considering long-term ideal development projections) over departures and arrivals at Stockholm Arlanda airport. This objective is the primary focus of the study to highlight the noise impact of introducing hybrid-electric aircraft into realistic air traffic.
- **Emission reduction potential:** CO_2 emissions assessment of traffic scenarios (conventional fleet versus electrified fleet considering long-term ideal development projections) over entire mission and over landing and take-off (LTO) operations, considering only domestic flights. This objective is to quantify the potential of CO_2 emissions reduction through adopting hybrid-electric technology over conventional fossil-fuel-based regional travels.
- **Socioeconomic analysis:** All the noise and emissions results are monetized using a unified framework, allowing for a direct and transparent comparison of disparate environmental effects.

The following sections are organized as follows. First, the methods and models for assessing air traffic noise and emissions are described in detail in Section 2, starting with the fleet composition and aircraft models, followed by the air traffic development scenarios and the noise and emissions prediction methodology. The cost-benefit analysis method adopted in this work as well as a general literature review on aviation related noise and emissions costs used in different cost-benefit studies are then presented in Section 3. In Section 4, the study results are presented with the noise impact assessment given for single events and the cumulative effect. This is followed by the CO_2 emissions prediction for the different scenarios, and finally, the socioeconomic cost-benefit analysis comparing

Table 1
Aircraft types and number of flight movements for Arlanda airport in 2023, (Jägemar and Forsström, 2024, 2025).

Aircraft type	Number of movements (2023 data)	Number of movements (2024 data)
B738	39236	33154
A20N	37839	48889
A320	25798	19856
CRJ9	16130	12847
B38M	10253	16541
AT72	9576	7769
A321	7474	7924
F50	5133	7003
A319	3921	4973
A21N	3422	3216
Other	30473	28586
Total	189255	190758

the noise related impact with the CO_2 emissions in a common currency. Lastly, in Section 5 the key findings are summarized, and uncertainties and limitations are discussed in Section 6.

2. Methodology

2.1. Fleet composition

The most common aircraft types operating at Arlanda are published by the airport operator, Swedavia, in two publicly available environmental reports (Jägemar and Forsström, 2024 and Jägemar and Forsström, 2025). The data are presented in Table 1, and the ten most common aircraft types and the number of movements per type for the year 2023 and 2024 are shown. For simplification, two types were selected to cover the majority of operations at the selected airport. The first type covers the twin-jet narrow body aircraft, including mainly Airbus A320 family A319, A320 and A321, A320neo family A320neo (A20N) and A321neo (A21N), Boeing 737-800 (B738), and Boeing 737 MAX8 (B38M), and the second type covers the twin-engine turboprop regional aircraft, ATR 72 (AT72) and Fokker 50 (F50). Representatives of each type were modeled based on A20N and AT72, and are here referred as JA and TA, to represent the categories of jet aircraft and turboprop regional aircraft.

As concluded by Amadori et al. (Amadori et al., 2023), the Swedish domestic air traffic demand could be divided into two distinct categories: small volume that requires aircraft with up to 34 seats, and a middle market with some 76-seat requirement. In terms of range, the top 10 major routes within Sweden represent 71% of all passenger demand, such as Stockholm-Göteborg (385 km), Stockholm-Malmö (507 km), Stockholm-Luleå (724 km), Stockholm-Umeå (511 km) and Stockholm-Visby (186 km). To be able to reflect the realistic demand and consider existing electric and hybrid-electric aircraft development projects as recently reviewed by Raihan (Raihan, 2025), a hybrid-electric aircraft was modeled based on the top-level requirements of Heart Aerospace's ES30 (ES-30, 2025) concept, which is a regional hybrid-electric aircraft, under development, with a standard seating capacity of 30 passengers. The initial electric-only range of the aircraft has been designed to 200 km with a hybrid option extending it to 400 km. In the long term, in late 2030s, advancements in battery technology are expected to allow a hybrid range of 600 km according to Heat Aerospace's development roadmap. This selection is further supported by a socioeconomic benefit analysis of electric aircraft (Avogadro and Redondi, 2024) which concludes that early adoption is most feasible for 19-20 seat aircraft on regional routes (under 400 km) by 2030-2035, driven by anticipated reductions in aircraft and battery costs. Larger electric aircraft will require second-generation technological advancements for cost-effectiveness and broader market penetration.

Due to the lack of design characteristics of ES-30, an aircraft model, in this paper referred as HE (hybrid-electric), was developed as a retrofit of the Dornier 328 (Turboprop, 2025) using commercial aircraft modelling tool Pacelab (PACE Aerospace Engineering & Information Technology GmbH, 2022). Following the expected trend as published by (ES-30, 2025), it was assumed that by 2050, a hybrid range of 800 km could be achievable. The HE aircraft model can be viewed in Fig. 1. Some of the key characteristics and assumptions for the three modeled aircraft types are presented in Table 2, while a short summary of the key HE modelling choices is given as bullets below.

- Number of propellers. Although no propeller details in terms of performance and acoustics are included in the system-level HE aircraft model, the number of propellers is increased to 4 with a reduced diameter assuming the same propeller performance map as used in the default Dornier 328 aircaft model in Pacelab. Considerations behind this retrofit include the improved redundancy for the increased complexity and noise reduction potential through phase synchronization (Pascioni et al., 2019; Zarri and de Prenter, 2025).
- Hybrid mode. The modeled HE aircraft operates at a constant power split of 50% – 50% between fuel and battery throughout the entire mission, except for: 1. LTO cycle which is electrical-power-only because of local air quality consideration, 2. Reserves which are 100% fuel due to the low energy density of batteries, self discharge and calendar degradation risk. These assumptions, however, lead to a 25% heavier propulsion system.

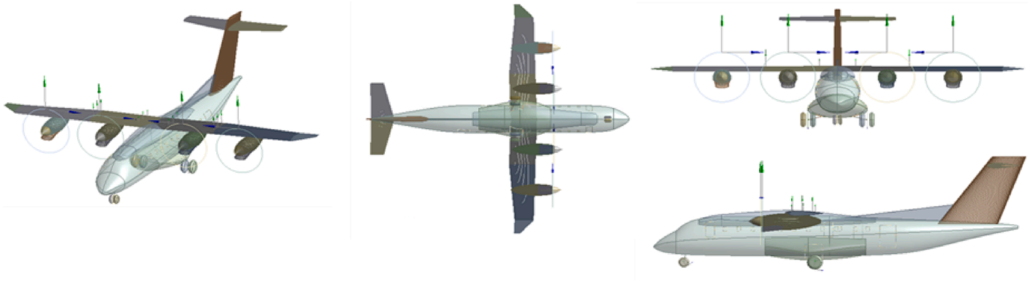


Fig. 1. Hybrid electric aircraft retrofitted from Dornier 328.

Table 2
Key characteristics and assumptions for the three modeled aircraft types.

Aircraft type	JA	TA	HE
Passenger capacity	180	72	30
Wingspan	35.8 m	27.1 m	20.9 m
Length	44.5 m	27.2 m	21.1 m
Engines	2 x turbofans	2 x turboprops with 6-blade propellers	4 x hybrid-electric with 6-blade propellers
Capacity	174	72	30
Typical range	6400 km	1400 km	400 km (800 km Y2050)
Battery assumption	–	–	400 Wh/kg (800 Wh/kg Y2050)

- Airframe sizing. The wing loading for the HE aircraft has been set to 380 kg/m^2, while the high-lift systems were scaled using the same spanwise ratios and the landing gears were assumed unchanged.
- Battery sizing. A full initial State of Charge (SoC) was assumed, with the battery sized to ensure a 20% residual SoC at the end of the block mission as listed in Table 2. This resulted in a battery mass of 2265 kg for the year 2035 design (15% of the aircraft maximum take-off mass (MTOM)) and 2198 kg for the year 2050 design (14% of the aircraft MTOM). Half of the baggage volume was assumed to be used to accommodate the batteries, however, the need for airframe structure enhancement was not considered and center of gravity not regarded.

Comparing to a recent conceptual design study of a hybrid-electric aircraft retrofitting from a 40-seat Dornier 328eco conducted by Staats et al. (2025), a similar design strategy was adopted in our study. However, as their study targets at lower hybridization degrees (12 – 34% for climb and cruise only) for missions of 200-350 NM, no direct comparison can be made. Nevertheless, their increased mass of about 11% of the aircraft MTOM due to a 34% hybridization for the climb and cruise phases of a 200 NM mission is at the same level as our retrofit considering the lower battery energy density of 250 Wh/kg as reported in their study. In another conceptual design study of hybrid-electric aircraft (Abu Salem et al., 2023b), the specific choice of designing the electrical powertrain to meet the power required for the LTO cycle, whereas fuel is used in the other phases, is considered as an effective way of suppressing local air quality problems.

2.2. Air traffic model

Four air traffic scenarios were developed for the present study; a baseline scenario simulating the domestic air traffic in 2024 with the current fleet, a near-term scenario in 2035 simulating the domestic air traffic development 5 years after the introduction of electric aircraft, and two long-term scenarios in 2050 simulating the domestic air traffic with an advanced electrified fleet and with the current fleet assuming frozen technology. The frozen technology assumption, which means no incremental technology improvements are considered, is justified by two considerations. First is the longevity of the most representative aircraft in the fleet, the A320neo family. As introduced in 2014, the A320neo family currently holds a backlog of over 7000 aircraft according to Airbus (2025). At the current production rate of approximately 800 units per year, this backlog alone will sustain production until 2035. In addition, the major competitor Boeing 737 MAX family also holds a high backlog, while ATR 72 family, which has a lower production rate and less strong demand, has reported a total backlog of over 150 units. Given typical aircraft lifespans, these aircraft will remain a dominant force in global fleets through 2050. Secondly, the next generation successors are anticipated for the late 2030s, while publicly available data remains limited. Emerging concepts like the Open Fan engine show promising fuel consumption reduction of 20%, yet they present significant modelling challenges regarding noise- a problem that remains an active issue for researchers worldwide. Strategically, this study adopts the "frozen technology" assumption for the conventional fleet to isolate the impacts of radical innovations, specifically the hybrid-electric technology. While sustainable aviation requires a mix of air traffic management improvements, alternative fuels, and economic measures, the noise footprint is most directly influenced by radical shifts in propulsion and airframe. By avoiding the speculative and often inaccurate prediction of incremental technology gains, this study ensures a clear, direct comparison between today's established standards and the potential of an electrified future.

Table 3
Air traffic scenarios.

Scenario	2024	2035	2050 - electrified fleet	2050 – frozen technology
Passengers per year	2027470	2337001	2836616	2836616
Arrivals per year	24688	49169	141480	34522
Arrivals per day				
Total	68	134	387	94
JA	38	33	3	52
TA	30	27	2	42
HE	–	74	382	–

(a) Arrivals.

Scenario	2024	2035	2050 – electrified fleet	2050 – frozen technology
Passengers per year	2079033	2396431	2908756	2908756
Departures per year	25327	52031	145064	35416
Departures per day				
Total	69	142	397	97
JA	38	33	3	54
TA	31	27	2	43
HE	–	82	392	–

(b) Departures.

Table 4
Runway usage at Arlanda airport for year 2023 and 2024.

		2023 Usage			2024 Usage		
	Runway	Day	Evening	Night	Day	Evening	Night
Landing	01L	22%	26%	28%	18%	20%	27%
	01R	12%	8%	2%	10%	7%	0%
	19L	14%	10%	5%	35%	30%	3%
	19R	8%	10%	17%	11%	16%	43%
	26	40%	43%	47%	25%	27%	27%
Take-off	01L	13%	10%	12%	13%	10%	12%
	08	30%	36%	42%	27%	32%	39%
	19L	26%	24%	43%	4%	4%	46%
	19R	28%	29%	3%	56%	54%	3%

The four scenarios are presented in Table 3(a) and (b) for domestic arriving and departing flights, indicating the number of passengers and flights and the number of movements per aircraft type and day. For the baseline scenario, the number of passengers and aircraft was based on data published by the Swedish Transport Agency - Transportstyrelsen (EntryScape Tabular Data, 2025), by downselecting all domestic flights arriving or departing from Arlanda Airport. With a load factor of 0.64 obtained from official statistics of Swedish domestic flights for 2024 (Melkersson and Holmström, 2025), the total number of movements was calculated from the typical passenger capacity of each aircraft type, assuming a fixed load split of 3:1 between JA and TA. The number of movements per aircraft for a year was evenly distributed across each day. The hybrid-electric aircraft were assumed to enter service in 2030, with an initial production rate of 20 aircraft and a 10% increase in production rate per year. Limited by the range capability, the hybrid-electric aircraft were only employed for the routes that can be performed with the assumed hybrid range.

The increase in passenger demand per year was estimated at 1.3%, following the Base scenario in EUROCONTROL's Aviation Outlook 2050 report (EUROCONTROL, 2022) for Sweden. From the number of passengers, it was possible to estimate the number of landings and take-offs for each aircraft type. These were then distributed among the runways for each interval of a 24-hour period (day, evening, and night) using the data presented in Table 2 (Tabell 2) of Swedavia's 2023 environmental report (Jägemar and Forsström, 2024) and Table 4 (Tabell 4) of Swedavia's 2024 environmental report (Jägemar and Forsström, 2025). The reason for using the runway usage from two different years is to investigate the robustness of the study and demonstrate the sensitivity. As for year 2023 runway 26 was the busiest runway for landing taking over 40% of all landings while for year 2024 runway 19L took the position and the utilization of runway 26 for landing reduced to around 25%; for take-offs, runway 08, 19L and 19R topped the usage in 2023 while in 2024 the usage of runway 19R reached 56% and 19L has almost got abandoned for take-off during daytime. The arrivals and departures were modelled based on the RNP AR and SID procedures, respectively, that can be found in Sweden's Civil Aviation Administration, LFV, website (IAIP, 2025). If for a runway, more than one landing or take-off procedure were available, the number of movements was equally distributed among them. A schematic plot for the runways for Arlanda airport is shown in Fig. 2 and the detailed runway usage distribution is given in Table 4.

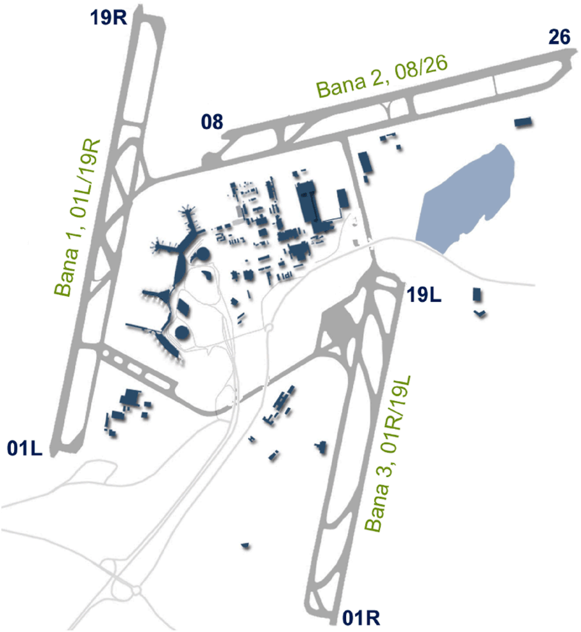


Fig. 2. Illustration of the runways at Arlanda airport. Swedavia (2026).

As the noise impact is a cumulative effect, extracting the noise impact of domestic flights only would be considered incomplete. Therefore, all flights (international and domestic) arriving and departing from Arlanda were considered to assess the impact that the changes in domestic air traffic would have on the cumulative effect. For the non-domestic flights, a simplification was made considering only the JA aircraft type with flight numbers as reported by Swedavia (Swedavia, 2025a) for 2024. The same annual increase in the number of flights was adopted as for the domestic travel demand increase.

Summarizing the total movements for each scenario, the significant increase in arrivals and departures driven by the introduction of HE aircraft poses a challenge to both air traffic management and runway capacity. For year 2050, the electrified fleet—based on our assumptions—could lead to nearly six times the number of domestic flights seen in 2024, reaching as many as 800 movements per day. Meanwhile, assuming a 1.3% annual growth rate for international traffic, we calculate a total of 205,454 annual flights, or approximately 563 movements per day. Combined, domestic and international arrivals and departures total 1,363 daily movements. According to the runway scheduling limits published by Swedavia for Arlanda Airport (Swedavia, 2025b) , a maximum of 84 movements per hour can be achieved between 06:00 and 22:00. This results in a total day time capacity of 1,344 movements for year 2026. This comparison shows that the runway capacity is nearly sufficient to meet the traffic volume requirements based on these assumptions. Nevertheless, these estimations exclude cargo, private, and taxi flights. In addition, due to the closure of Bromma Stockholm Airport (not officially but activities are continuously decreasing), the traffic demand for the Bromma airport has been redirected to Arlanda in this study.

2.3. Noise and emissions assessment methodology

To allow for the assessment of the noise impact, several simulation tools were incorporated into a multidisciplinary analysis framework for aircraft and propulsion systems. The framework has been used and described in several studies (Thoma et al., 2020; Thoma and Zhao, 2025) and includes a trajectory design module, an aircraft and engine performance module, integrated with engine conceptual design, an emissions prediction module, and a noise prediction module. An illustration of the framework is given in Fig. 3.

The assessment process begins with the procedure design and flight mechanics model. In this study, procedures are designed based on predefined approach and departure procedures that are used at Arlanda airport. These can be found in Sweden's Civil Aviation Administration, LFV, website (IAIP, 2025). Based on these definitions, trajectories are designed using a series of waypoints and segments that define the horizontal and vertical path, as described in (Thoma and Zhao, 2025). For the vertical profile, altitude and speed at each waypoint are defined separately for each aircraft type according to publicly available data. Such data can be found, for example, in EUROCONTROL's Aircarft Performance Database, e.g. for Dornier 328 (Aircraft Performance Database D328, n.d.). However, as only a few flight levels are included in EUROCONTROL's database, intermediate levels can be complemented with speed, altitude, configuration setting, and rate of climb/descent parameters from the default procedural steps included in the Aircraft Noise and Performance (ANP) database (ANP, 2023a). Required performance characteristics can then be estimated using flight mechanics equations, (Thoma and Zhao, 2025), and an estimate of the lift-to-drag ratio, which can, for example, be derived from the aerodynamic coefficients included in the ANP database, (ANP, 2023a).

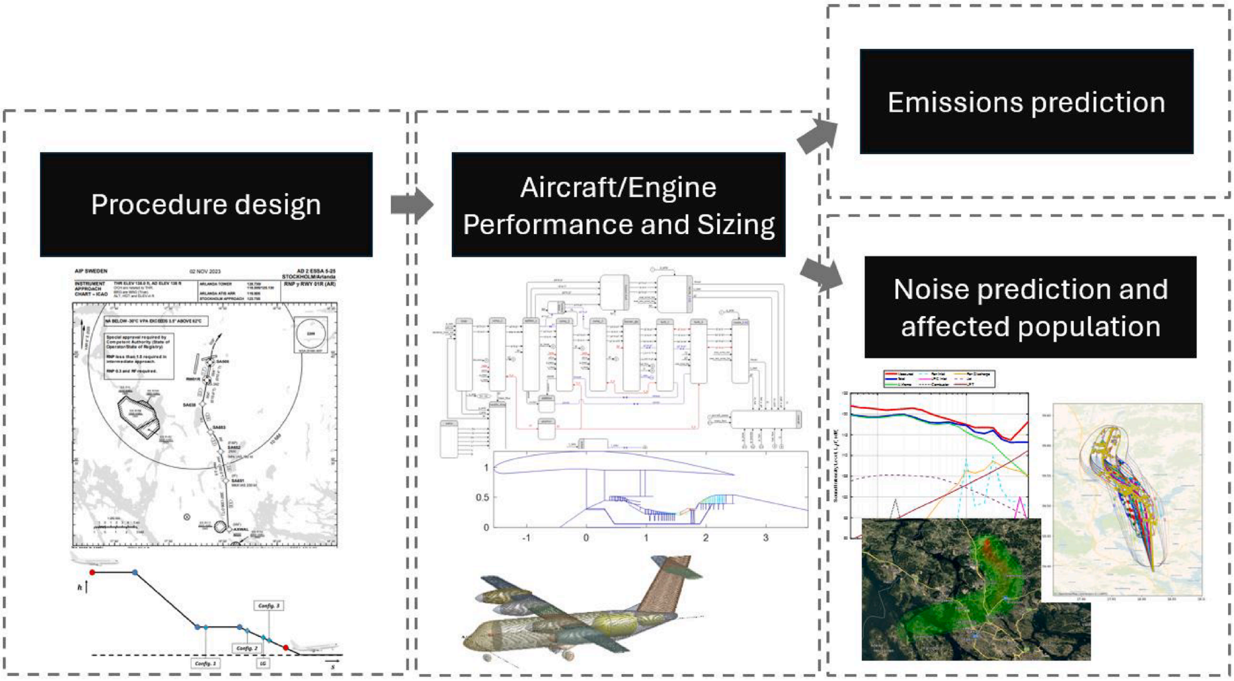


Fig. 3. Multidisciplinary modeling and analysis framework illustration.

The aircraft performance characteristics are then fed into the in-house engine performance code, GESTPAN, (Grönstedt, 2000), which in turn feeds data to the engine conceptual design and sizing tool, WEICO, (Grönstedt et al., 2009), to estimate the geometric characteristics of the engine components. The engine performance data are used to estimate the exhaust emissions from the JA and TA operations, which in this study is limited to CO_2 emissions. For the HE aircraft, pure electric LTO operation is assumed hence no gas emissions are emitted at take-off and initial climb as well as approach, landing and taxing phases. Climb-cruise-descent (CCD) fuel burn is obtained from aircraft modelling. In all cases, CO_2 emissions are directly estimated from the fuel consumption calculated using a factor of $3.15\ kgCO_2/kgFuel$.

The emissions calculation is followed by the noise prediction, which employs a component-based approach where each noise component is modeled using publicly available empirical and semi-empirical methods. More specifically, fan and compressor noise are modeled based on the method introduced by Heidmann (Heidmann, 1979) and later updated by Kontos (Kontos et al., 1996). According to this, the predicted noise for the fan or compressor inlet duct, consists of broadband, discrete, and combination tone noise, and for the fan discharge duct consists of broadband and discrete tone noise. The inputs required for the prediction are the mass flow rate, total temperature rise for a fan or compressor stage, and design and operating point values of the rotor-tip relative inlet Mach number. The total noise for the inlet and exhaust are estimated in one-third octave-band frequencies by summing the spectrum of each of the components on an energy basis. The combustor noise prediction model was based on the method described by Gliebe et al. (Gliebe et al., 2000, 2022). The method includes correlations for single annular and dual annular combustors, which are based on combustor geometry, cycle conditions, spectral frequency content, and directivity. The peak overall sound pressure level and normalized sound pressure level are computed at specified peak frequencies and directivities, which are then combined to derive the sound pressure level at every frequency and directivity. Turbine noise is modeled as a combination of broadband and discrete tone noise according to the method presented by Dunn and Peart (Dunn and Peart, 1973) and requires as input the last stage relative tip velocity, primary mass flow, local speed of sound at the turbine exit and the stator/rotor spacing. The resultant spectrum is given in one-third octave-bands normalized with respect to the fundamental blade passage frequency of the last stage of the turbine. Jet noise from coaxial jets, as presented by Russell (Russel, 1984), is calculated in one-third octave-band sound pressure level as a function of the jet state properties of an equivalent single-stream jet with the same mass flow, energy flow, and thrust as the coaxial jet. These properties include the equivalent jet velocity, the equivalent jet total temperature, the velocity ratio of the outer stream to the inner stream, the temperature ratio and the area ratio. Finally, airframe noise is predicted as the sum of independent non-propulsive sources, including clean wing and tailplanes, high-lift devices (flaps and slats), and landing gear. Wing, tail surfaces and high-lift noise follow the method proposed by Fink (Fink, 1977, 1979), which is based on the aircraft speed, boundary-layer thickness, wing or tail span, flap area, flap deflection angle and Strouhal number for the flap chord. The landing gear noise is modeled according to the method proposed by Sen et al. (Rahul et al., 2004), according to which four components can be assumed; the low-frequency component generated by the struts, the mid-frequency component caused by the hydraulic pipes near the break assembly, the high-frequency component from electric wires and small pipes, and the tire noise component. Required inputs for each of these components are the local speed of sound, a length scale parameter and the number of main struts and tires. To compute the total airframe noise all components are combined as uncorrelated sources to produce the overall free-field noise spectrum. These described methods are implemented in the open-source noise prediction tool CHOICE (Thoma et al., 2022, 2023), which has been validated against measurements for state-of-the-art turbofan aircraft. The comparison showed a good agreement between the measurements and the predictions, with deviations of less than 3 dB in total sound intensity level and notable similarities in spectral patterns (Thoma et al., 2023). For turboprop and hybrid-electric aircraft, a propeller noise prediction was additionally implemented. This was modeled according to the method proposed by Dunn and Peart (Dunn and Peart, 1973), which includes broadband vortex noise and discrete-tone, rotational noise. The prediction requires several geometric characteristics, including the total projected blade area, the number of blades, the propeller diameter, and the blade thickness, chord length, and angle of attack at 0.7 span. The required performance characteristics are the aircraft Mach number and atmospheric temperature, the angle between the propeller axis and the direction of aircraft motion, the propeller thrust, and the shaft power and speed. The propeller noise model was compared with the down-scaled propeller acoustics measurements conducted by Quaroni et al. (Quaroni et al., 2024, 2025), where an acceptable broadband noise prediction was observed but the tonal noise levels were over-predicted. However, since the low frequency tonal noise will be attenuated by the A-weighting, the broadband noise contribution becomes more important for A-weighted sound levels. The propeller model is, therefore, believed to be acceptable for the presented study. An electric propulsion system would also require a gearbox and an electric motor; however, the noise generated from these components was neglected as studies have shown that their contribution to the overall noise is insignificant (Riboldi et al., 2020; Huff et al., 2016).

The generated noise at the source can then be predicted and propagated on a ground-based grid centered around Arlanda airport. The noise prediction on the ground has been compared, in past studies, with measurements and recordings of landing aircraft, (Thoma, 2024; Thoma et al., 2023), and it was observed that the predicted noise level at the overhead point and before was somewhat overpredicted in certain cases; however, the predictions were always within a limit of 3 dB in terms of A-weighted sound exposure level (SEL) and maximum sound pressure level ($L_{A,max}$), (Thoma, 2024). For the present study, ISA conditions were assumed, and the propagation included the effects of atmospheric absorption, spherical spreading, characteristic impedance change effects, and ground reflection. The predicted noise on the ground was used to interpolate the population grid derived from the EU GHSL - Global Human Settlement Layer (Global Human Settlement, 2023b) and estimate the noise-affected population.

3. Socioeconomic cost-benefit analysis

Extensive research has been conducted for assessing aviation's socioeconomic cost-benefits, particularly regarding different sustainable development routines, yet these studies predominantly emphasize decarbonization aspects. The key future strategies that have been mostly discussed and explored are sustainable aviation fuel (SAF) (Cui and Chen, 2024; Farooq et al., 2025), electrification of aircraft propulsion (Avogadro and Redondi, 2024; Marciello et al., 2024; Shoukat and Redondi, 2025), hydrogen-powered aircraft (Akbiyik et al., 2025), and advanced air traffic management (Rodríguez-Sanz and Rubio Andrada, 2023).

For electric aircraft, the socioeconomic cost-benefit analysis performed by Avogadro and Redond (Avogadro and Redondi, 2024) concludes that short-term emissions reductions from first generation technologies are limited, while the medium-to long term outlook for advanced electric aircraft suggests substantial environmental benefits. From a policy perspective, the study highlights that initial electrification will contribute marginally to net-zero goals, necessitating complementary policies. The transition also implies increased travel times for passengers, requires airport infrastructure adaptation, and demands strategic network planning from airlines, with regional carriers best positioned for early adoption. Compared to the other sustainable development routines, Shoukat and Redondi (Shoukat and Redondi, 2025) also suggest that to achieve carbon neutrality, hybrid-electric aircraft and biofuels offer early emission reductions. This necessitates a range-based fuel strategy, where electric/hybrid solutions suit regional flights, and biofuels/hydrogen are prioritized for medium to long-range operations. In (Marciello et al., 2024), focusing on hybrid-electric aircraft for 50 passengers, the analysis shows that hybrid-electric aircraft would incur significantly higher direct operating costs (up to 69.8% more) due to the inherent complexity and mass penalties of their architecture, impacting acquisition, maintenance, and charges. The study highlights an urgent need for targeted policies and incentives to drive sustainable aviation adoption, and suggests SAF with conventional propulsion as a promising interim, cost-advantageous solution, provided a reliable large-scale supply can be secured.

Noise related aspects are however largely overlooked in the literature, often only acknowledged as a secondary co-benefit in studies such as (Shoukat and Redondi, 2025) and (Avogadro and Redondi, 2024). Although noise related charges are considered in (Marciello et al., 2024), a more important truth of the consequences of noise pollution on public health as reported in (Park et al., 2025) requires far greater attention. The latter study estimated that increased aircraft noise exposure would produce incremental long-term mortality and morbidity for hundreds of thousands of dollars, alongside losses of tens of thousands of quality-adjusted life years for the case examined.

3.1. Aviation noise on population, health-related costs

Quantifying the population and health-related costs associated with aviation noise impact, however, remains highly uncertain. As studied in (Park et al., 2025), the aircraft noise effects on population and health-related costs considered are the risk of hospitalization for cardiovascular diseases, increased annoyance, development of anxiety disorders, and low birth weight. Despite the detailed nature of the study presented in (Park et al., 2025), the models developed in the study are difficult to apply directly to other contexts. Their specificity to epidemiological research on the chronic effects of aircraft noise, which requires a high level of detail, limits their broader applicability. In the present study, the analysis is hence performed according to the methods and calculations values provided by authorities, which are considered more applicable for transportation related research. In addition, as the noise related cost is largely dependent on the statistics of the local regions with several key factors, such as income, population density and age, three cost tables developed within Europe were collected. These cost values were estimated considering the marginal costs associated with increases in aircraft noise above baseline values for the health and well-being outcomes including sleep disturbance, annoyance, acute myocardial infraction and hypertension. The cost curves adopted in this study are presented below in Fig. 4, and details of the cost curves are given below.

- **EU27 + UK:** The cost curves labeled with EU27 + UK are derived from the total cost (i.e. annoyance and health) of aviation traffic noise as published by European Commission (Van Essen et al., 2019) based on the studies performed by Bristow et al. (Bristow et al., 2015) and Dickens et al. (Dickens et al., 2014). As these are reports from 2019 and 2014 respectively, adjustments in currency and inflation as given in (EUROCONTROL, 2025) are adopted for year 2024. Linear extrapolation is used for years beyond, i.e. 2035 and 2050. The A-weighted average noise level throughout the day, evening and night (L_{den}) is used for calculating the cumulative cost as presented in the curves.
- **UK:** The cost curves labeled with UK are derived from the total cost (i.e. health, sleep disturbances, and annoyance) of aviation traffic noise as published by the Department for Environment, Food & Rural Affairs (DEFRA) of UK (Dickens et al., 2014). As the report was published in 2014, adjustments in currency and inflation as given in (EUROCONTROL, 2025) are adopted for year 2024. Linear extrapolation is used for years beyond, i.e. 2035 and 2050. Different from the EU27 + UK cost curves, DEFRA UK separates the cost tables into daytime noise related health and annoyance costs and night time sleep disturbance cost. For the day time, the A-weighted average sound level over the 16-hour period of 0700-2300 hours is considered ($L_{eq,16h}$) and the A-weighted average sound level over the 8-hour night period of 2300-0700 hours is calculated for night time (L_{night}). Penalties accounted for increased residential population exposure during evening and night as used in the calculation of L_{den} are not added to $L_{eq,16h}$ and L_{night}. In Fig. 4, the UK cost curves are presented separately for daytime and night.
- **Sweden Trafikverket:** The cost curves labeled with Sweden Trafikverket are derived from the noise cost published by Swedish Transport Administration Trafikverket (ASEK, 2024). As the reported cost values are provided for 2019 and 2045, linear interpolation and extrapolation are used for intermediate years and years beyond for each cost table, i.e. 2024, 2035 and 2050. The A-weighted average noise level throughout the day, evening and night (L_{den}) is used for calculating the cumulative cost as presented in the curves.

Noticeable differences can be observed from the cost curves as plotted in Fig. 4. DEFRA UK lists a lower noise exposure threshold for accounting for annoyance and health related cost than the values recommended by Eurocontrol EU and Trafikverket Sweden. The lower threshold of 45 dB actually follows the recommendation of the average noise exposure level for aircraft noise from the WHO and UN guidance on health and environment, (World Health Organization, 2024). Whilst the cost tables given in (Van Essen et al., 2019; EUROCONTROL, 2025) and (Dickens et al., 2014) report values per dB, the values in Fig. 4 represent accumulated costs from the threshold. In addition, the UK cost is per household while the other two are per person. According to (Statista, 2025), the average household size was 2.15 residents per household in 2023 and this number is adopted in the study. The costs in different currencies have been converted into Euros using the average exchange rate in 2024 (EUR/SEK 11.43217 and EUR/GBP 0.84638) for a direct comparison.

3.2. Emissions related cost

Evaluating the climate impact of different emissions involves uncertainties comparable or even higher to those observed in studies of noise-related health impacts. Studies focusing on aviation and climate change, including (Grewe et al., 2021) and (Lee et al., 2009), in their estimation of total aviation radiative forcing, report 2-3 digits percentage of uncertainty in a 90% confidence estimation range. There is no doubt that these studies have revealed the importance of implementing measures to reduce emissions from aviation activities, but monetary quantification of the impacts is rare and difficult. This is particularly true for the non-CO_2 emissions as indicated in (Grewe, 2020), due to the much shorter lifetime of the non-CO_2 climate agents, the warming effect of the non-CO_2 emissions largely dependends on the location, time as well as the meteorology at the time of emission. In (Klophaus and Lauth, 2022), the authors presented 4 categories of monetary measures for climate cost calculation, with different combinations of considering and ignoring non-CO_2 emissions and minimum compensation per passenger which does not represent actual climate cost but a political measure. Using Bremen Airport as an example, the authors calculated that the average climate costs per ton of CO_2 caused by passengers departing from the airport are around 55 EUR. This is however lower than the carbon price recorded in EU emissions trading system (ETS) since 2022.

To reduce carbon emissions, most European countries have been implementing carbon taxes and ETS. Among them, Sweden levies the highest carbon tax rate at 123.7 USD per metric ton of CO_2e for 2024 and 144.62 USD for 2025, which covers the aviation sector (Group, 2025). However, this carbon tax varies even more dramatically crossing different countries, for some other countries the carbon taxes can be neglectable and the aviation sector is even excluded. The EU ETS, on the other hand, is a more unified system in force since 2005 covering all EU member states. The price per metric ton of CO_2e in the system has been increased sharply from around 20 EUR in 2020 to 64.74 EUR in 2024 and higher than 80 EUR in 2025. In the presented study, only the carbon price within the ETS is adopted for the socioeconomic cost-benefit analysis of emissions. The decision, was made mainly based on the considerations of eliminating the uncertainties of non-CO_2 emissions cost and the huge differences in the local regulations. Furthermore, the study places greater emphasis on examining the noise implications of aircraft electrification, a topic that has received limited attention within realistic air traffic scenarios. The values for 2024 are based on the average emissions price within EU Emissions Trading System (ETS), while for 2045 values are estimated according to EU Commission's forecast. The cost values, expressed in EUR per ton

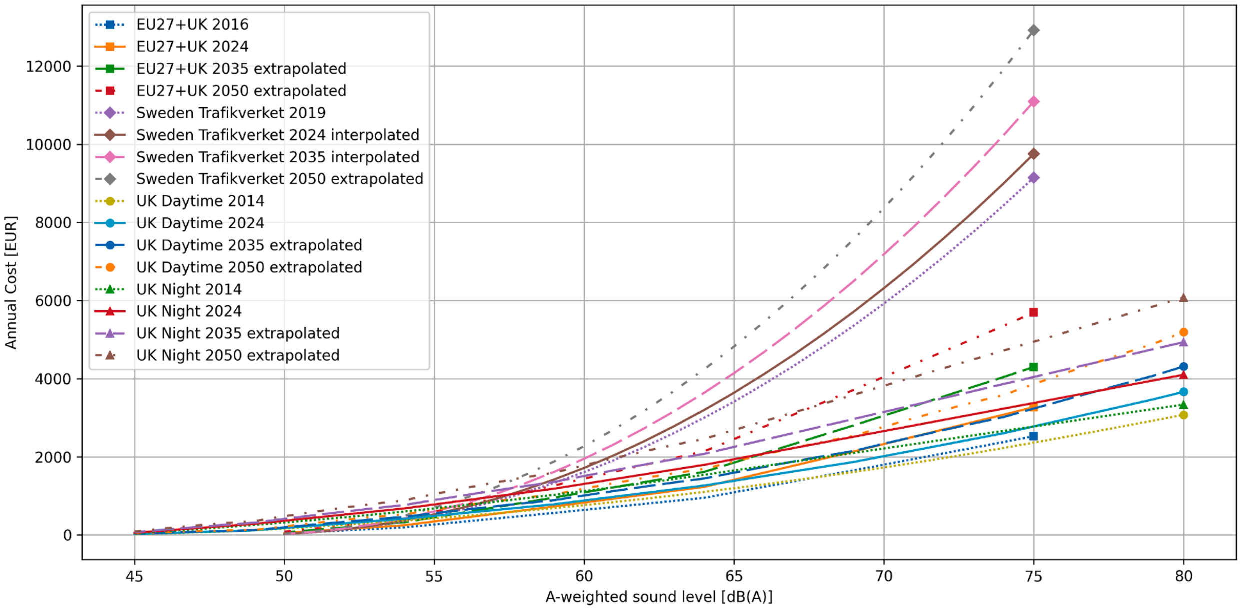


Fig. 4. Annual cost for noise from aircraft derived from different sources: EU (per person, EUROCONTROL, 2025; Van Essen et al., 2019), Sweden (per person, ASEK, 2024) and UK (per household, Dickens et al., 2014; EUROCONTROL, 2025).

of CO_2, are 64.74 for 2024 and 348 for 2045 according to the Swedish Transport Administration calculations. Linear interpolation and extrapolation are applied for the years of 2035 and 2050, respectively, although these interpolated values fall below the necessary measures to reach the intermediate target by 2030.

4. Results

4.1. Noise impact assessment

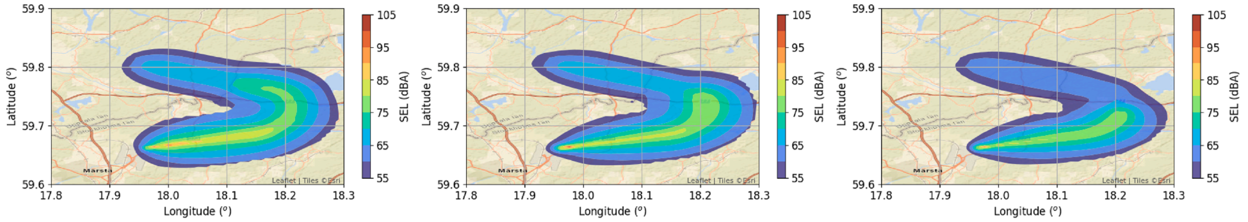
4.1.1. Noise impact of single events

The sound exposure level of the three aircraft during a single approach event is compared in Fig. 5. The comparison is performed for an approach procedure on the runway with the highest utilization for landing in 2023 and the second highest in 2024, i.e. runway 26. In Fig. 5(d), operational characteristics of the three aircraft during the specified procedure are presented. These include the flap and landing gear schedule, the aircraft altitude and the true airspeed. The labels showing the configuration settings are identical to the ones used in the ANP database, for the A20N, AT72 and DO328. However, in the ANP data for the Dornier 328, only one approach configuration setting is indicated with flaps at 32^o, while according to the EASA Type Certificate Data Sheet (EASA, 2025), an intermediate flap position at 20^o exists. Therefore, two approach configurations are assumed for the Dornier 328 retrofit, HE, while it is assumed that the landing gear is extended during both settings.

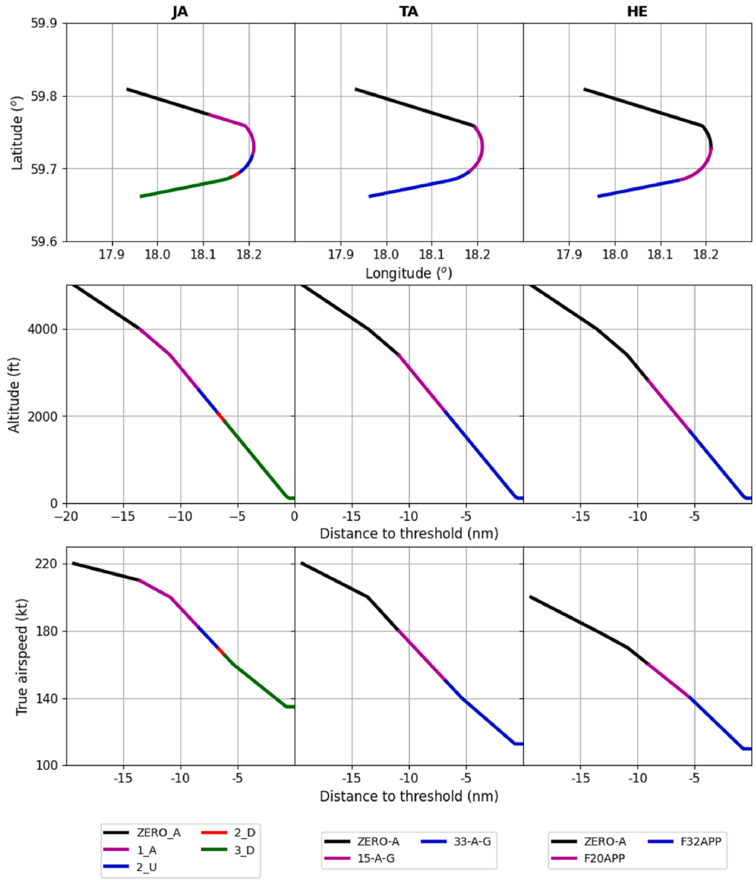
Comparing Fig. 5(a) and (b), it can be observed that although the turboprop seems quieter during clean configuration, once the high-lift systems are extended, a sharp increase in the contour areas is observed. This is attributed to the fact that the configuration settings of the TA are much simpler than for the JA, which can gradually increase the flap angle and allow for independent control of the high-lift and landing gear system. The TA has no slats and only three flap angles at $0^o, 15^o, 30^o$ with the landing gear being extended at the same time as the flaps. When both aircraft are in the landing configuration, configuration 3_D for JA and 33-A-G for TA in Fig. 5(d), the TA shows slightly improved noise impact, partly attributed to the lower landing speed. The hybrid-electric aircraft, shown in Fig. 5(c), appears to be significantly quieter compared to both JA and TA, as only the propeller and airframe noise components are present. At this point, it should be noted that the installation and interaction effects between the propellers on the hybrid-electric aircraft have not been included and some modifications on the level and especially on the spectral characteristics of the source noise can be expected. However, these modifications are not expected to significantly alter the results presented here, but could contribute to changes in the annoyance level.

In Fig. 6, the sound exposure level for the three aircraft during departure from the busiest runway is shown. The corresponding operational characteristics are presented in Fig. 6(d). The departure procedures were modelled until a flight altitude of 10000 ft was reached. As the climb performance for the JA is better, the procedure for this aircraft type is shorter than for the TA. The HE climb performance is limited by the battery characteristics, which result in a climb gradient lower than the original Donier 328 and rather similar to the TA.

In terms of noise impact, the hybrid-electric aircraft, Fig. 6(c) indicates a significant reduction compared to both JA and TA, shown in Fig. 6(a) and (b), respectively. This is mainly attributed to the smaller and less powerful propellers assuming the same



(a) JA (b) TA (c) HE



(d) Procedure characteristics.

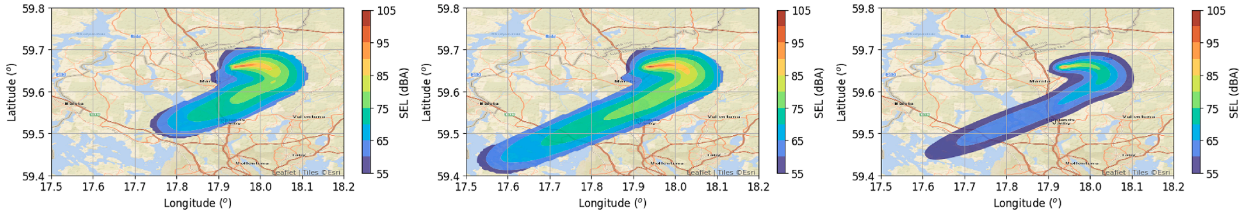
Fig. 5. Sound exposure level of a single event of each aircraft during arrival.

design tip Mach number, and the lack of noise sources such as the high-speed jet and combustor, which, during take-off, are significant contributors to the overall noise level. The JA and TA indicate very similar noise patterns close to the airport, with the former resulting in reduced noise level further away as it climbs faster. The difference is, however, somewhat diminished by the higher speed.

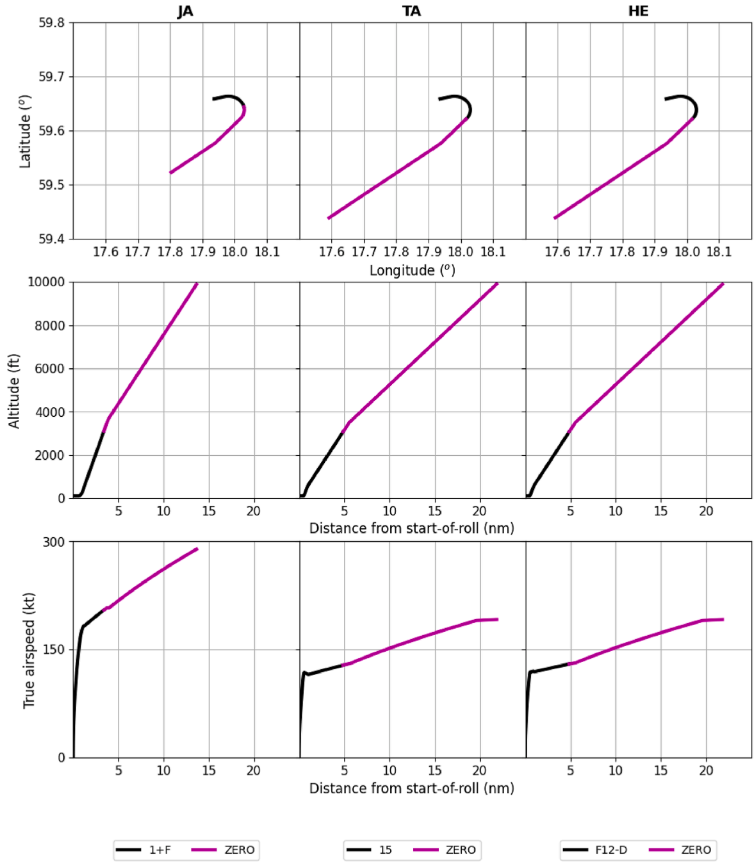
4.1.2. *Noise impact of scenarios*

The noise impact of traffic scenarios (cumulative noise impact) is presented in terms of the day-evening-night noise level (L_{den}), which is a metric that expresses a person's exposure to noise over 24 hours. It is, therefore, an equivalent noise level that depends on the individual events' noise level, the number of events and the distribution of events over a 24-hour period. Calculation of the metric consists of calculating the A-weighted equivalent noise level for the day, evening and night periods, which are then combined, considering a penalty of 5 dBA for the evening and 10 dBA for the night, (European Aviation Environmental Report, 2025).

The L_{den} contours, for the traffic scenarios given in Table 3 with two historical runway usages as shown in Table 4, are presented in Figs. 7–10. Each figure includes the L_{den} contour with domestic flights only on the left and the L_{den} contour with all flights on the right. The first scenario is shown in Fig. 7 and presents the noise exposure for the domestic flights in 2024. The contour is in line with



(a) JA (b) TA (c) HE

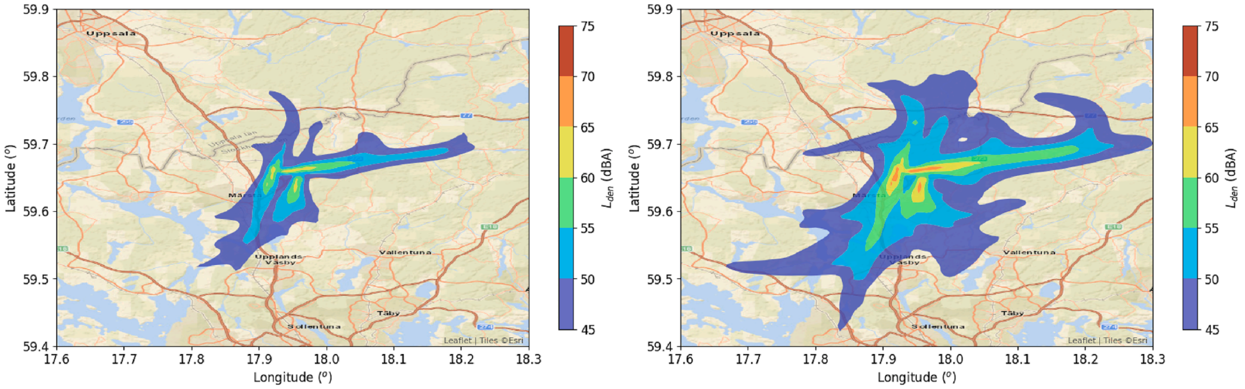


(d) Procedure characteristics.

Fig. 6. Sound exposure level of a single event of each aircraft during departure.

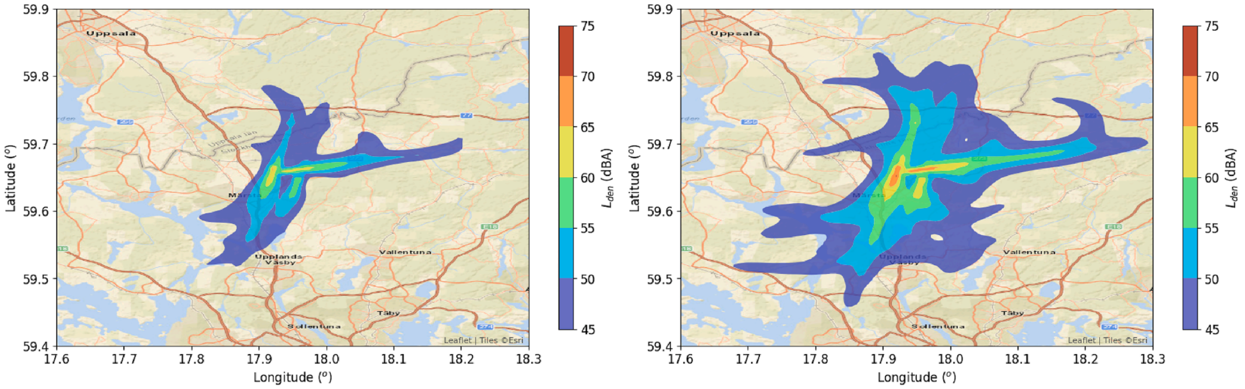
the results presented in the environmental report published by Swedavia (Jägemar and Forsström, 2025). Although differences exist, this can be attributed to several reasons. Firstly, the results in the present study concern domestic flights mainly, and simplification for the fleet has been applied, in particularly for the non-domestic flights. Secondly, as the exact frequency of use of each procedure was not available for the present study, an equal distribution among the procedures for each runway was assumed, which could potentially result in deviations from the real distribution. Taking those differences into consideration, it is believed that the results presented in Fig. 7 are a realistic representation of the actual noise exposure from air transport operations around Arlanda airport.

Compared to the 2024 baseline, the increase in contour area and noise levels across all scenarios is evident and is mainly driven by the substantial increase in daily arrivals and departures needed to meet the increased passenger demand. Under domestic flights only conditions, if frozen technology is assumed, Fig. 10(a) and (c), the rise in contour area is reduced considerably at the northern and southern parts compared to the 2050 scenario with electrified fleet, Fig. 9(a) and (c), while the eastern corner shows the opposite, although higher noise levels are reached. This is primarily because of the concentrated RNP approach procedures for runway 26 (approaching from the east) and the departures from runway 08 turning towards north and south before intersecting with these RNP approach procedures. Hence, the increase in the number of arrivals results in a more focused noise footprint. As observed in the single event noise mapping, the HE noise footprint is narrower; consequently, the contour shape from the east in Fig. 9(a) and (c) is



(a) Domestic flights only with 2023 runway usage

(b) All flights included with 2023 runway usage



(c) Domestic flights only with 2024 runway usage

(d) All flights included with 2024 runway usage

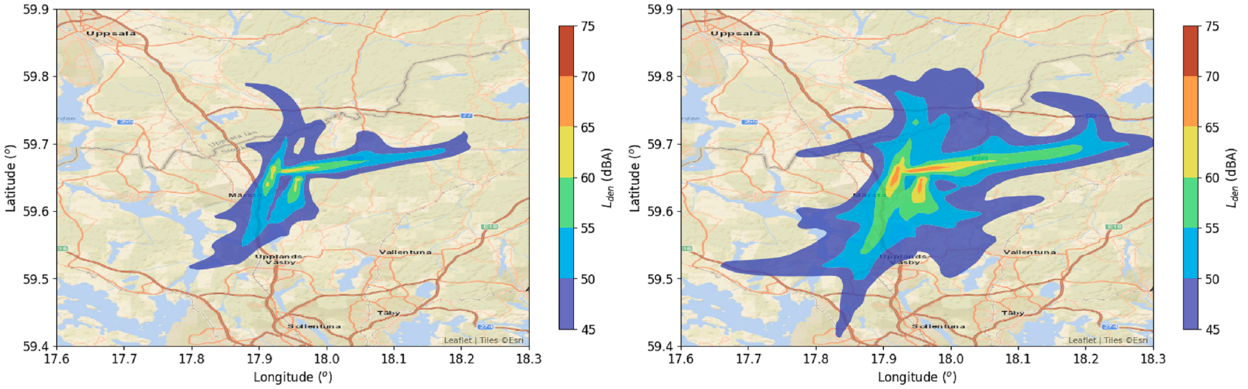
Fig. 7. Day-evening-night noise level for the baseline, 2024, scenario.

thinner but exhibits higher noise levels along the centerline path compared to the frozen technology case as shown in Fig. 10(a) and (c). On the other hand, the extensive use of runway 01L/19R for landings and take-offs significantly enhances the noise at the north and south parts along the runway both in strength and affected areas, due to the equally distributed procedures which are spatially intersected/deviated from each other.

In all figures from Figs. 7–10, when considering all flights including non-domestic flights, the impact of the domestic fleet variation is however weakened. This can be expected since the number of international flights is about 3.5 times than the domestic flights in 2024, and the aircraft are generally larger for international flights. One has to look more carefully to be able to realize the difference from the noise mapping contours, which as before is mainly observed at the north-western and south-western corners.

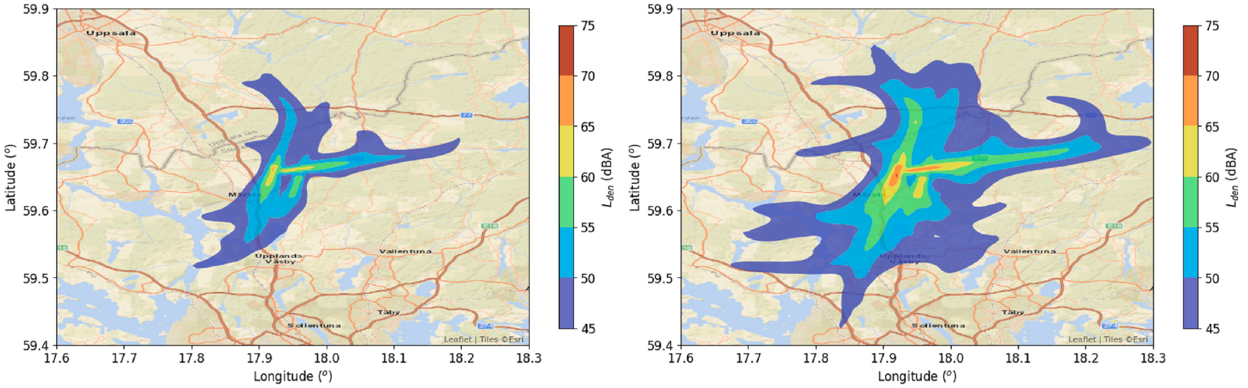
The comparison of the noise contours derived from 2023 and 2024 runway usage data reveals a significant shift in the spatial distribution of noise impact. This divergence is primarily attributed to changes in operational patterns: in 2024, a higher volume of arrivals was concentrated on runway 19L during daytime and runway 19R during nighttime (displacing the 2023 reliance on runway 26). Particularly the 10 dB penalty for nighttime flights added up when the number of flights increase with the use of electrified fleet. Consequently, the 2024 acoustic footprint shows a marked intensification in the northern part, whereas the 2023 data reflects a more pronounced impact to the east (runway 26 usage related). Consequently, these operational shifts directly influence the population exposure to aircraft noise.

Next, the noise affected population is presented. The total population affected by L_{den} above 45 dBA and 50 dBA is presented in Table 5. As expected, there is a clear increase in the number of people affected by noise from arriving and departing aircraft for the 2035 and 2050 scenarios, compared to the 2024 baseline scenario. However, a surprising trend emerges when comparing the two 2050 scenarios, although the contour area for the frozen technology scenario is smaller, the number of affected people above 45 dBA and 50 dBA appears to be larger. This phenomenon is attributable to the specific environment of Arlanda Airport. Due to rigorously defined noise abatement procedures and the low population density in the north-western and south-western regions, an expansion of



(a) Domestic flights only with 2023 runway usage

(b) All flights included with 2023 runway usage



(c) Domestic flights only with 2024 runway usage

(d) All flights included with 2024 runway usage

Fig. 8. Day-evening-night noise level for the near-term, 2035, scenario.

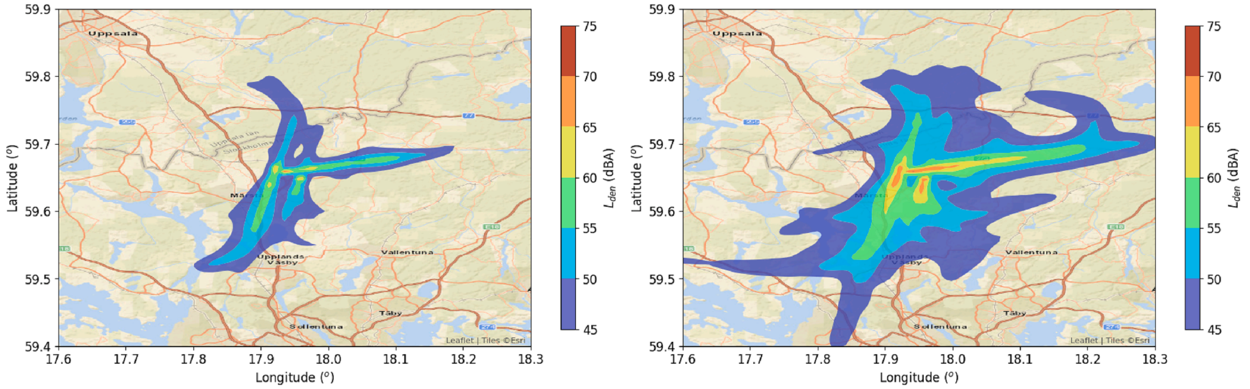
Table 5
Noise-affected population above 45 dBA and 50 dBA for the four scenarios.

	45 dBA above	50 dBA above	45 dBA above	50 dBA above
Domestic flights only	With 2023 runway usage		With 2024 runway usage	
2024	13213	5650	14073	6921
2035	13440	6482	14196	7563
2050 - electrified fleet	14579	6668	14850	7570
2050 - frozen technology	15688	7902	15938	9450
All flights included	With 2023 runway usage		With 2024 runway usage	
2024	49638	14853	48872	15191
2035	59892	15767	60307	16253
2050 - electrified fleet	83137	18092	82733	17555
2050 - frozen technology	83261	18672	88240	17901

the noise contour does not correlate with a proportional increase in the affected population. Essentially, the noise footprint extends primarily over sparsely inhabited areas.

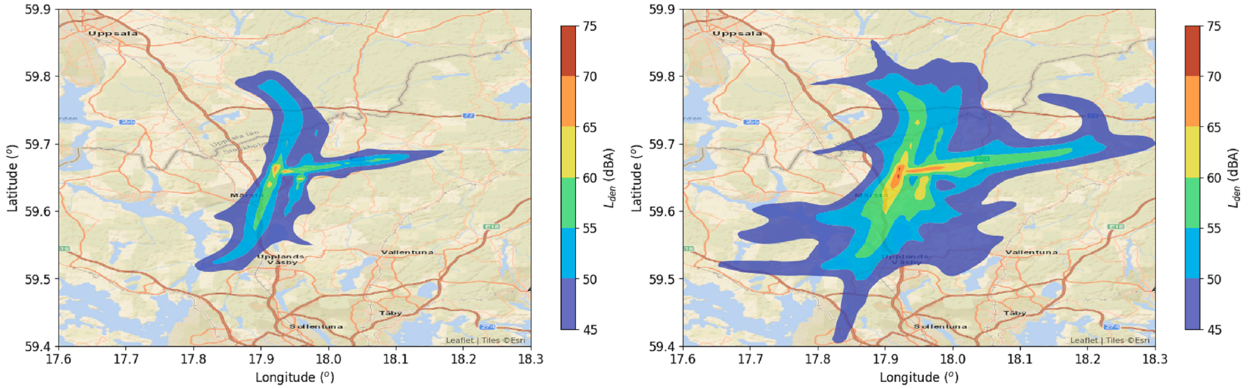
In Fig. 11, the noise-affected population distributed at different noise levels is shown. The amount of population shown for each level in Fig. 11 corresponds only to the people affected by noise between that level and the next one, e.g., between 50 dBA and 51 dBA. It should also be noted that the 45 dBA of L_{den} shown here is not equivalent to the 45 dBA of $L_{eq,16h}$ or L_{night} as used in the DEFRA noise cost estimation. The difference, as previously mentioned, is due to the penalties added to the evening and night.

As observed in Fig. 11(a), there is a notable drop in the amount of affected population between noise levels 47 and 53 dBA for the 2050 electrified fleet scenario, while more people are shifted into higher noise levels between 54 and 55 dBA compared to 2050 frozen



(a) Domestic flights only with 2023 runway usage

(b) All flights included with 2023 runway usage



(c) Domestic flights only with 2024 runway usage

(d) All flights included with 2024 runway usage

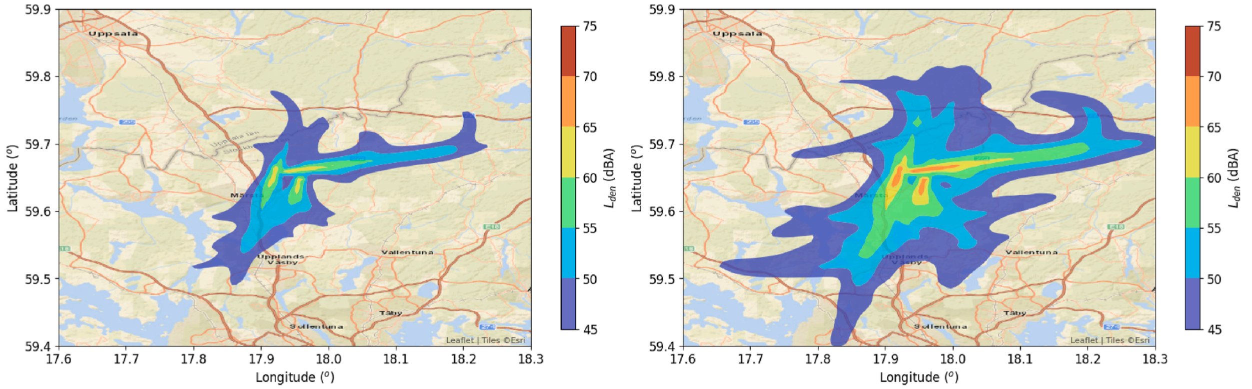
Fig. 9. Day-evening-night noise level for the long-term, 2050, scenario, with electrified fleet.

technology scenario when using 2023 runway usage data. If 2024 runway usage data is applied, as can be seen in Fig. 11(c), this trend is however diminished and becomes more turbulent. Beyond 55 dBA, the differences in noise-affected population between various scenarios become less pronounced. When all flights are included, the differences between the two 2050 scenarios are diminished, as can be noticed from Fig. 11(b) and (d). A higher peak is observed at 46 dBA for the 2050 electrified fleet scenario with 2023 runway usage, which, however, quickly drops and follows the same trend as the 2050 frozen technology scenario. The results demonstrate that: while noise impact is highly sensitive to operational variability (such as runway usage), the underlying trend associated with the adoption of the electrified fleet in the studied scenarios remains consistent. One of the reasons is that noise impact has been carefully integrated in the procedure designs and runway usage consideration in the studied case.

4.2. Emissions assessment

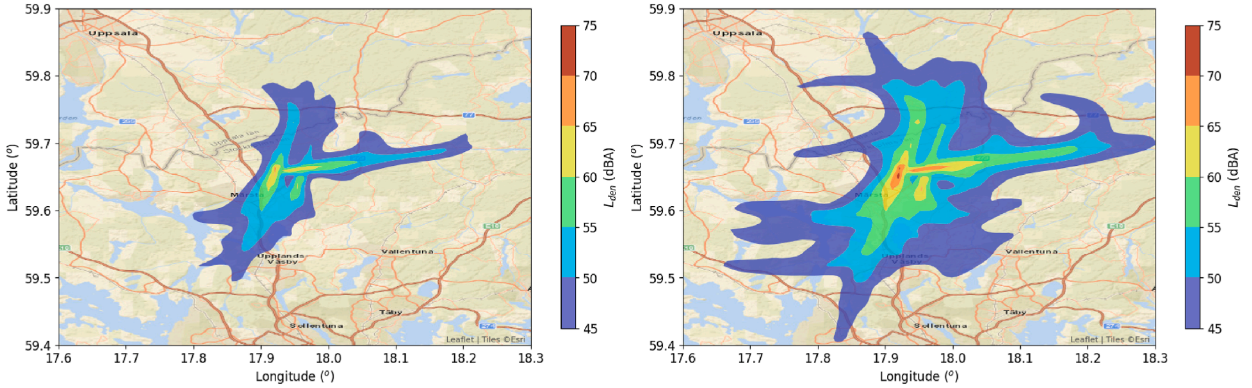
Emissions are calculated for every flight route and for every aircraft considering the domestic flights only. As the cost of emissions is not dependable on their cumulative effect, it has been decided to focus solely on the emissions from domestic flights aligning the scope with the electrification strategy. With the air traffic conditions as given in Section 3, the CO_2 mass for the 4 busiest routes and the total CO_2 emissions are listed in Table 6. For 2024, the total CO_2 emissions of the domestic flights departing from and arriving at Stockholm Airport is estimated as 0.257 million tonnes. Compared to the preliminary estimation of 0.27 million tonnes CO_2 from domestic air transport as published by the Swedish Environmental Protection Agency (Naturvåardsverket-the Swedish Environmental Protection Agency, 2025), the 5% lower value obtained from the presented model is considered reasonable given that the passengers traveling from/to Stockholm Airport through regular flights is about 98% of the total domestic travel demand, and the model incorporates a simplified aircraft fleet and a constant load factor assumption.

As travel demand projection increases by about 15% for 2035 compared to 2024, the estimated CO_2 emissions of 280424 tonnes, which is just about 9% increase, shows the benefit of introducing the first generation of hybrid electric aircraft on in-flight emissions.



(a) Domestic flights only with 2023 runway usage

(b) All flights included with 2023 runway usage



(c) Domestic flights only with 2024 runway usage

(d) All flights included with 2024 runway usage

Fig. 10. Day-evening-night noise level for the long-term, 2050, scenario, with current fleet frozen technology.

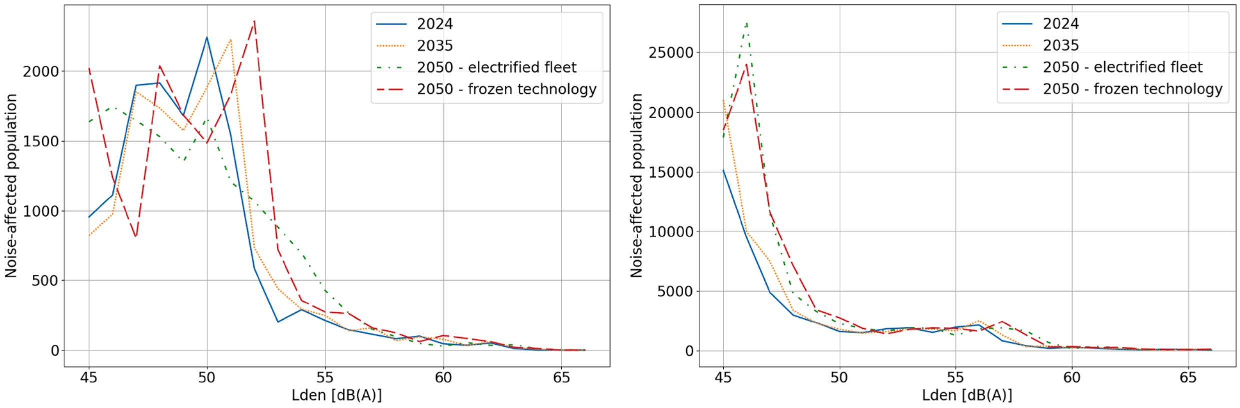
Table 6
CO_2 emissions (in tonnes) of the four scenarios for the 4 busiest routes and total CO_2 emissions for domestic flights.

Route	2024	2035	2050 - electrified fleet	2050 - frozen technology
Stockholm-Luleå	67553	77855	80672	94517
Stockholm-Umeå	37516	43215	44682	52475
Stockholm-Malmo	29194	33626	34695	40837
Stockholm-Gothenburg	26382	23445	0	36910
……				
Total (Domestic)	257130	280424	242081	359573
Total (Domestic LTO)	65258	57819	5062	91252

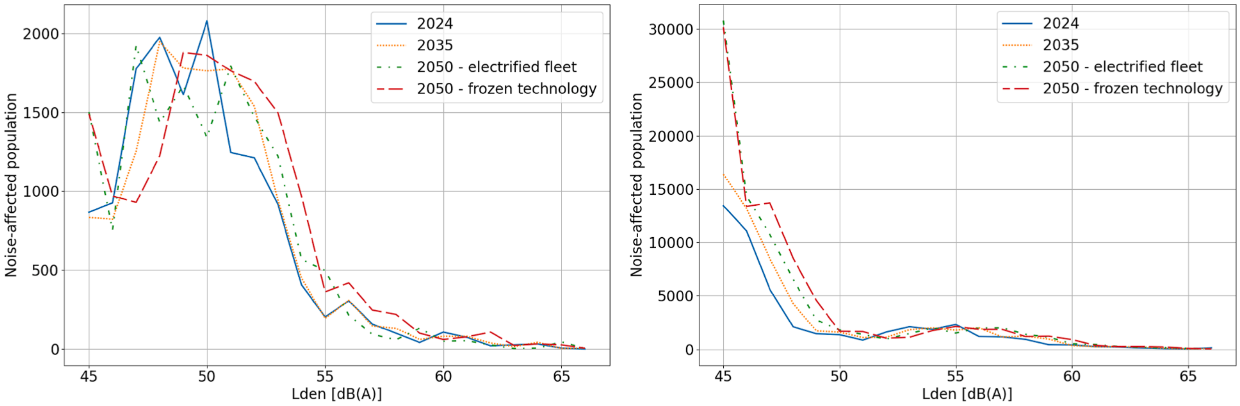
Moving to 2050, with the further development of the hybrid electric aircraft, the in-flight CO_2 emissions is expected to be lower than the level back to 2024. Comparing to the scenario of 2050 - frozen technology, a reduction of 33% can be achieved.

4.3. Socioeconomic cost-benefit assessment

In the previous sections, independent assessments of the noise and emissions impact of the introduction of hybrid-electric aircraft into Swedish air traffic were performed. In order to assess the combined effect, the results of a cost-benefit analysis, as described in



(a) Domestic flights only with 2023 runway usage (b) All flights included with 2023 runway usage



(c) Domestic flights only with 2024 runway usage (d) All flights included with 2024 runway usage

Fig. 11. Noise-affected population at different noise levels.

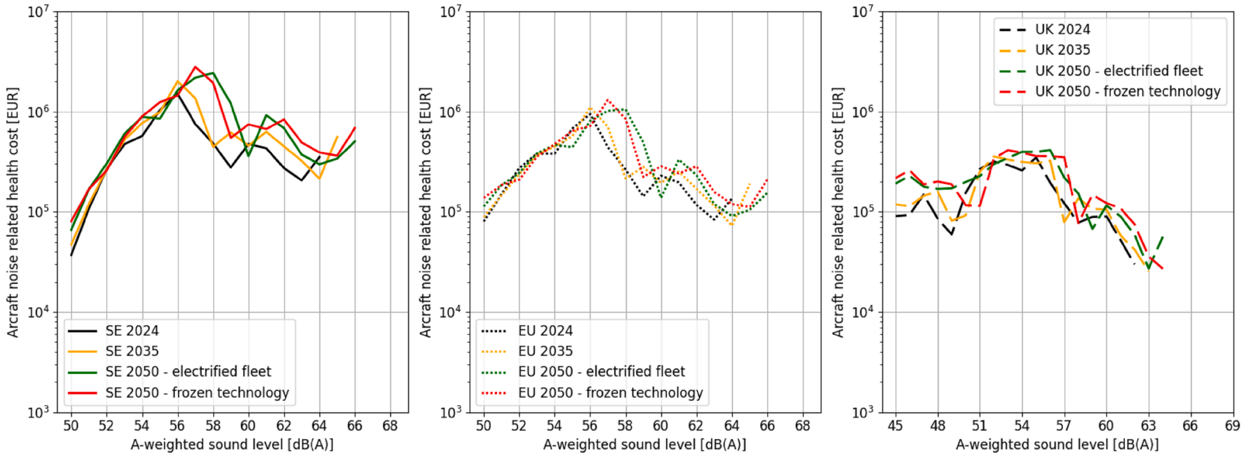
Section 3, are presented here. As previously mentioned, due to the cumulative effect of noise, only the noise results with all flights are considered.

A detailed cost analysis of the noise-affected population is presented in Fig. 12. The figure shows and compares the total costs for each scenario across noise levels, calculated using the noise cost tables recommended by the authorities of Sweden, the UK, and the EU. The cost presented for each level accounts for all the people that are affected by noise between that level and the next one, e.g., the cost for the noise level of 50 dBA refers to people experiencing noise equal to or above 50 dBA but below 51 dBA. The trend between the different scenarios is clear, as it is largely driven by the data presented in Fig. 11, with the two 2050 scenarios generally showing the highest cost at all noise levels.

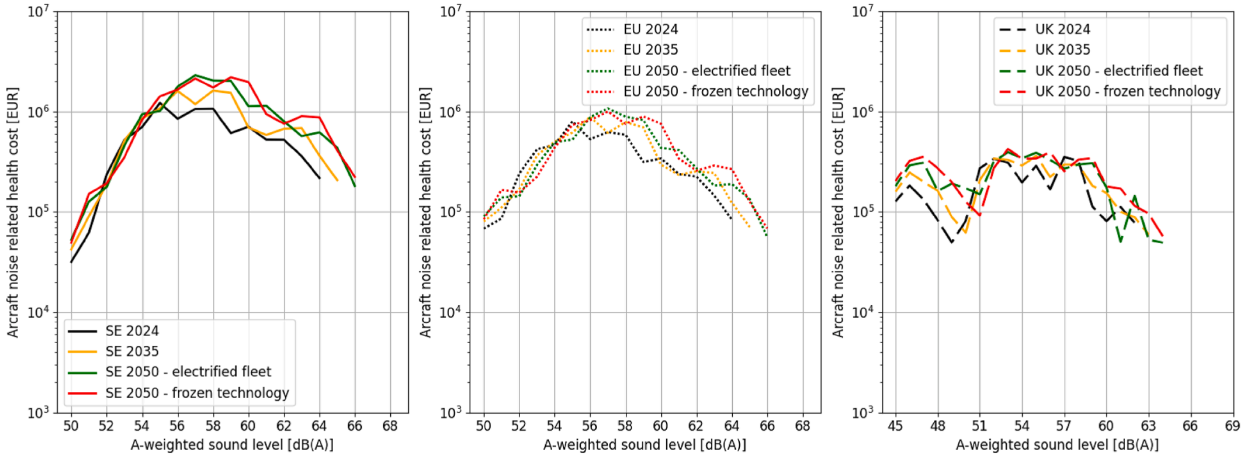
The total noise related health costs computed using the cost tables show a similar trend between the two 2050 scenarios as given in Table 7. The 2050 - electrified fleet scenario results in marginal cost differences relative to the 2050 - frozen technology scenario, using any cost table and runway usage. Although discrepancies exist in the noise results as presented in previous section which highlights the complexity and uncertainty, the conclusion from the socioeconomic cost-benefit assessment of noise related health impacts is consistent.

A more direct comparison between the results using different cost tables is illustrated in Fig. 13, where the noise cost in the calculation recommended by DEFRA UK is divided into day and night values. One noticeable outcome is that the noise cost from day time dominates the total noise cost from the calculation using UK cost table, except for the lower noise levels around $45 - 51$ dBA ($L_{eq,16h}$ and L_{night} values) where the night noise cost is at the same level or even surpasses the daytime noise cost. In addition, the night noise costs are rather stable for different scenarios, as a result of much lower flight movements during the night time. Nevertheless, the substantial growth in flight volume may lead to operational spillover into nighttime hours, as daytime traffic may exceed the airport's peak capacity limits.

A summary of noise related and CO_2 emissions costs are given in Table 7 for the scenarios investigated in this paper. As an indirect comparison, the socioeconomic cost prediction as presented in (Brodl et al., 2020) for exposure above 55 dBA from aviation noise (including all Swedavia airports and millitary operations) is estimated to be 70 million SEK (about 6400 kEUR) within Sweden in 2018.



(a) All flights included with 2023 runway usage

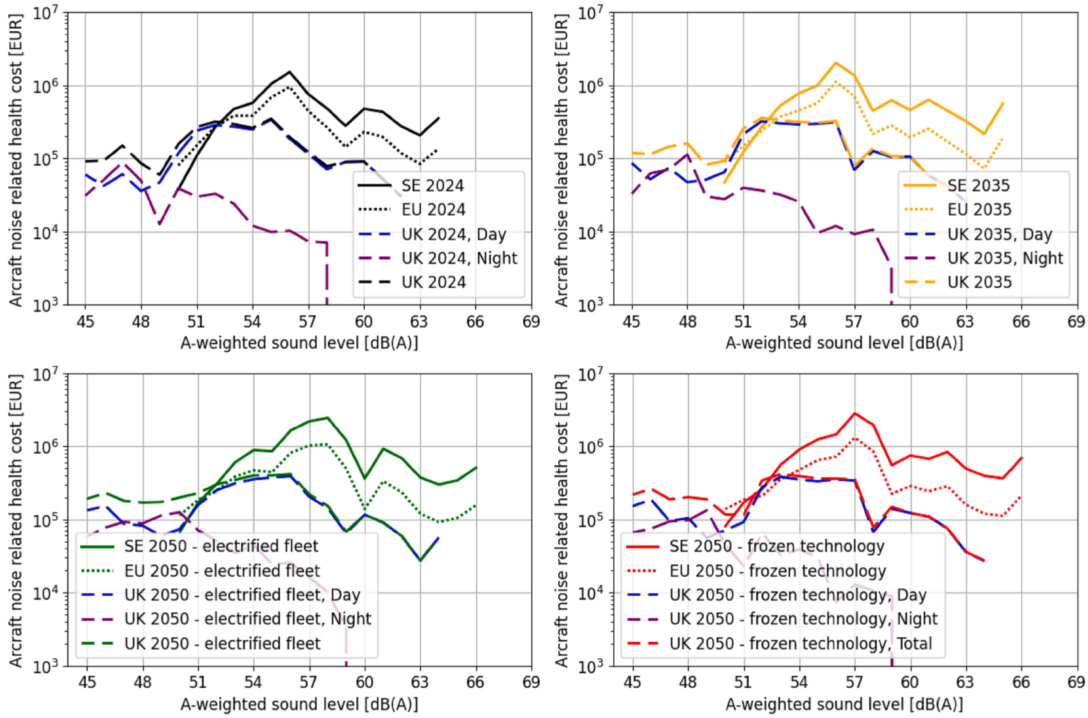


(b) All flights included with 2024 runway usage

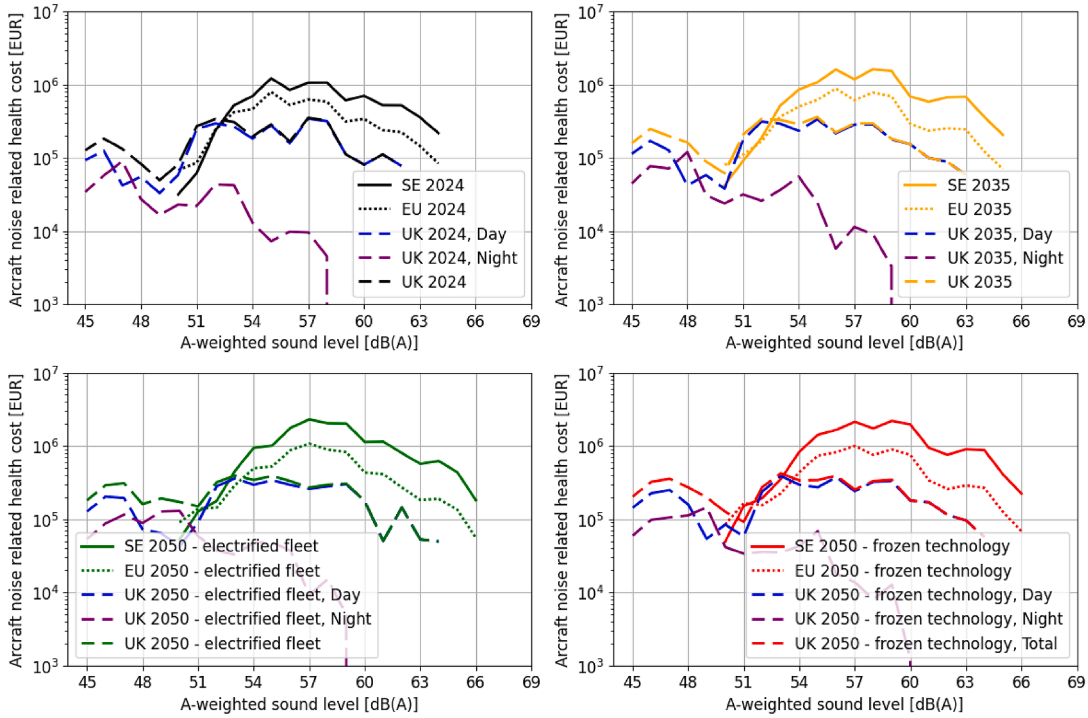
Fig. 12. Noise cost calculated using cost tables from authorities of Sweden, UK and EU; L_{den} at x axis for Sweden and EU; $L_{eq,16h}$ and L_{night} at x axis for UK.

Combining the forecast of ETS carbon price, the LTO CO_2 emissions cost is estimated as roughly 3.6 times for the 2035 scenario comparing to 2024. When looking at the 2050 scenarios, even though the CO_2 emissions could be reduced to a lower level than that of the 2024 scenario by the use of hybrid electric aircraft, the cost can still be as high as 6 times comparing to 2024. The highest carbon price is seen for the 2050 - frozen technology scenario which is almost 9 times high as for 2024 scenario. With the assumption of using electrical power for the entire LTO operation, as listed in the table the use of the electrified fleet could largely eliminate the LTO CO_2 emissions. One can therefore expect a similar reduction of the other emissions which are important for the local air quality, however, not the noise.

While the noise related cost is “only” increased by $33-87\%$ for the two 2050 scenarios compared to the 2024 scenario, one must keep in mind that the forecast of the noise cost tables is however just a $30-75\%$ increase for 2050 compared to 2024, and the adopted ETS carbon price forecast is a 6.4 times increase. This leads to a decrease of the ratio comparing the noise related cost to the carbon emissions cost, from $17-47\%$ in 2024 to $4-17\%$ in 2050 - for the electrified scenario, and $3-10\%$ for the frozen technology scenario. Nevertheless, the noise cost considered here is for the centered airport with all flights, while the CO_2 emissions are calculated for the entire mission with domestic only flights. Comparing local impacts, the adoption of electrical-power-only LTO operations may make the communities concentrate more on noise than emissions as the ratio between noise cost and LTO emissions can be more than doubled.



(a) All flights included with 2023 runway usage



(b) All flights included with 2024 runway usage

Fig. 13. Noise cost calculated using cost tables from authorities of Sweden, UK and EU;L_{den} at x axis for Sweden and EU; $L_{eq,16h}$ and L_{night} at x axis for UK.

Table 7
Total cost (in kEUR) for noise and emissions.

Cost (kEUR)	2024	2035	2050 - electrified fleet	2050 - frozen technology
Mission CO_2	16647	59762	100571	149382
LTO CO_2	4225	12322	2103	37910
Results with all flights included with 2023 runway usage				
Noise (SE)	8019	10488	14585	14880
Noise (EU)	4796	5403	6620	6738
Noise (UK)	2932	3306	4123	4256
Results with all flights included with 2024 runway usage				
Noise (SE)	9907	13324	17355	18509
Noise (EU)	5640	6512	7504	7890
Noise (UK)	3523	4063	4777	5118

5. Discussion and conclusion

Despite the notably reduced noise impact of hybrid-electric aircraft at single event, the increasing passenger demand and lower passenger capacities of hybrid electric aircraft will lead to more frequent flights, resulting in a larger cumulative noise contour area compared to modern fleets. In the present study, the total population affected by air traffic noise above 50 dBA (L_{den}, the threshold for noise related health cost consideration within EU) around Stockholm Arlanda airport assuming an electrified fleet was estimated to be about $2-3\%$ less than the case of frozen technology modern fleet, considering all flights using 2023 and 2024 runway usage data. Although the noise footprint pattern is altered and noise affected area is larger, the population affected by aircraft noise with the introduction of hybrid electric aircraft is not directly correlated due to the spatially distributed population around Arlanda airport and well-designed procedures. Furthermore, the constraint of applying electrified fleet to only domestic flights limits the influence of electrification.

The socioeconomic cost-benefit analysis showed consistent conclusions for the electrified fleet compared to the conventional fleet when the noise cost tables from different authorities and runway usage from different years were used. The 2050 - electrified fleet scenario shows lower noise related health cost which varies from $2-7\%$ relative to the 2050 - frozen technology scenario. When comparing with the 2024 baseline scenario, noise related health cost can be more than doubled in 2050 as long as the travel demand increase persists despite the fleet used.

In terms of emissions, the trend is clear. As the travel demand and carbon price continuously rise, the CO_2 emissions cost from the domestic flights departing from and arriving at the Arlanda airport can be expected to be 9 times higher compared to today for year 2050. The hybrid electric aircraft, as introduced in the presented study, can reduce the cost by 33%. In particular, at LTO phases, nearly no emissions operations can be expected while noise may become the major concern of the local communities.

Limited to the studied case, the noise related health cost for the selected airport was estimated based on all flights because of the cumulative effect of noise while the CO_2 emissions were calculated for domestic flights related to the airport. Based on this, comparing the two costs, the noise related cost is $17-47\%$ of the carbon cost in 2024, and drops to $4-17\%$ and $3-10\%$ for the two 2050 scenarios, electrified and frozen technology respectively. This decrease, however, is not due to the ease of noise related impact but mainly a result of an imbalanced price forecast between noise and carbon emissions.

Overall, from the study, some recommendations can be made for the development and utilization of electric and hybrid-electric aircraft:

- The development of low-passenger capacity hybrid-electric aircraft needs to be incorporated with the use of spatially distributed small airports to avoid concentrated noise footprint from frequent take-off and landing operations, and to ease the pressure on local air traffic management.
- Keeping the modern centralized airport mode would require the design of hybrid-electric aircraft moving closer to the passenger capacity of today's widely adopted aircraft models, which may set an even higher energy density requirement on the batteries.

6. Uncertainties and limitations

As the scope of the study focuses on the introduction of hybrid-electric aircraft into the Swedish domestic air traffic network and centered around the largest Swedish airport, limitations exist in some aspects.

First, compared to the domestic air traffic, the volume of international travel demand is about 4 times larger. According to the statistics published by the Swedish Environmental Protection Agency (Naturvårdsverket), the CO_2 emissions from international flights in 2024 is about 6.7 times higher than that from the domestic air traffic. The inclusion of international flights in emissions could dilute the impact of introducing regional radical concept for sustainable aviation. On the other hand, a common sense in the research community is that hybrid-electric aircraft is more applicable to the regional market, while the kick-off use of it is more feasible from a pair of cities in a single country due to differences in policy and infrastructure development across different countries. Hence the study has limited the scope considering these practical issues.

Second, there are some uncertainties with regard to the noise prediction methods, especially for the propeller noise. Although, the models have been assessed against noise measurements for turbofan aircraft, such data were not available for propeller aircraft. As briefly touched in the methodology, the propeller noise model was only compared with down-scaled propeller acoustics measurements. The propeller noise prediction adopted is rather simple and while the method is expected to capture the dominant tonal and broadband noise characteristics, deviations from actual levels may occur. Many propeller noise prediction models account for the propeller performance, including parameters such as blade loading. However, as the propeller performance was not studied in detail, this simplified method was implemented. Furthermore, as propeller noise is often dominated by low-frequency tonal components, the use of A-weighted metrics, which attenuate the low-frequency content, can fail to capture significant sound energy that causes annoyance. Consequently, the reported A-weighted noise levels may not be fully representative of annoyance effects and perhaps higher annoyance would be expected during the hybrid-electric and turboprop aircraft operation. However, as the cost estimation requires the A-weighted day-evening-night noise level, this metric was implemented in the study. Finally, the noise prediction of the hybrid-electric aircraft neglects interaction effects that would be present in a distributed propulsion system. Such effects are dependent on the phase angle of the propellers which can cause either constructive or destructive interference, as presented by Zarri and de Prenter (2025), and alternations in the frequency spectrum. Modeling of these effects would require detailed knowledge of the propeller operation and the relative phase relationships which is not evaluated in the present study. Hence, the prediction of interaction effects would be largely based of speculations and it is therefore considered appropriate to omit for the presented analysis.

Third, the CO_2 emissions analysis covers only the direct/in-flight emissions from fuel consumption. Since Sweden has a significantly high share of renewable electricity production, the CO_2 emissions from electricity generation has been neglected. A more general consideration, as adopted in Abu Salem et al. (2023a), Hoelzen et al. (2018), is a reference value of 0.42 kg CO_2/kWh provided by International Energy Agency IEA (2016), with ±50% trend assumptions. Using the reference value of CO_2 emissions for electricity generation, the total CO_2 emissions for 2035 and 2050 - electrified fleet scenarios are increased by 3.5% and 23.7% respectively. This diminishes the CO_2 emissions reduction potential, through the comparison of the two 2050 scenarios, to 16.7%, about half of the number as shown earlier. In addition to the electricity production emissions, when assuming the same usage frequency of the HE as the modern regional turboprops, the battery system would experience several charge/discharge cycles per day. Considering the high end of typical power battery's cycle life (1000-2000 cycles before degradation to 80% of the full capacity), replacement may be scheduled every year or two. That is saying, emissions from the production/cycling of batteries will be also a critical point to be considered, which is unfortunately not a topic that can be detailed in this study. According to Schäfer et al. (2019), Kim et al. (2016), values range from 39–196 kg of CO_2 equivalent per kWh were collected from electric vehicle's battery production data, while a more recent study (Xu et al., 2022) predicts 10–45 kg CO_2 equivalent per kWh in 2050. A simple calculation using the latter values suggests 9-41 tonnes of CO_2 emissions for the battery production used on the 2035 first generation HE aircraft and 18-79 tonnes CO_2 emissions for the 2050 HE aircraft. This is roughly $1.4 - 6.3\%$ increase in annual total CO_2 emissions for the 2050-electrified fleet scenario.

Fourth, the evaluation of aircraft noise impact on health is a combination of aircraft operation, traffic volume and planning, inhabitants' conditions and healthcare system development. The presented study utilizes a simplified method to integrate the widely spread disciplines to assess the overall effect based on a single airport. This is however a specific choice due to the fact that Nordic countries like Sweden have a very concentrated air traffic condition. Following the current domestic travel statistics, Stockholm will be affected the most when novel aircraft concept is adopted. Another feature of Nordic cities, even the largest ones, is the relatively low population and spatial residential conditions. This is particularly true for the area around the airports. A significantly larger impact should be expected when such a study is conducted for mega cities, such as in the central Europe or China. On top of that, a limitation of this study is that it does not consider dynamic population effects. The movement of people to work during the day and back to residential zones in the evening means that nighttime noise conditions may carry greater weight in terms of actual human exposure and impact. In addition, although the runway usage assumed in the study follows historical distribution data (still the historical runway usage varies from time to time), the assumption of an equal share of available procedures introduces a degree of uncertainty. However, this impact is considered limited as the procedures were developed under rigorous noise protocols, which is particularly true for the take-off procedures that a noise dispersion area is applied (Zhao et al., 2024). Moreover, the considered flights include only high precision navigation based procedures which is another simplification to avoid excessive computation and data exhaust for spatially spreading realistic air traffic paths. While meteorological conditions significantly influence traffic planning and noise propagation, they were excluded from this study due to the prohibitive computational cost associated with modeling complex atmospheric effects. In the end, although incorporating exhaustive detail may enhance the accuracy of a specific case study, it often reduces the model's generalizability to other scenarios. Adopting appropriate idealized conditions is therefore a strategic choice, as it could provide a representative baseline that reflects nominal operating conditions.

Finally, non-CO_2 climate impacts of aviation, which have been a strategic research focus since the 1970s, include the impacts from pollutions NO_x, CO, SO_x, HC and $nvPM$ as well as contrails. These non-CO_2 climate impacts are primarily characterized as short-lived and local/regional but have significant immediate warming impact (Lee et al., 2010; Azar and Johansson, 2012; Lee et al., 2023). While HE aircraft could potentially mitigate these unfavorable impacts, the high uncertainty in the non-CO_2 impacts makes it difficult to measure using standard monetary methods (Lee et al., 2010; Prather et al., 2025; Megill et al., 2024; Matthes et al., 2021), although related policy is on its way and financial measures could potentially be implemented in the short-term according to Lee et al. (2020), Niklaß et al. (2019). Studies do exist on the conceptual design of HE aircraft from local air quality and climate change point of view (Abu Salem et al., 2023b) and on all-electric aircraft from comprehensive prospects (Schäfer et al., 2019), from which the potential of eliminating local pollutions is one of the key conclusions from both studies. In most studies, the $CO_2 - eq$ is a measurement unit that is used to compare the climate impact of various greenhouse gases and is calculated using a factor, namely the global warming potential (GWP), which converts the amount of a non-CO_2 gas to the equivalent amount of carbon dioxide, Glossary (2001). The global warming potential values for various gases can be found in the IPCC Fifth Assessment Report, Myhre et al. (2013a). The GWP for NO_x among the non-CO_2 emissions has been the major topic of many studies, Lasek and Lajnert (2022), Köhler et al. (2013), Myhre et al. (2013b), as its impact on the greenhouse effect can vary depending on different parameters, from the type of activity, e.g. aviation, shipping, etc., to the geographical latitude where the activity is taking place. Here in this section, only NO_x is briefly discussed by considering an emissions index of conventional kerosene/JetA and SAF as proposed by Aamaas et al. (2025) together with the CO_2-eq value of 27 for NO_x as suggested by Köhler et al. (2013) for the 100-year time horizon for aviation within Europe. The emissions index given in Aamaas et al. (2025) for NO_x is the same value of 14.86 g/kg fuel for fossil kerosene/JetA and SAFs. These assumptions would lead to about 13% increase of CO_2-eq emissions cost for all cases.

Beyond the global warming impact, the impacts of the non-CO_2 emissions on near-airport residential air quality is more crucial to the people living nearby and is indeed a more critical trade-off to local noise impact. Nevertheless, studies including Schürmann et al. (2007), Lee et al. (2013), Yim et al. (2015), Hudda et al. (2020), Riley et al. (2021), Alzahrani et al. (2024) have all highlighted the complexity of local air quality assessment which is not possible with just macro scale of quantification of emissions. Learning from Kim et al. (2015), the evidence supporting quantitative health risk assessment is more limited for CO, NO_2, and SO_2, relative to ozone and fine PM, mainly because levels of these pollutants tend to be difficult to capture. Local meteorological conditions also significantly affect the impact which is, however, not possible for long-term forecast. Finally, an integrated detailed noise and local air quality assessment system is a future direction of evaluating sustainable aviation systems.

CRediT authorship contribution statement

Evangelia Maria Thoma: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization; **Xin Zhao:** Writing – review & editing, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Data availability

Data will be made available on request.

Acknowledgement

This work was financially supported and facilitated by the Swedish Transport Administration, Trafikverket, through the project - Noise Exposure in Future Air Traffic (NEFAT, TRV 2022/106392), and by the Chalmers Transport Area of Advance (SOT), under the project- Investigation of the impact of technological developments in batteries on Swedish future air transportation (BATSFLY).

References

Aamaas, B., Lund, M.T., Fuglestvedt, J.S., Totterdill, A., Owen, B., Skowron, A., Lee, D.S., 2025. Continued global warming from aviation even under high-ambition mitigation scenarios. One Earth 8 (10), 101451. https://doi.org/10.1016/j.oneear.2025.101451

Abu Salem, K., Palaia, G., Quarta, A.A., 2023a. Impact of figures of merit selection on hybrid-electric regional aircraft design and performance analysis. Energies 16 (23). https://doi.org/10.3390/en16237881

Abu Salem, K., Palaia, G., Quarta, A.A., Chiarelli, M.R., 2023b. Medium-range aircraft conceptual design from a local air quality and climate change viewpoint. Energies 16 (10). https://doi.org/10.3390/en16104013

Airbus, 2025. Ramping up a320 family production. https://www.airbus.com/en/newsroom/stories/2025-10-ramping-up-a320-family-production.

Aircraft Performance Database D328, n.d. https://contentzone.eurocontrol.int/aircraftperformance/details.aspx?ICAO=D328&.

Akbiyik, T., Öztürk, O., Yıldız, M., Kale, U., Kilikevičius, A., 2025. The future of hydrogen fuel in aviation: Economic analysis of current applications. Int. J. Hydrogen Energy 143, 650–658. https://doi.org/10.1016/j.ijhydene.2025.04.324

Alzahrani, S., Kılıç, D., Flynn, M., Williams, P.I., Allan, J., 2024. International airport emissions and their impact on local air quality: chemical speciation of ambient aerosols at madrid–barajas airport during the AVIATOR campaign. Atmos. Chem. Phys. 24 (16), 9045–9058.

Amadori, K., Jouannet, C., Zhao, X., 2023. Towards Zero-Emission Transportation in Scandinavia. https://doi.org/10.2514/6.2023-1909

ANP, 2023a. ANP legacy data EASA. https://www.easa.europa.eu/en/domains/environment/policy-support-and-research/aircraft-noise-and-performance-anp-data/anp-legacy-data#group-easa-dataset.

ASEK, 2024. Analysmetod och samhällsekonomiska kalkylvärden, ASEK - Bransch. https://bransch.trafikverket.se/for-dig-i-branschen/Planera-och-utreda/Samhallsekonomisk-analys-och-trafikanalys/samhallsekonomi/analysmetod-och-samhallsekonomiska-kalkylvardenasek/.

Avogadro, N., Redondi, R., 2024. Demystifying electric aircraft's role in aviation decarbonization: are first-generation electric aircraft cost-effective? Transp. Res. Part D Transp. Environ. 130, 104191.

Azar, C., Johansson, D. J.A., 2012. Valuing the non-CO2 climate impacts of aviation. Clim. Change 111 (3), 559–579.

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

Bradley, M.K., Droney, C.K., 2015. Subsonic Ultra Green Aircraft Research: Phase 2: Hybrid Electric Design Exploration - Volume 2. Technical Report. Langley Research Center. Hampton, Virginia. https://ntrs.nasa.gov/citations/20150017039.

Bristow, A.L., Wardman, M., Chintakayala, V. P.K., 2015. International meta-analysis of stated preference studies of transportation noise nuisance. Transportation 42 (1), 71–100.

Brodl, L., Andersson, S., Leung, W., Lindén, J., Villamor, G., Justesen, M., 2020. Mapping and socioeconomic analysis of transportation noise in Sweden, 2018.

Cui, Q., Chen, B., 2024. Cost-benefit analysis of using sustainable aviation fuels in South America. J. Cleaner Prod. 435, 140556. https://doi.org/10.1016/j.jclepro.2024.140556

Da-Ronch, A., Liu, Y., Luo, M., Yildiz, B., Förster, P., Feuerle, T., Hecker, P., 2024. Flow-based assessment of the impact of an all-electric aircraft on european air traffic. Aerospace 11 (8), 602. https://doi.org/10.3390/AEROSPACE11080602

Dickens, R., Angulo, M., Turner, S., Gill, J., Abdul, M., Hirani, H., 2014. Environmental noise: valuing impacts on: sleep disturbance, annoyance, hypertension, productivity and quiet. Kew London, United Kingdom Nat. Archives.
Dunn, D.G., Peart, N.A., 1973. Aircraft Noise Source and Contour Estimation. Technical Report NASA-CR-114649. NASA. Boeing Commercial Airplane Co. Seattle, WA, United States.
E-Fan X-Airbus, 2020. E-Fan X—Airbus. https://www.airbus.com/en/innovation/low-carbon-aviation/hybrid-and-electric-flight/e-fan-x.
EASA, 2025. Type Certificate Data Sheets (TCDS). https://www.easa.europa.eu/en/document-library/type-certificates?search = 328&year = &year_to = .
EcoPulse, 2024. EcoPulse—Airbus. https://www.airbus.com/en/innovation/energy-transition/hybrid-and-electric-flight/ecopulse.
EntryScape Tabular Data, 2025. EntryScape Tabular Data API. https://transportstyrelsen.entryscape.net/rowstore/dataset/4742f5c5-e877-4baa-b45c-4e3ab39a629e/html.
ES-30, 2025. ES-30™—Heart Aerospace. https://heartaerospace.com/es-30/.
EUROCONTROL, 2022. EUROCONTROL Aviation Outlook 2050 Main Report. Technical Report. EUROCONTROL. https://www.eurocontrol.int/sites/default/files/2022-04/eurocontrol-aviation-outlook-2050-main-report.pdf.
European Aviation Environmental Report, 2025. European Aviation Environmental Report. https://www.easa.europa.eu/en/domains/environment/eaer/aviation-environmental-impacts/noise.
EUROCONTROL, 2025. Eurocontrol standard inputs for economic analyses. Release 10.0.1.
Farooq, Z., Wetterlund, E., Mesfun, S., Furusjö, E., 2025. Uncovering the economic potential of sustainable aviation fuel production pathways: a meta-analysis of techno-economic studies. Energy Convers. Manage. 341, 120076. https://doi.org/10.1016/j.enconman.2025.120076
Fink, M.R., 1977. Airframe Noise Prediction Method. Technical Report FAA-RD-77-29. Federal Aviation Administration (FAA). Washington, D.C.
Fink, M.R., 1979. Noise component method for airframe noise. J. Aircr. 16 (10), 659–665. https://doi.org/10.2514/3.58586
Geyer, T.F., Enghardt, L., 2023. Conceptual estimation of the noise reduction potential of electrified aircraft engines. Acta Acust. 7, 22. https://doi.org/10.1051/AACUS/2023009
Gliebe, P., Mani, R., Connell, S., Salamah, S., Sober, J., Coffin, R., 2022. AST Critical Propulsion and Noise Reduction Technologies for Future Commercial Subsonic Engines Aeroacoustic Prediction Codes - Supplement: Code Descriptions and Users Guides. Technical Report NASA-CR-20220004640. NASA Glenn Research Center. Cleveland, Ohio, Contractor Report (CR).
Gliebe, P., Mani, R., Shin, H., Mitchell, B., Ashford, G., Salamah, S., Connell, S., 2000. Aeroacoustic Prediction Codes. Technical Report NASA/CR-2000-210244. NASA. Glenn Research Center.
Global Human Settlement, 2023b. Global Human Settlement - Download - European Commission. https://ghsl.jrc.ec.europa.eu/download.php?ds = pop.
Glossary:Carbon dioxide equivalent - Statistics Explained - Eurostat, 2001. https://ec.europa.eu/eurostat/statistics-explained/index.php?title = Glossary:Carbon_dioxide_equivalent.
PACE Aerospace Engineering & Information Technology GmbH, 2022. Preliminary aircraft & systems design - pacelab APD egineering workbench 8.1.
Grewe, V., 2020. Aviation emissions and climate impacts. In: Aviation and climate change. Routledge, pp. 4–15.
Grewe, V., Gangoli Rao, A., Grönstedt, T., Xisto, C., Linke, F., Melkert, J., Middel, J., Ohlenforst, B., Blakey, S., Christie, S., et al., 2021. Evaluating the climate impact of aviation emission scenarios towards the paris agreement including COVID-19 effects. Nat. Commun. 12 (1), 3841.
Grönstedt, T., 2000. Development of methods for analysis and optimization of complex jet engine systems. Ph.D. thesis. Chalmers University of Technology. Gothenburg, Sweden.
Grönstedt, T., Au, D., Kyprianidis, K.G., Ogaji, S., 2009. Low-Pressure System Component Advancements and Its Influence on Future Turbofan Engine Emissions. In: Proceedings of ASME Turbo Expo 2009: Power for Land, Sea and Air. Orlando, Florida, USA. https://doi.org/10.1115/GT2009-60201
Group, W.B., 2025. Carbon pricing dashboard. https://carbonpricingdashboard.worldbank.org/.
Heidmann, M.F., 1979. Interim Prediction Method for Fan and Compressor Source Noise. Technical Report NASA-TM-X-71763. NASA. Lewis Research Center, Cleveland, Ohio.
Hoelzen, J., Liu, Y., Bensmann, B., Winnefeld, C., Elham, A., Friedrichs, J., Hanke-Rauschenbach, R., 2018. Conceptual design of operation strategies for hybrid electric aircraft. Energies 11 (1). https://doi.org/10.3390/en11010217
Hudda, N., Durant, L.W., Fruin, S.A., Durant, J.L., 2020. Impacts of aviation emissions on near-airport residential air quality. Environ. Sci. Technol. 54 (14), 8580–8588.
Huff, D.L., Henderson, B.S., Envia, E., 2016. Motor noise for electric powered aircraft. in: 22nd AIAA/CEAS Aeroacoustics Conference, 2016 https://doi.org/10.2514/6.2016-2882
IAIP, 2025. IAIP - ESSA STOCKHOLM/Arlanda. https://aro.lfv.se/Editorial/View/IAIP?folderId = 55.
International Energy Agency IEA, 2016. Recent trends in the OECD: energy and CO2 emissions.
Jägemar, K., Forsström, T., 2024. Miljörapport 2023 Stockholm Arlanda Airport Swedavia AB Stockholm Arlanda Airport. Technical Report. Swedavia AB. Stockholm. https://www.swedavia.se/.
Jägemar, K., Forsström, T., 2025. Miljörapport 2024 Stockholm Arlanda Airport Swedavia AB Stockholm Arlanda Airport. Technical Report. Swedavia AB. Stockholm. https://www.swedavia.se/.
Juretzko, P.G., Immer, M., Wildi, J., 2020. Performance analysis of a hybrid-electric retrofit of a RUAG Dornier Do 228NG. CEAS Aeronaut. J. 11 (1), 263–275. https://doi.org/10.1007/S13272-019-00420-2/FIGURES/15
Kim, B., Nakada, K., Wayson, R., Christie, S., Paling, C., Bennett, M., Raper, D., Raps, V., Levy, J., Roof, C., 2015. Understanding Airport Air Quality and Public Health Studies Related to Airports. Project 02-42.
Kim, H.C., Wallington, T.J., Arsenault, R., Bae, C., Ahn, S., Lee, J., 2016. Cradle-to-gate emissions from a commercial electric vehicle li-ion battery: a comparative analysis. Environ. Sci. Technol. 50 (14), 7715–7722.
Kinene, A., Birolini, S., 2024. Optimization of subsidized air transport networks using electric aircraft. Transp. Res. Part B Methodol. 190, 103065. https://doi.org/10.1016/J.TRB.2024.103065
Klophaus, R., Lauth, G.J., 2022. Monetary mapping of the climate footprint of air travel to a single airport. J. Air Transp. Manage. 101, 102204. https://doi.org/10.1016/j.jairtraman.2022.102204
Köhler, M.O., Rädel, G., Shine, K.P., Rogers, H.L., Pyle, J.A., 2013. Latitudinal variation of the effect of aviation NOx emissions on atmospheric ozone and methane and related climate metrics. Atmos. Environ. 64, 1–9. https://doi.org/10.1016/J.ATMOSENV.2012.09.013
Kontos, K.B., Janardan, B.A., Gliebe, P.R., 1996. Improved NASA-ANOPP Noise Prediction Computer Code for Advanced Subsonic Propulsion Systems. Technical Report 195480. NASA Lewis Research Center. Cincinnati, OH United States. https://ntrs.nasa.gov/citations/19960048499.
Lasek, J.A., Lajnert, R., 2022. On the issues of NOx as Greenhouse gases: an ongoing discussion…. Appl. Sci. 2022, Vol. 12, Page 10429 12 (20), 10429. https://doi.org/10.3390/APP122010429
Lee, D., Arrowsmith, S., Skowron, A., Owen, B., Sausen, R., Boucher, O., Faber, J., Marianne, L., Fuglestvedt, J., van Wijngaarden, L., 2020. Updated analysis of the non-CO2 climate impacts of aviation and potential policy measures pursuant to EU Emissions Trading System Directive Article 30 (4). European Aviation Safety Agency.
Lee, D.S., Allen, M.R., Cumpsty, N., Owen, B., Shine, K.P., Skowron, A., 2023. Uncertainties in mitigating aviation non-CO2 emissions for climate and air quality using hydrocarbon fuels††electronic supplementary information (ESI) available. Environ. Sci. Atmosp. 3 (12), 1693–1740. https://doi.org/10.1039/d3ea00091e
Lee, D.S., Fahey, D.W., Forster, P.M., Newton, P.J., Wit, R. C.N., Lim, L.L., Owen, B., Sausen, R., 2009. Aviation and global climate change in the 21st century. Atmos. Environ. 43 (22), 3520–3537. https://doi.org/10.1016/j.atmosenv.2009.04.024
Lee, D.S., Pitari, G., Grewe, V., Gierens, K., Penner, J.E., Petzold, A., Prather, M.J., Schumann, U., Bais, A., Berntsen, T., et al., 2010. Transport impacts on atmosphere and climate: Aviation. Atmos. Environ. 44 (37), 4678–4734.
Lee, H., Olsen, S.C., Wuebbles, D.J., Youn, D., 2013. Impacts of aircraft emissions on the air quality near the ground. Atmos. Chem. Phys. 13 (11), 5505–5522.
Liu, H., Zhao, X., Li, J., Feng, Y., Zhang, L., 2025. Noise reduction of distributed propulsion by optimized phase synchronization. J. Propul. Power 41 (2), 113–124.

Marciello, V., Cusati, V., Nicolosi, F., Saavedra-Rubio, K., Pierrat, E., Thonemann, N., Laurent, A., 2024. Evaluating the economic landscape of hybrid-electric regional aircraft: a cost analysis across three time horizons. Energy Convers. Manage. 312, 118517.

Matthes, S., Lim, L., Burkhardt, U., Dahlmann, K., Dietmüller, S., Grewe, V., Haslerud, A.S., Hendricks, J., Owen, B., Pitari, G., Righi, M., Skowron, A., 2021. Mitigation of non-CO2 aviation's climate impact by changing cruise altitudes. Aerospace 8 (2). https://doi.org/10.3390/aerospace8020036

Megill, L., Deck, K., Grewe, V., 2024. Alternative climate metrics to the global warming potential are more suitable for assessing aviation non-CO2 effects. Commun. Earth Environ. 5 (1), 249.

Melkersson, M., Holmström, A., 2025. Trafikanalys - Luftfart. https://www.trafa.se/luftfart2/luftfart/.

Mitici, M., Pereira, M., Oliviero, F., 2022. Electric flight scheduling with battery-charging and battery-swapping opportunities. EURO J. Transp. Logist. 11, 100074. https://doi.org/10.1016/J.EJTL.2022.100074

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013a. Anthropogenic and Natural Radiative Forcing. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report. Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA. https://www.ipcc.ch/report/ar5/wg1/anthropogenic-and-natural-radiative-forcing/.

Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., Zhang, H., 2013b. Anthropogenic and Natural Radiative Forcing Supplementary Material. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical Report. Cambridge University Press. Cambridge, United Kingdom and New York, NY, USA.

Naturvåardsverket-the Swedish Environmental Protection Agency, 2025. Inrikes transporter, utsläpp av växthusgaser. https://www.naturvardsverket.se/data-och-statistik/klimat/vaxthusgaser-utslapp-fran-inrikes-transporter/.

Niklaß, M., Dahlmann, K., Grewe, V., Maertens, S., Plohr, M., Scheelhaase, J., Schwieger, J., Brodmann, U., Kurzböck, C., Schweizer, N., et al., 2019. Integration of Non-CO2 Effects of Aviation in the EU ETS and under CORSIA. Umweltbundesamt.

Park, J.-e., Muennig, P.A., Zafari, Z., 2025. Projecting the economic burden of health impacts of aircraft noise: a case study of baltimore washington international thurgood marshall airport. J. Exposure Sci. Environ. Epidemiol. 35 (1), 107–117.

Pascioni, K.A., Rizzi, S.A., Schiller, N., 2019. Noise reduction potential of phase control for distributed propulsion vehicles. In: AIAA Scitech 2019 Forum, p. 1069.

Prather, M.J., Gettelman, A., Penner, J.E., 2025. Trade-offs in aviation impacts on climate favour non-CO2 mitigation. Nature 643 (8073), 988–993.

Quaroni, L.N., Merino-Martinez, R., Monteiro, F.d., Kumar, S.S., 2024. Collective blade pitch angle effect on grid turbulence ingestion noise by an isolated propeller. In: 30th AIAA/CEAS Aeroacoustics Conference (2024), p. 3209.

Quaroni, L.N., Sinnige, T., Merino-Martinez, R., 2025. Investigation of noise generation by a model-propeller in turbulent inflow through advanced signal processing techniques. In: AIAA Aviation Forum and Ascend 2025, p. 3147.

Rahul, S., Hardy, B., Yamamoto, K., Guo, Y.-P., Miller, G., 2004. Airframe Noise Sub-Component Definition and Model. Technical Report NASA/CR-2004-213255. NASA. Langley Research Center, Hampton, Virginia.

Raihan, A., 2025. Sustainable aviation: A critical review of policies, technologies, and future pathways. J. Air Transp. Res. Soc. 5, 100080.

Riboldi, C. E.D., Trainelli, L., Mariani, L., Rolando, A., Salucci, F., 2020. Predicting the effect of electric and hybrid-electric aviation on acoustic pollution. Noise Mapping 7 (1), 35–56. https://doi.org/10.1515/noise-2020-0004

Riley, K., Cook, R., Carr, E., Manning, B., 2021. A systematic review of the impact of commercial aircraft activity on air quality near airports. City Environ. Interact. 11, 100066.

Rodríguez-Sanz, Á., Rubio Andrada, L., 2023. Cost-benefit analysis of investments in air traffic management infrastructures: a behavioral economics approach. Aerospace 10 (4). https://doi.org/10.3390/aerospace10040383

Russel, J.W., 1984. An empirical method for predicting the mixing noise levels of subsonic circular and coaxial jets. Technical Report NASA-CR-3786. NASA. Langley Research Center, Hampton, VA, United States.

Sahoo, S., Zhao, X., Kyprianidis, K., 2020. A review of concepts, benefits, and challenges for future electrical propulsion-based aircraft. Aerospace 7 (4). https://doi.org/10.3390/aerospace7040044

Salem, K.A., Palaia, G., Quarta, A.A., 2023. Review of hybrid-electric aircraft technologies and designs: Critical analysis and novel solutions. Prog. Aerosp. Sci. 141, 100924.

Schäfer, A.W., Barrett, S. R.H., Doyme, K., Dray, L.M., Gnadt, A.R., Self, R., O'Sullivan, A., Synodinos, A.P., Torija, A.J., 2018. Technological, economic and environmental prospects of all-electric aircraft. Nat. Energy 4 (2), 160–166. https://doi.org/10.1038/s41560-018-0294-x

Schäfer, A.W., Barrett, S. R.H., Doyme, K., Dray, L.M., 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.

Schürmann, G., Schäfer, K., Jahn, C., Hoffmann, H., Bauerfeind, M., Fleuti, E., Rappenglück, B., 2007. The impact of NOx, CO and VOC emissions on the air quality of zurich airport. Atmosp. Environ. 41 (1), 103–118.

Shoukat, R., Redondi, R., 2025. Ghg emissions evaluation of conventional, electric, hybrid, biofuel, and hydrogen aircraft. J. Air Transp. Res. Soc. 4, 100067.

Staats, A.N., Troeltsch, F., Bardenhagen, A., 2025. Conceptual design of a hybrid-electric aircraft based on a dornier 328 demonstrator. Aerospace 12 (12), 1085.

Statista, 2025. Number of households in sweden from 2013 to 2023. https://www.statista.com/statistics/526001/sweden-number-of-households/.

Swedavia, 2025a. Flygstatistik. https://www.swedavia.se/om-swedavia/statistik/.

Swedavia, 2025b. Stockholm Arlanda Airport Scheduling declaration summer 2026 - Appendix 1 - Coordination Parameters at Stockholm Arlanda Airport. Technical Report. Swedavia AB. Stockholm. https://airportcoordination.com/wp-content/uploads/2025/10/ARN_S26_CP.pdf.

Swedavia, 2026. Stockholm arlanda airport information. https://www.swedavia.se/arlanda/grannar.

Synodinos, A.P., Self, R.H., Torija, A.J., 2018. Preliminary noise assessment of aircraft with distributed electric propulsion. 2018 AIAA/CEAS Aeroacoust. Conf. https://doi.org/10.2514/6.2018-2817

Thoma, E.M., 2024. Aircraft Noise Prediction: from Trajectory to Synthesis. Ph.D. thesis. Chalmers University of Technology. https://research.chalmers.se/en/publication/540965.

Thoma, E.M., Grönstedt, T., Otero, E., Zhao, X., 2023. Assessment of an open-source aircraft noise prediction modelusing approach phase measurements. J. Aircr. https://doi.org/10.2514/1.C037332

Thoma, E.M., Grönstedt, T., Zhao, X., 2020. Quantifying the environmental design trades for a state-of-the-art turbofan engine. Aerospace 7 (10). https://doi.org/10.3390/aerospace7100148

Thoma, E.M., Zhao, X., 2025. Analysis of noise optimal approach procedures with on-site statistical meteorological effects. In: Towards Sustainable Aviation Summit, TSAS2025 proceedings. Toulouse, France. https://doi.org/10.60711/TSAS25.20250302.7445355283170957

Thoma, E.M., Zhao, X., Grönstedt, T., 2022. CHOICE - CHalmers nOIse CodE. https://github.com/emthm/CHOICE.

Turboprop, 2025. D328 Turboprop. https://www.deutscheaircraft.com/products/d328-turboprop.

Van Essen, H., Van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., Brambilla, M., Fiorello, D., Fermi, F., Parolin, R., et al., 2019. Handbook on the external costs of transport, version 2019. 18.4 K83. 131.

Voskuijl, M., van Bogaert, J., Rao, A.G., 2018. Analysis and design of hybrid electric regional turboprop aircraft. CEAS Aeronaut. J. 9 (1), 15–25. https://doi.org/10.1007/S13272-017-0272-1/TABLES/3

Wandelt, S., Blom, H., Krömer, M.M., Li, D., Mitici, M., Ryley, T., Stumpf, E., Wang, K., Yang, B., Zanin, M., et al., 2025. Design and be smart: Eleven engineering challenges to achieve sustainable air transportation under safety assurance in the year 2050. J. Air Transp. Res. Soc. 4, 100045.

Withanachchi, O.W., 2024. Analysis of Passenger Demand for Electric Air Transportation in Sweden. https://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-208775.

World Health Organization, 2024. Compendium of WHO and other UN guidance on health and environment: version with International Classification of Health Intervention (ICHI) codes. World Health Organization.

Xu, C., Steubing, B., Hu, M., Harpprecht, C., van der Meide, M., Tukker, A., 2022. Future greenhouse gas emissions of automotive lithium-ion battery cell production. Resour. Conserv. Recycl. 187, 106606. https://doi.org/10.1016/j.resconrec.2022.106606

Yim, S. H.L., Lee, G.L., Lee, I.H., Allroggen, F., Ashok, A., Caiazzo, F., Eastham, S.D., Malina, R., Barrett, S. R.H., 2015. Global, regional and local health impacts of civil aviation emissions. Environ. Res. Lett. 10 (3), 034001.

Zarri, A., de Prenter, F., 2025. Numerical investigation on tonal noise directivity in distributed propulsion systems. In: 11th Convention of the European Acoustics Association (Euronoise). European Acoustics Association, EAA, pp. 1705–1710.

Zhao, X., Ziverts, U., Ekstrand, H., Ullvetter, M., Lukic, P., Näs, A., Olsson, E., Ridal, M., Johansson, Å., Wall, M., et al., 2024. Curved flight procedure construction with site-specific statistical meteorological data: a Swedish example. J. Air Transp. Manage. 121, 102694.

Zumegen, C., Strathoff, P., Stumpf, E., Wensveen, J.v., Rischmüller, C., Hornung, M., Geiß, I., Strohmayer, A., 2022. Technology selection for holistic analysis of hybrid-electric commuter aircraft. CEAS Aeronaut. J. 13 (3), 597–610.