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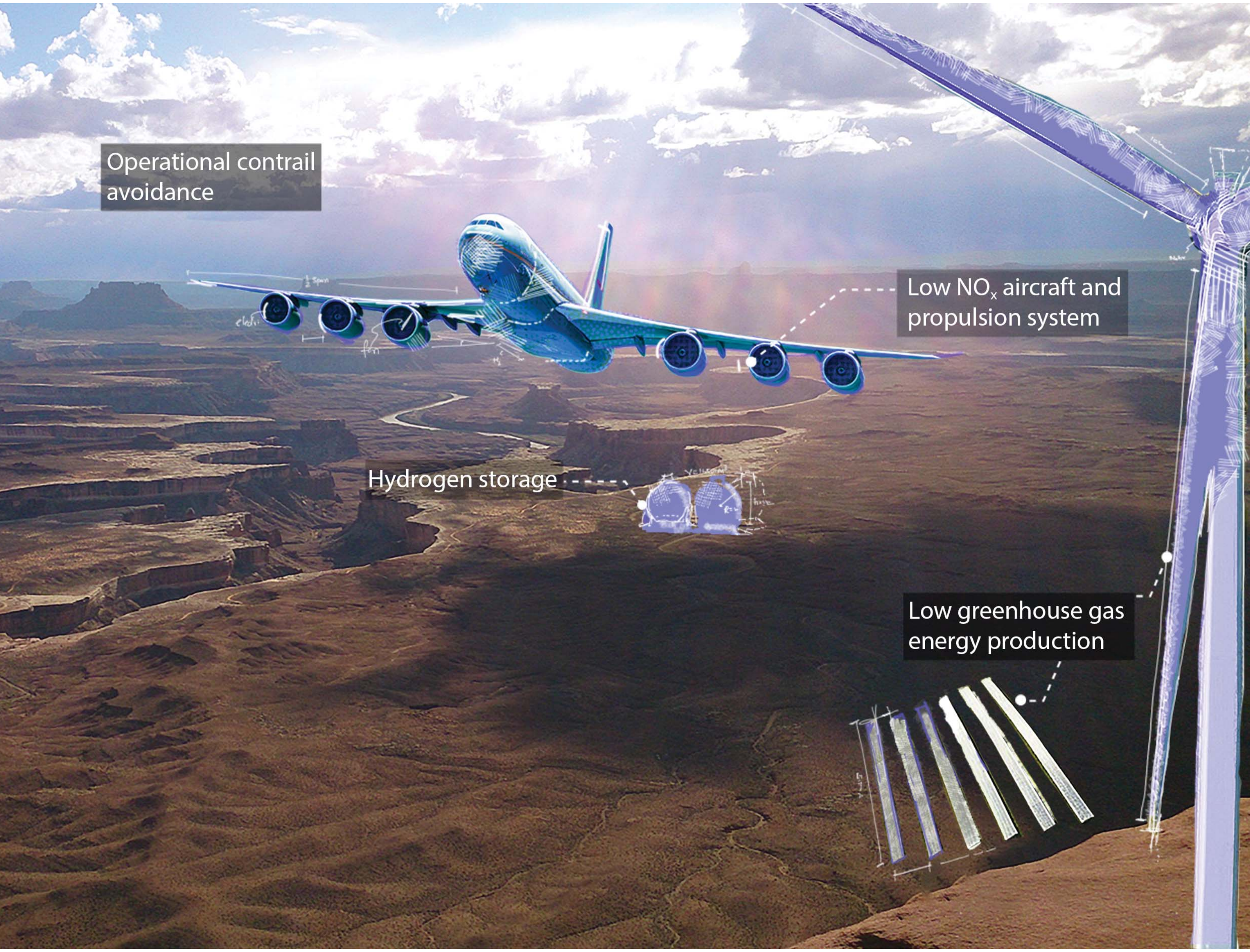

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ROYAL SOCIETY OF **CHEMISTRY**

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Prakash Prashanth, Steven R. H. Barrett *et al.*
Near-zero environmental impact aircraft

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Near-zero environmental impact aircraft†

Prakash Prashanth, * Jad Elmourad, Carla Grobler, Stewart Isaacs, Syed Shayan Zahid, James Abel, Christoph Falter, Thibaud Fritz, Florian Allroggen, Jayant S. Sabnis, Sebastian D. Eastham, Raymond L. Speth and Steven R. H. Barrett *

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The fundamental challenge facing today's aviation industry is to achieve net zero climate impacts while simultaneously sustaining growth and global connectivity. Aviation's impact on surface air quality, which is comparable to aviation's climate impact when monetized, further heightens this challenge. Prior studies have proposed solutions that aim to mitigate either aviation's climate or air quality impacts. No previous work has proposed an aircraft-energy system that simultaneously addresses both aviation's climate and air quality impacts. In this paper we (1) use a multi-disciplinary design approach to optimize aircraft and propulsion systems, (2) estimate lifecycle costs and emissions of producing sustainable fuels including the embodied emissions associated with electricity generation and fuel production, (3) use trajectory optimization to quantify the fuel penalty to avoid persistent contrail formation based on a full year of global flight operations (including, for the first time, contrail avoidance for a hydrogen burning aircraft), and (4) quantify climate and air quality benefits of the proposed solutions using a simplified climate model and sensitivities derived from a global chemistry transport model. We propagate uncertainties in environmental impacts using a Monte-Carlo approach. We use these models to propose and analyze near-zero environmental impact aircraft, which we define as having net zero climate warming and a greater than 95% reduction in air quality impacts relative to present day. We contrast the environmental impacts of today's aircraft-energy system against one built around either "drop-in" fuels or hydrogen. We find that a "zero-impact" aircraft is possible using either hydrogen or power-to-liquid "drop-in" fuels. The proposed aircraft-energy systems reduce combined climate and air quality impacts by 99%, with fuel costs increasing by 40% for hydrogen and 70% for power-to-liquid fueled aircraft relative to today's fleet (*i.e.*, within the range of historical jet fuel price variation). Beyond the specific case presented here, this work presents a framework for holistic analysis of future aviation systems that considers both climate and air quality impacts.

1. Introduction

Aviation plays a crucial role in connecting people and enabling global trade. However, emissions from aviation result in adverse environmental impacts. Forecasts[1–3] suggest that aviation attributable carbon dioxide (CO_2) emissions in 2050 could be 1.5 to 2.4 times the emissions in 2019 (accounting for several COVID-19 related recovery scenarios). Aviation emissions of CO_2 currently account for ~2.5% of global anthropogenic CO_2 emissions,[4] however, as other sectors decarbonize aviation may become a significant contributor[5] to anthropogenic CO_2 emissions posing an existential challenge to aviation.

To address this challenge, the sector has committed to increasingly stringent decarbonization goals such as the International Air Transport Association (IATA) 2021 resolutions to achieve net-zero CO_2 emissions by 2050.[6] National governments have also set similar goals, such as the US Aviation Climate Action plan[7] or the UK Jet Zero[8] strategy. However, assessments have shown that the aviation industry is not yet on track to meet older, less ambitious commitments such as the IATA 2009 goal of a 50% net reduction in CO_2 emissions by 2050 relative to 2005.[9–11] Furthermore, aviation's climate impacts are not limited to those caused by in-flight CO_2 emissions. Lee *et al.*[4] report that 66% of aviation's net effective radiative forcing (ERF) is caused by non-CO_2 emissions, specifically condensation trails (contrails) and contrail-cirrus, oxides of nitrogen and sulfur (NO_x and SO_x), water vapor (H_2O), and soot.

Exacerbating the challenge is aviation's contribution to air pollution. Aviation emissions of NO_x and SO_x have been associated with ~24 000 premature mortalities each year[12] due to increased population exposure to ozone and particulate matter

Laboratory for Aviation and the Environment, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge MA, USA. E-mail: sbarrett@mit.edu; prash@mit.edu

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($PM_{2.5}$). The total air quality and climate impact of aviation (including fuel lifecycle emissions) is estimated at 1600 USD per tonne of jet fuel burned (∼2 times the impact of in-flight CO_2 emissions alone), of which 32% is due to degraded air quality (see ESI, Section S1†). To holistically evaluate the environmental impacts due to novel technology or policy, both the air quality and climate impacts of aviation (including fuel life-cycle emissions and non-CO_2 climate forcers) need to be quantified.

Prior studies have quantified or proposed solutions that address one or two aspects of aviation's environmental impact. Older assessments,[9,10] for example, cover only climate impacts due to CO_2. A recent meta-assessment of aviation environmental impacts by Lee *et al.*[4] estimates the climate impacts due to aviation CO_2 and non-CO_2 sources but does not quantify aviation's air pollution impacts (∼1/3rd of aviation's environmental impact). Numerous recent studies that have assessed energy and CO_2 pathways to reduce aviation climate impacts[13–15] have also neglected air pollution impacts. The few studies that propose solutions to aviation environmental impacts have been narrowly focused on singular aspects of the challenge (*e.g.*, sustainable aviation fuels (SAF) to address aviation CO_2; operational solutions to address contrails;[16] technological solutions to address air quality[12]). There has been no assessment to date, that proposes solutions that simultaneously tackle the climate (including lifecycle emissions and non-CO_2 impacts) as well as air quality impacts of aviation in a single consistent study. An assessment that simultaneously evaluates the approaches that minimize aviation's climate and air quality impacts on a consistent basis is needed to capture the interdependencies and coupling between various mitigation options. Such an assessment is crucial to evaluate the feasibility of reducing aviation environmental impacts to near-zero.

In this paper we identify and assess an air transportation system with near-zero environmental impact (accounting for aviation's climate and air quality impacts). We define such a system as having a net-zero climate impact and a 95% (or greater) reduction in air quality impacts relative to present day. We quantify the lifecycle emissions and costs of producing alternate fuels and bound the range of likely values based on the literature. Aircraft concepts compatible with the chosen fuel are modeled using an aircraft-propulsion system multi-disciplinary design and optimization (MDAO) approach. We also optimize flight trajectory to minimize persistent contrail length and quantify the associated increase in fuel burn. We propose and assess a solution for the single aisle market with a design range of 3000 nautical miles and capacity of 220 seats because aircraft in this market (*i.e.*, Airbus A320 and Boeing 737 family) accounted for 44% of aviation fuel burn in 2019 (see ESI-S2†). We propagate the uncertainties in modeling the environmental impacts using a Monte-Carlo approach and indicate the 95% confidence interval (CI) in the figures presented in this work.

While this work does not quantify aircraft related community noise (estimated to be an order of magnitude lower than monetized climate and air quality impacts[17]), the solutions presented here do not preclude the use of noise reducing technology and operational procedures.

Beyond the specific case of the aircraft system proposed, the methods used here demonstrate a robust approach to using aircraft-propulsion MDAO models and trajectory optimization coupled with lifecycle assessments, simplified climate models, and global chemistry transport models to evaluate the climate and air quality impacts of future sustainable aviation systems across various market segments. The ability to make such holistic assessments can guide future technology development and policy decisions.

2. Methods

An aircraft with near-zero environmental (excluding noise) impacts needs to address (see ESI-S3†): (1) emissions of greenhouse gases (GHG) associated with the production and combustion of fuels (which currently account for ∼61% of aviation's total monetized climate and air quality impacts); (2) persistent contrail formation (16% of aviation's total impacts); (3) air quality degradation that is caused by aviation NO_x emissions (28% of aviation's total impacts).

First, the near-zero environmental impact (ZIA) aircraft system needs a fuel with zero (or minimal) GHG emissions along its lifecycle. Here we consider a synthetic drop-in hydrocarbon sustainable aviation fuel (SAF) as well as a non-drop-in liquid hydrogen (LH_2) fuel. We consider the GHG emissions associated with the entire lifecycle starting from feedstock production to fuel combustion onboard the aircraft. The hydrogen required in the production of both fuels is assumed to be obtained *via* electrolysis of water using renewable electricity (specifically wind and solar electricity are considered). The assumptions and methods used to estimate the cost and emissions associated with both LH_2 and SAF is presented in Section 2.1.

Second, an aircraft with near-zero environmental impact needs to be designed such that it is compatible with the proposed fuels above while also enabling a 95% or greater reduction in air quality impacts. We propose using post-combustion emissions control (PCEC)[12] to remove NO_x emissions from the gas turbine exhaust. The MDAO approach taken to design and optimize the aircraft and propulsion system along with PCEC is detailed in Section 2.2.

Third, the operation of the aircraft proposed above needs to minimize the formation of persistent contrails (*via* "contrail avoidance"), which account for 16% of aviation's monetized environmental impacts (see ESI-S2†) and 57% of effective RF[4]. The modelling approach taken is outlined in Section 2.3.

2.1 Life-cycle emissions and costs of LH_2 and SAF production

Liquid hydrogen (LH_2) in this study is assumed to be produced using renewable electricity *via* proton exchange membrane (PEM) electrolysis followed by liquefaction. We choose PEM electrolyzers over other commercial (*e.g.*, alkaline electrolyzers) or near-commercial systems due to their high differential operating pressure (reducing compression system requirements and costs), high efficiency, and high current and power densities (leading to smaller footprints)[18] and lower balance of plant cost forecasts that suggest scale-up potential.[19]

SAF is produced *via* a Power-to-Liquid (PtL) pathway. We assume CO_2 is sourced from the atmosphere *via* direct air capture (DAC) and synthesized with green hydrogen to produce fuel *via* the reverse water gas shift and Fischer–Tropsch (FT) processes. We assume the use of low-temperature adsorption-based CO_2 capture as the lower heating requirements of these solid adsorbents may allow for co-optimization of waste heat usage from the FT process (thereby reducing process emissions and energy demand). We use atmospheric CO_2 since it has no direct adverse air quality impacts[20] (assuming use of clean renewable electricity) and does not face the feedstock availability constraints that biomass derived SAF does[21] – ensuring a long-term perspective for the fuel production. We use methods from Isaacs *et al.*[22] to determine the net energy demand and mass conversion ratios for the inputs of energy, CO_2 and H_2 into PtL SAF output. The modelling of each process step including the assumptions are detailed in ESI-S4.†

We develop a model to evaluate LH_2 transport since the required infrastructure is not yet available. LH_2 can be transported in gaseous form *via* pipeline, as a liquid *via* trucking and shipping, or it can be produced on-site at an airport by transmitting renewable electricity *via* high voltage transmission lines. Our model evaluates the cost of each option for a given transport distance and fuel volume and selects the least costly option. We find that the volumes required (∼2000–5000 tonnes of Jet A equivalent fuel per day at medium to large airports) make transmitting electricity the cheapest option for the major airports evaluated.[23] We assume high voltage transmission lines operating at 500 kV. We assume that the hydrocarbon PtL-based SAF is transported using existing infrastructure used to transport conventional jet fuel.

The total cost of each fuel production pathway is determined by summing the production, transport, and fueling costs. The levelized cost of electricity (LCOE) and capacity factors (CF) reported in the NERL Annual Technology Baseline report[24] are used for photovoltaic (PV) and wind electricity generation costs in 2050. Equipment cost of the process equipment are obtained from literature and used to estimate the capital cost of production facilities. We amortize the capital cost over a 25 years lifetime using a 6% weighted average cost of capital (WACC) consistent with current market based cost of equity and debt.[25] Tabulated details can be found in the ESI-S4.† While we rely on estimates of investment and maintenance costs from the literature, the relevant details have been extracted and all process cost calculations have been harmonized throughout our analysis using consistent WACCs, LCOEs and capacity factors for electricity, annuity factors and plant lifetimes to amortize capital costs.

Lifecycle emissions for the fuels are determined by using emissions intensities of 4.4 gCO_2e per kW h and 44 gCO_2e per kW h for wind[26] and PV electricity,[27] respectively, and are then reduced by 50% (to 2.2 and 22 gCO_2e per kW h respectively) to account for decarbonization in the manufacturing value chain[28] for wind and solar generation devices anticipated by 2050. The energy requirement of each process in the fuel production is multiplied by the emissions intensity values to determine total production emissions. While the ISO guidelines of life cycle analysis do not account for embodied emissions of the fuel production plants, we estimate them based on available sources as detailed in ESI-S3.† We ensure that the process step emissions from literature used in our emissions calculations are technologically consistent with sources we use for cost estimates.

2.2 Aircraft design and optimization

The aircraft design and optimization is performed using a multi-disciplinary approach that builds on the Transport Aircraft System Optimization (TASOPT) code which has been used in numerous studies.[29,30] The physics-based approach ensures that the results stemming from unconventional designs such as the use of a turbo-electric powertrain and cryogenic hydrogen fuel are not artifacts of extrapolations of historical data. Ref. 29 and 30, provide a detailed documentation of TASOPT. We optimize the aircraft to minimize the payload fuel energy index (PFEI) defined as the energy consumed by the aircraft per weight of payload per distance.

2.2.1 Propulsion system design. A turbo-electric powertrain that decouples the thrust production from the conversion of on-board energy to shaft power is used. Gas turbine performance is modelled using the Numerical Propulsion System Software (NPSS).[31] A two-spool architecture is chosen for the gas turbines. The low-pressure (LP) spool is connected to a boundary layer ingesting (BLI) ducted propulsor as well as an electric generator. A gearbox is used to allow the propulsor to spin slower than the LP turbine and the generator. This allows the generator to be sized for higher shaft speeds and therefore higher specific powers. Variable speed electric machines are chosen allowing the LP shaft to directly power the generators and eliminating the need for a separate constant speed turbine. The motors and generators are assumed to be permanent magnet synchronous machines (PMSMs) due to their demonstrated high specific power and efficiency.[32,33] The three key loss sources for PMSMs – windage loss, ohmic loss and core loss are explicitly modeled. Further details on design of the PMSMs including the loss models are provided in the ESI-S5.†

The high-pressure turbine (HPT) is cooled using bleed air from the last HP compressor stage following the semi-empirical method proposed by Gauntner.[34] Alternate turbine cooling strategies using any available cryogenic fuel are not considered here and might be possible at the cost of increased complexity in design.

2.2.2 Cryogenic LH_2 tanks. To confidently model the use of LH_2 fuel it is insufficient to assume a fixed gravimetric index for the cryogenic tanks. We size the cryogenic tanks from first principles (and therefore calculate the gravimetric index of the tank) in each iteration of the aircraft design optimization. The LH_2 tank is assumed to be cylindrical in shape with elliptical heads. A combination of an Al 2219 inner wall encased by two closed-cell foam-based insulation layers is selected due to their optimum material specifications as evaluated by prior studies[35] (material properties and further details can be found in the ESI-S5†).

2.2.3 Post-combustion emissions control. A selective-catalytic reduction (SCR) based post-combustion emissions control system (PCEC) is modelled following Prashanth *et al.*[12] The sizing of the PCEC system is coupled to the gas turbine sizing outlined above. Pure anhydrous ammonia is used as the reductant and is sprayed upstream of monolithic zeolite catalysts. The catalyst used in this work is assumed to have 900 cells per square inch (CPSI). Details are given in the ESI-S5.† The estimated life time of the catalyst system based on current ground based systems is ~40 000–60 000 hours[12] which implies a catayst replacement every 5–7 aircraft maintenance cycles (assuming C-checks every ~7500 hours).[12]

2.3 Contrail avoidance

We develop a contrail avoidance model to estimate the impact on persistent contrail length and mission fuel burn by rerouting flights (which results in a fuel burn penalty) above or below regions of the atmosphere that are supersaturated with respect to ice and where the temperature and humidity satisfy the Schmidt-Appleman Criterion, referred to here as the persistent contrail conditions (PCC). The lateral flight track is fixed to the great circle route, and only vertical deviations are applied relative to the vertically-wind-optimized baseline trajectory.

We calculate the fuel burn penalty (*i.e.*, excess fuel burned as a result of climbing or descending to avoid contrail forming regions, and potentially flying at suboptimal altitudes as a result) using an aircraft performance deck (*i.e.*, fuel flow rate as a function of operating altitude). The aircraft performance is calculated using the aircraft design and optimization code outlined above (Section 2.2) for each aircraft concept designed.

Our algorithm minimizes contrail length; the climate impact of contrails, however, has diurnal and geographic variation and depends on the surface albedo, the contrails' altitude, optical depth, lifetime, and the natural cloudiness surrounding them. Accounting for these factors in the context of a full aircraft design optimization along with fuel energy considerations is out of the scope of this paper and may be subject of future refinements. However, we note that our fuel burn penalty estimates are likely high as contrail avoidance may not be worth implementing for all daytime flights, thereby reducing the number of deviations and associated fuel penalty.

Contrail length of a flight is determined based on data from the ERA5 dataset provided by the European Centre for Medium-Range Weather Forecasts. Aircraft performance metrics are calculated using the aircraft design and optimization tool described above. We simulate contrail avoidance by randomly sampling flights from the 2019 global flight schedule, for flights that were operated by the Boeing 737 or the Airbus A320 family of aircraft. The flight schedule accounts for ~23 million flights. Random sampling is continued until the values for fleet-wide contrail length reduction and the fleet-wide fuel burn penalty converge. The sample values are then generalized to the fleet. The fleet-wide fuel burn penalty is calculated by dividing the sample's total fuel burn when performing contrail avoidance by the sample's total fuel burn without contrail avoidance. Further details are provided in ESI-S6.†

2.4 Emissions and environmental impact

Total emissions are derived using the 2019 OAG schedule and the Aviation Emissions Inventory Code (AEIC) model.[36] Landing and takeoff (LTO) emissions are computed based on ICAO time in flight modes, using the methodology described by Stettler *et al.*[37] Non-LTO fuel burn and emissions are calculated assuming great circle flight and corrected for routing inefficiencies.[38] Further details on calculating the flight emissions are provided in the ESI-S9.†

Air quality impacts are quantified using the cost metrics presented in Grobler *et al.*[39] Climate impacts are quantified using Aviation environmental Portfolio Management Tool-Impacts Climate (APMT-IC) as described in Grobler *et al.*[39] To align with the most recent state of the science, three updates are made, specifically to the contrail forcing, the NO_x-methane pathway, and the costs associated with global warming. These adjustments are documented in the ESI-S9† along with details regarding modelling of contrail impacts associated with the combustion of SAF and LH_2.

3. Results and discussion

The following sections detail a zero-impact aircraft system that has a net-zero climate impact and a 95% reduction in air quality impacts relative to present day.

3.1 Fuel production with near-zero GHG emissions

We calculate (assuming wind electricity and expected year-2050 process efficiencies – see ESI-S4† for details) that using either PtL-based SAF or LH_2 can reduce the lifecycle GHG emissions relative to Jet A by ~93% or ~97%, respectively. The lifecycle GHG emissions are 5.7 gCO_2e per MJ for PtL-SAF (58% reduction relative to biomass-based SAF pathways[40] using waste fats, oil, and grease (FOG) as feedstock) and ~2.3 gCO_2e per MJ for LH_2 as shown in Fig. 1. For the subsequent analyses presented here we assume the use of wind powered electricity and present a sensitivity case of using PV derived fuels in Fig. S17 of the ESI.† We note that either PtL-based SAF or LH_2 are likely going to be powered by a combination of various renewable electricity sources in the future (including wind and solar PV). We also consider a sensitivity scenario for renewable energy consistent with present-day values (we consider LCOE and CF values for 2021 from the NREL ATB,[24] see Section 3.7 and ESI-S10†).

LH_2 and SAF with low lifecycle GHG emissions cost ~1.8 to 2.3 times as much as jet fuel (pre-Russia-Ukraine war), respectively. We estimate PtL-based SAF to cost 1.3 $ per L (~1.4 times the cost of FOG-based SAF[41]) and LH_2 to cost ~1.0 $ per L of jet fuel equivalent as shown in Fig. 1. The cost premium of LH_2 is driven by the cost of producing and liquefying hydrogen, while the cost of atmospheric CO_2 capture and production of hydrogen are the main components of the SAF cost. We calculate electricity demand associated with the production of LH_2 and PtL SAF to be 0.46 kW h MJ and 0.68 kW h MJ respectively. Further breakdown on the electricity demand is provided in Table S4 of the ESI.†

The lower lifecycle GHG emissions (−82%) and lower cost (−30%) of LH_2 relative to the PtL SAF are due to fewer process steps and lower electric energy intensity (−32%) of the LH_2 pathway (see ESI-S4†). The cost advantage of LH_2 is uncertain (see overlap in range of costs in Fig. 1.) and partly results from

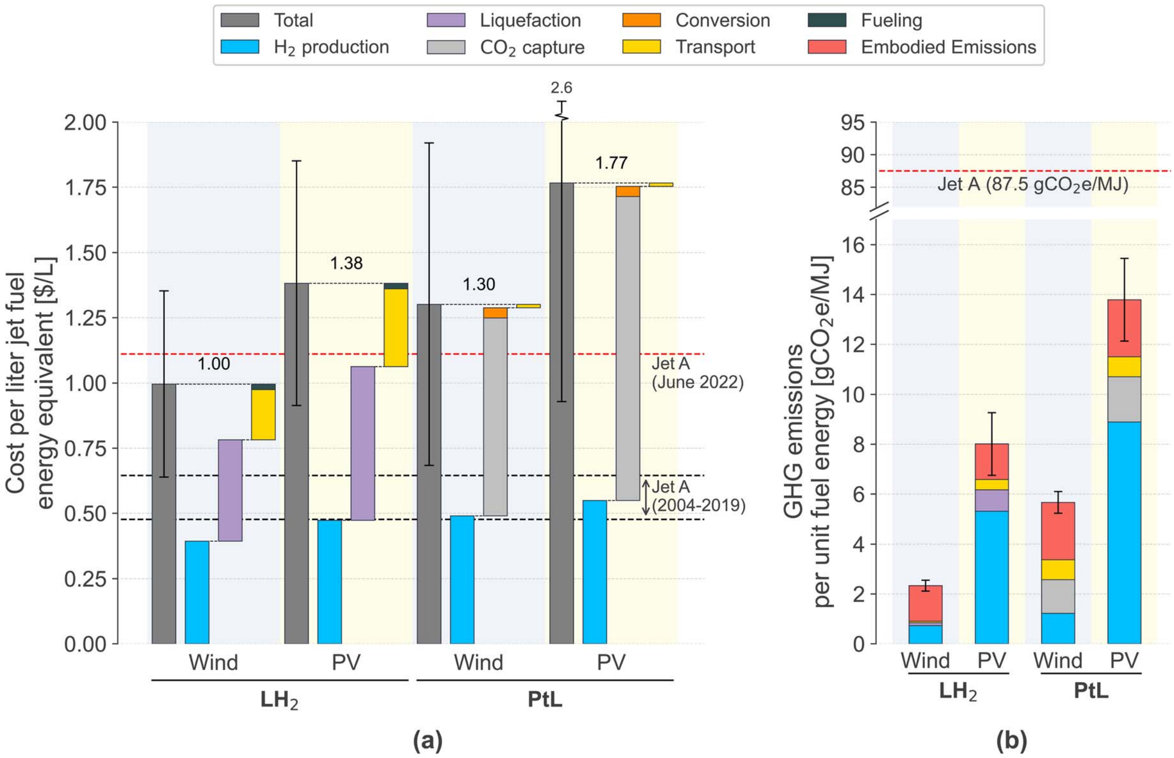

Fig. 1 LH_2 and PtL SAF characteristics in (a) costs in dollars per liter of jet fuel energy equivalent in 2050 and (b) lifecycle GHG emissions in gCO_2e per MJ. Error bars represent the upper and lower bounds of costs and emissions that result from the technological and economic assumptions detailed in the ESI.† Dashed black lines in panel (a) show the 2.5–97.5 percentile range of the jet A price from 2004–2019 and the dashed red line shows the price of jet A at time of writing. Embodied CO_2 in panel (b) represents the CO_2 emitted in the construction and setup of the process plants in each process. Note, the lower GHG emissions and costs of a wind-based system relative to a PV-based system are due to the higher embedded emissions and lower capacity utilization factors for solar PV power generation.

the high-cost PtL-based SAF pathway. In addition, the use of LH_2 requires both new fuel infrastructure and redesigned aircraft to use cryogenic fuel with lower volumetric energy density (we do not estimate in this work the research and development cost of redesigning aircraft to use cryogenic fuel).

3.2 Aircraft and propulsion systems designed to minimize NO_x emissions

We propose an aircraft concept that meets the ZIA requirements and is consistent with our target market. The resulting "zero-impact aircraft" concepts fueled by liquid hydrogen (ZIA-LH_2) and PtL SAF (ZIA-SAF) are shown in Fig. 2.

We assume a tube-and-wing configuration aircraft with a PCEC system housed within its fuselage (due to its size). Two small-core gas turbines housed within the fuselage power aft mounted boundary layer ingesting propulsors as well as variable speed generators (located within the fuselage) to produce electrical power for distributed wing mounted electric propulsors. The core exit gas from the aft mounted small-core gas turbines is fed to the PCEC system where the NO_x is reduced to N_2 and water[12] before exhausting into the atmosphere. (We do not consider fuel cells as it is unclear at this stage if they will ever be viable for this size class of aircraft.)

The operating empty weight of the ZIA-LH_2 is ~11% higher than the ZIA-SAF with the cryogenic LH_2 tank alone accounting for 98% of the weight increase relative to the ZIA-SAF. However, the maximum take-off weight of ZIA-LH_2 is ~7% lower than for ZIA-SAF, given the lower fuel weight. The ZIA-SAF aircraft has a lift-to-drag (L/D) ratio of 19 which is ~27% higher than the ZIA-LH_2 (L/D = 15). The PFEI of the ZIA-SAF and ZIA-LH_2 are 0.72 J N^{-1} m^{-1} and 0.60 J N^{-1} m^{-1} respectively as shown in Fig. 2. This indicates that the aircraft energy required for the design mission (with the same payload and range) is ~20% greater for ZIA-LH_2 than ZIA-SAF due to the increased empty weight and drag of the LH_2 powered aircraft and is consistent with prior literature.[42,43] Thermodynamic cycle innovations using the cryogenic LH_2 fuel are not accounted for here and may provide additional benefits for ZIA-LH_2. Details on the aircraft including the weight and drag build-ups and comparison to conventional B737-like aircraft are provided in the ESI-S5.† Furthermore, alternate design approaches such as the lifting double-bubble fuselage of the "D8"[29] can provide additional benefits for both aircraft.

3.3 Operational contrail avoidance

We find that contrail avoidance can reduce the length of persistent contrails by 76% and 67% for the SAF and LH_2 designs, respectively. Differences in aircraft fuel consumption, climb capability, and cruise ceiling combined with increased emissions of water from the combustion of hydrogen relative to

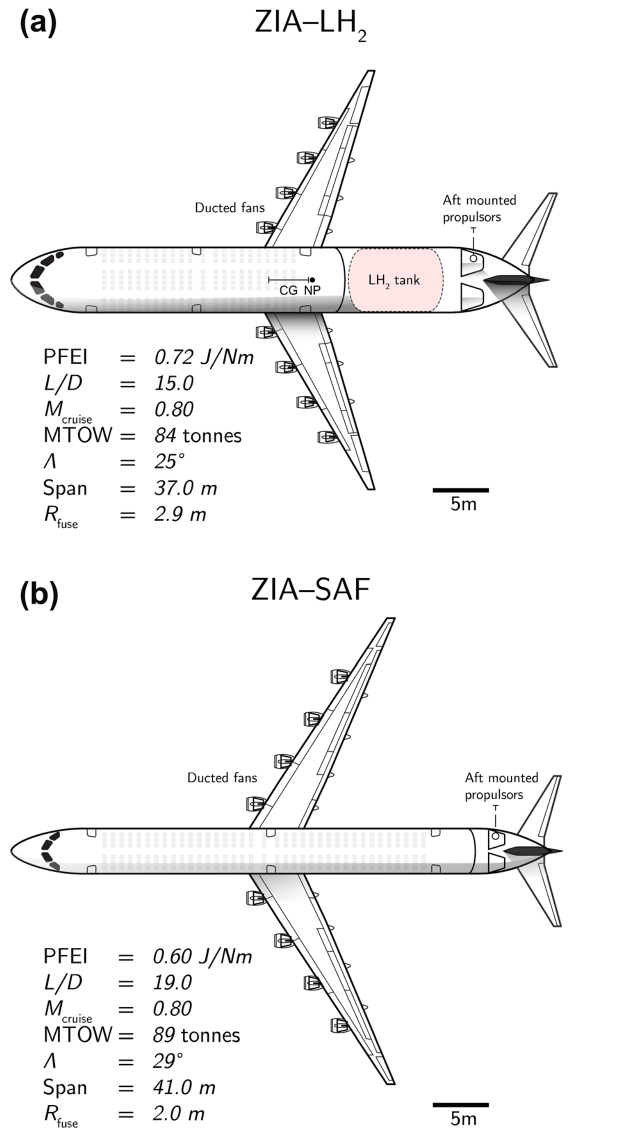

Fig. 2 (a) Optimized liquid hydrogen aircraft (ZIA-LH_2) (b) optimized SAF aircraft (ZIA-SAF). The inset summarizes key performance metrics such as the payload fuel energy index (PFEI), maximum take-off weight (WMTO), wingspan, wing sweep (Λ), fuselage radius (R_{fuse}), and lift-to-drag ratio (L/D).

the SAF, leads to lower persistent contrail length reductions for the ZIA-LH_2 relative to the ZIA-SAF. The fleet-wide fuel burn penalty is ~1.0% for both the ZIA-SAF and ZIA-LH_2. Comparisons to other studies on contrail avoidance as well as sensitivity studies on the design parameters of contrail avoidance are found in ESI-S6.†

3.4 Atmospheric CO_2 removal and sequestration

We estimate that adopting the above system changes (low life-cycle GHG fuel, aircraft with PCEC, and contrail avoidance) can reduce the environmental impact of aviation by almost two orders of magnitude (quantified in following section). However, we find that the climate impacts of such a system is still non-zero. We, therefore, consider carbon capture and storage (CCS) to achieve net-zero climate impacts. Removal of CO_2 from the atmosphere is needed to address the residual climate impacts associated with the fuel production and contrails that are prohibitively expensive to avoid. Here we assume direct air capture of CO_2 using low-temperature adsorption-based DAC systems along with storage in geological formations. The primary source of emissions in these systems are those associated with the production of the adsorbent, the required electricity, and the embodied emissions. We calculate that the DAC systems will cost ~112–341 \$ per tonne of captured CO_2 assuming the use of wind electricity. In addition, transportation costs[44] add ~\$18–\$30 per tonne of CO_2 and geological storage costs[44] add ~\$8 per tonne of stored CO_2 (see ESI-S7† for further details) for a mean cost of ~\$250 per tonne of CO_2 captured and stored. Our estimated cost of DAC systems is within the 90% confidence interval of future DAC costs estimated in recent work by Sievert *et al.*[45] using differential experience rates (see SI–S10† for a sensitivity case where the calculated DAC costs are ~\$545 per tonne of CO_2).

3.5 Climate and air quality impacts of ZIA systems

We quantify the potential environmental benefits in the limiting case of replacing all global operations of Airbus A320 or Boeing 737 family aircraft with the ZIA-SAF or ZIA-LH_2 systems in the base year of 2019. We also quantify the fuel costs associated with such a scenario and put it in the context of direct operating costs for aircraft operators.

Without the use of CCS the "zero-impact" aircraft reduce total monetized climate and air quality impacts of the replaced flights (see ESI-S9† for monetization approach) by 93–94% (Fig. 3a), suggesting that both SAF or hydrogen aircraft are approximately equally capable of reducing environmental impacts (when combined with PCEC and contrail avoidance). Only replacing Jet A with drop-in SAF in the present-day fleet (*i.e.*, without PCEC, contrail avoidance, and CCS), achieves a 60% reduction in the monetized environmental impacts as in Fig. 3a (due to lower lifecycle CO_2 emissions). However, the air quality impacts remain largely unchanged if only a fuel switch from Jet A to drop-in PtL-based SAF is employed (~3.2% reduction in air quality impacts are due to zero fuel sulfur and fewer particle emissions associated with SAF).

3.5.1 Climate impacts.

The ZIA-SAF and ZIA-LH_2 system without CCS achieve a 92% and 90% reduction in climate impacts relative to the present-day fleet respectively (see ESI-S7† for detailed build-up). While the life-cycle CO_2 emissions for the SAF-based aviation system are ~2.5 times higher than for the LH_2-based system, ZIA-LH_2 is associated with greater energy consumption (see Fig. 2 and Section 3.2) and (potentially) larger non-CO_2 impacts. These non-CO_2 impacts comprise of hydrogen leaks in the supply chain and in-flight (that can perturb OH concentrations and lead to methane feedbacks; modeling and understanding these impacts may require comprehensive chemistry transport model which is subject of ongoing research), increased water vapor emissions from hydrogen combustion which increase the direct stratospheric water vapor impact and the range of atmospheric conditions

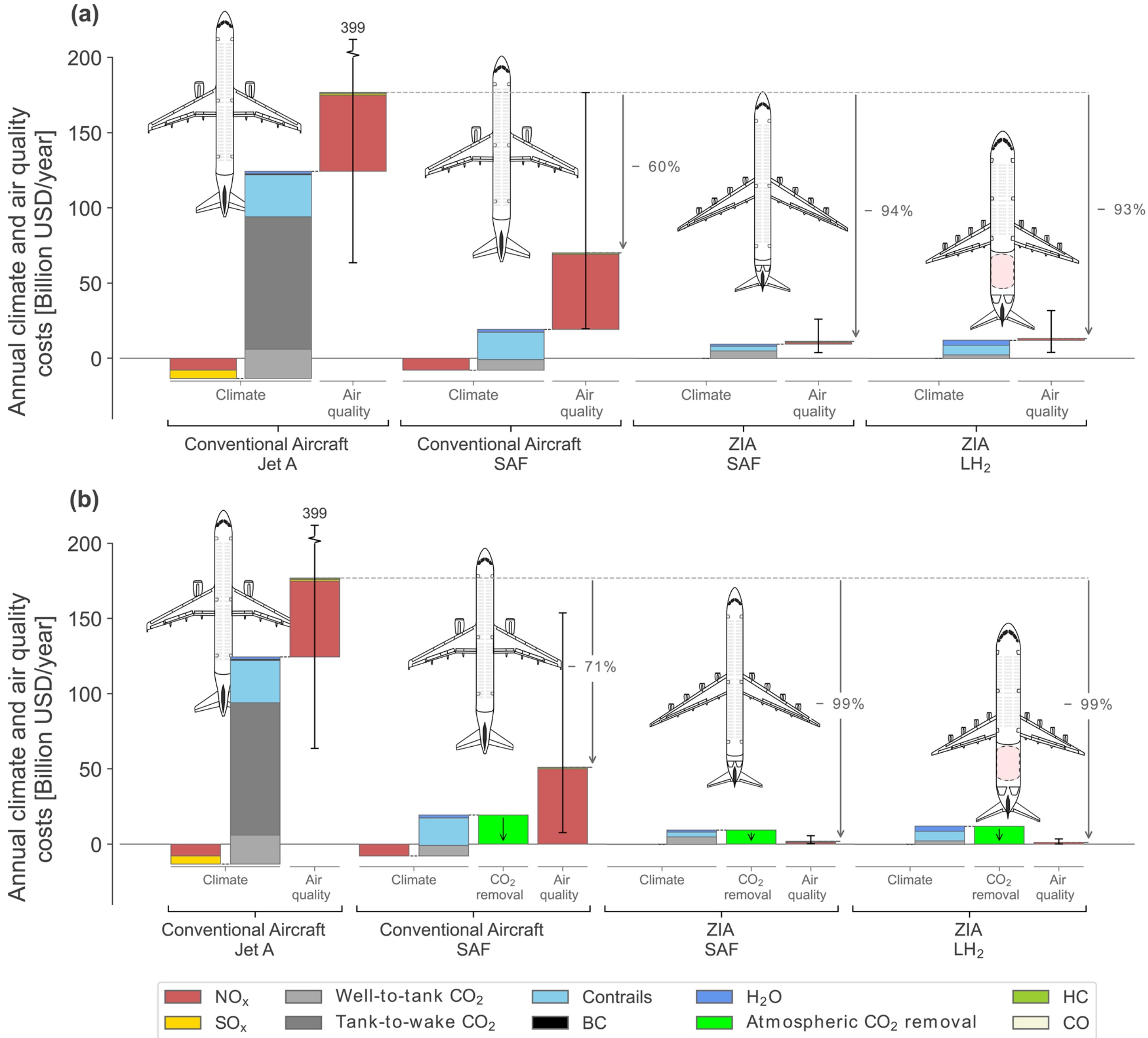

Fig. 3 (a) Comparison of the climate and air quality impacts from using SAF in the current fleet of Airbus 320 and Boeing 737 aircraft compared to the impact of SAF and LH_2 in the two Zero-Impact Aircraft (ZIA) combined with contrail avoidance. (b) CO_2 capture and removal is included to enable net-zero climate impact (indicated by the downward arrow) for the ZIA-SAF and ZIA-LH_2 systems. The reduction in environmental impact from the conventional aircraft fueled by Jet A is shown.

under which contrails may form. (It is, however, not certain if contrails would form due to lack of ice nuclei – but this analysis indicates that given the potential for contrail avoidance the net impact would be minimal either way.)

Since the residual climate impacts of the ZIA-SAF and ZIA-LH_2 systems are an order of magnitude lower than the present-day reference scenario, it is possible to use CCS on a small scale to offset the remaining impacts (removal of 41 and 50 Tg of CO_2 each year respectively) accounting for ∼1% of the estimated CCS deployment potential of 5000 Tg CO_2 per year (ref. 20) in 2050. This allows the system to meet the net-zero climate impact goal set out in this paper (Fig. 3b). Simply compensating aviation climate impacts in the present-day scenario (for global operations of A320 and B737 class aircraft) using CCS would require an order of magnitude more atmospheric CO_2 removal (∼510 Tg CO_2 per year) and is unlikely to be feasible given the estimated 2050 deployment potential.[20]

3.5.2 Air quality impacts. The ZIA-SAF and ZIA-LH_2 systems reduce the air quality impacts relative to the present-day fleet by 96% and 98%, respectively. Since 96% of the air quality impacts from the reference case is due to NO_x emissions, this reduction is enabled by PCEC. We note that the ZIA-SAF system does not address the small but non-zero (<2% of the baseline) air quality impacts associated with emissions of soot, hydrocarbons, and carbon monoxide. The net environmental impact of the system is reduced by 99% after the use of CCS (Fig. 3b) for both aircraft.

3.6 Fuel costs of ZIA systems

We estimate the fleet averaged fuel costs of the ZIA-LH_2 or ZIA-SAF system to be 1.4 or 1.7 times the fuel costs of the present system (pre-Russia-Ukraine war). The aviation industry has successfully managed fuel cost increases of this magnitude over short time periods; for example, between 2004 and 2012 fuel costs increased by ~160%, from 49 USD/barrel to 129.6 USD/barrel.[46] Furthermore, these increases in fuel costs are comparable with the estimated increase in aviation fuel costs (~0.82–1.32 $ per L in 2050) under various SAF adoption scenarios per the ICAO report on the feasibility of a long-term aspirational goal (LTAG) for international civil aviation CO_2 emissions reduction.[28]

The fuel cost advantage of ZIA-LH_2 over ZIA-SAF is a result of the lower cost of LH_2 per unit energy (−30%), which outweighs the increased energy consumption of ZIA-LH_2 fleet (+15%; thermodynamic cycle innovations exploiting the thermodynamic availability (exergy) in cryogenic LH_2 could produce further reduction in energy consumption that have not been considered here).

Our choice of the PtL-based SAF pathway using CO_2 from DAC contributes to the higher production cost of SAF relative to LH_2 reported here. While biomass-based SAF production costing between 0.6–0.8 $ per L (*vs.* 1.3 $ per L for the PtL-based SAF considered here) is plausible,[41] there is limited biomass feedstock available[21] and is unlikely to meet the demand of the aviation industry in the very long-term (see ESI-S8† for a comparison of PtL SAF against a biomass-based SAF). Given the energy requirement of the ZIA-LH_2 and ZIA-SAF fleet we calculate the annual electricity demand to provide the required fuel to be 1850 TW h and 2430 TW h respectively (corresponds to approximately a tenth of global electricity use in 2021 (ref. 47)). Further details on electricity use and approximate land area required is provided in Table S8.†

The aircraft operating cost consists of the cost associated with flying operations, maintenance, and depreciation and amortization of the aircraft capital cost collectively referred to as the direct operating cost[48] (DOC). Fuel costs represent only ~28% of the DOC[46] in present operations. Therefore, the increase in DOC associated with the increase in fuel cost is ~19% for ZIA-SAF and 12% for ZIA-LH_2 (this includes the additional fuel required for contrail avoidance) relative to the present system. CCS requirements to reach net-zero climate impacts add another 3% and 4% in DOC for the ZIA-SAF and ZIA-LH_2 respectively. An estimate of the net increase in DOC to the airline is shown in Fig. S14(a) of the ESI.†

3.7 Net societal costs and benefits of ZIA systems

We estimate that the societal cost (defined here as the sum of the monetized climate and air quality impacts, the costs of fuel, and CCS) associated with the transition to a ZIA system is 43% and 50% lower than the present-day system for the SAF and LH_2 systems respectively (see Fig. S14(b) of the ESI†). These costs are compared to three reference scenarios: a conventional aviation system using petroleum-derived jet fuel, a conventional system using petroleum-derived jet fuel and CCS to reach net-zero climate impacts, and a SAF-powered system with CCS. We find the three reference scenarios to have almost identical societal costs (Fig. S14(b)†). ZIA systems, however, have lower societal cost than the conventional system because the monetized environmental benefits outweigh the fuel and CCS cost. The benefits associated with the ZIA systems relative to the present-day fleet may be larger if additional efficiency improvements are made such as, thermodynamic cycle innovations, cryogenic electric machines, lifting fuselage designs (*e.g.*, D8 design[29]). The costs associated with these future technology innovations are not considered in this work and could also increase societal cost of the ZIA systems.

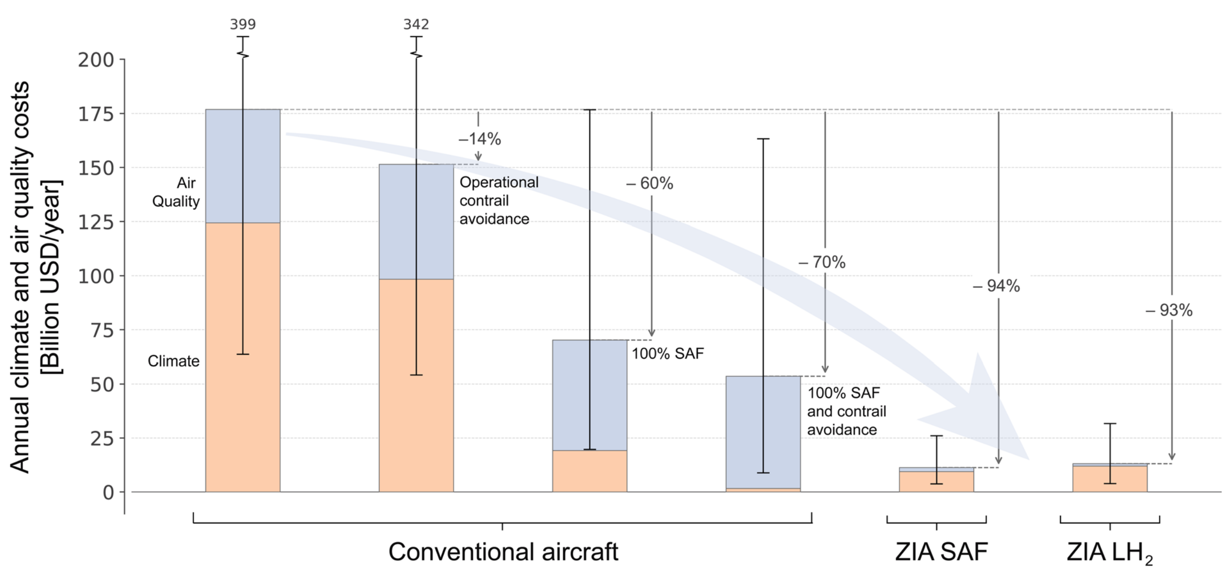

Fig. 4 Reduction in environmental costs (consisting of air quality and climate costs) for a series of interventions. The first stacked bar shows the monetized environmental impact of the present-day fleet. The next three scenarios show technologies that are compatible with the present-day fleet. Operational contrail avoidance is a near term strategy that could result in a reduction in climate impacts. Replacing conventional jet fuel with a low-GHG SAF such as the PtL-based SAF proposed in this work can yield a 60% reduction in environmental impacts and a 70% reduction when combined with contrail avoidance.

We emphasize that the societal benefits presented above are only achievable in the context of availability of low-cost renewable energy technology. To highlight this we consider a sensitivity scenario where we repeat the above calculations with LCOE and CF for renewable energy consistent with present-day values (we consider values for 2021 from the NREL ATB[24]). The results are shown in SI–S10.† Under the "present-day scenario" we find that the total societal cost associated with the ZIA-SAF and ZIA-LH_2 systems are 26% and 6% higher than the present-day fossil-based system. The increase in societal cost is driven by the cost of fuel (~2.0 $ per L jet fuel equivalent for LH_2 and ~2.7 $ per L for the PtL SAF) and the cost of DAC (~$545 per tonne of CO_2 captured). These findings highlight that aircraft re-design alone cannot create an economically feasible aviation system with near-zero climate and air quality impacts. The aviation system will rely on the availability of technology which can produce energy (and for SAF pathways: carbon) with low costs and emissions. Such progress is likely to be made through innovation outside the aviation sector.

3.8 Environmental impact reduction roadmap

The near-zero environmental impacts of the ZIA systems presented here are achieved by integrating targeted solutions to the dominant sources of impact – lifecycle GHG emissions, contrails, and NO_x. Reductions in some of these impacts are dependent on factors that are traditionally outside the scope of the aviation industry. It is likely that a transition to a future ZIA system will occur gradually. Fig. 4 isolates the reduction in environmental impacts associated with the key technological approaches presented in this work. A near-term implementation of operational contrail avoidance can result in a reduction of ~14% of the present-day environmental impact while maintaining the current fleet of conventional aircraft. An eventual complete transition from fossil-based Jet A to a low-GHG SAF such as the PtL-based SAF presented in this work can yield a 60% reduction in environmental impacts, which can be further reduced if employed along with contrail avoidance strategies (for a combined ~70% reduction in environmental impact). An aircraft and propulsion system with technology to minimize or eliminate NO_x emissions (*e.g.*, PCEC) is necessary to reduce the environmental impacts by ~93–94% (our work suggests that this is feasible for both drop-in PtL-based SAF like fuels or non-drop in LH_2). The residual climate impacts can be then offset using small scale atmospheric CO_2 removal.

4. Conclusions

We identify a technically feasible pathway towards an aviation system with near-zero environmental impacts for the single aisle market at reasonable DOC. This system integrates: (1) a fuel with low lifecycle GHG emissions; (2) an aircraft design that is compatible with the chosen fuel and accommodates PCEC to enable a >95% reduction in NO_x emissions; (3) strategies for persistent contrail avoidance; and (4) atmospheric CO_2 removal with CCS to offset hard-to-avoid emissions, especially in the fuel lifecycle. Even without CCS a 93–94% reduction in environmental impacts is possible, with only a 1% difference depending on fuel choice. The results presented here are based on forecasted lifecycle emissions and costs in 2050 which assume advancements in technology and reduction in the emissions intensity of the global supply-chain (see ESI-S10† for a sensitivity scenario).

We find that SAF and LH_2 are both compatible with the net-zero climate goal. Whether the aviation system moves towards LH_2 in the long-term, depends on availability and the cost trajectory of SAF relative to the production and distribution cost of LH_2, the cost premium of the LH_2 aircraft as well as safety, logistical and broader economic and political factors. Furthermore, there may be additional thermodynamic cycle innovations using cryogenic hydrogen as well as cryogenic electric machines that give LH_2 based aircraft an additional advantage. The cost of the CO_2 feedstock, and the fuel conversion pathways will also be important drivers of whether SAF or LH_2 dominate future aviation systems.

However, low-cost production of renewable electricity and hydrogen are critical for and will benefit both the LH_2 and the SAF pathway. As shown by our sensitivity case (see ESI-S10†) present day costs and capacity factors of renewable electricity generation does not prove to reduce net societal costs even with an advanced aircraft design. While our analysis suggests long-term cost advantages of an LH_2-based system, we emphasize that these cost advantages are uncertain. To achieve net climate neutrality, the ZIA system will also rely on small-scale capture and storage of atmospheric CO_2 (~1% of the estimated annual geological storage capacity), since neither LH_2 nor SAF are entirely carbon neutral from a lifecycle perspective. The costs associated with the use of DAC to capture and store atmospheric CO_2 is also uncertain (detailed in S7 of ESI†).

The use of post-combustion emission control mitigates the air quality impact associated with aviation. Here we adopted a turboelectric powertrain that enables the integration of PCEC to reduce NO_x emission to near-zero. However, further work is required to determine if similar integration can be achieved through mechanical systems. Furthermore, since such systems will increase energy consumption as well as the system cost, incentives towards substantially reducing air pollutants are needed to drive research and development in PCEC as well as ultimately its adoption.

Contrail avoidance in the form of small vertical flight path deviations come at low costs (fuel burn penalties of ~1%), while having substantial climate benefits. Even under the significant uncertainties of contrail climate impacts, this strategy is highly likely to be beneficial. Implementation at scale is possible in the short-term with the existing fleet subject to regulatory and air traffic hurdles.

Our analysis is focused on commercial passenger aviation currently served by Airbus A320 and Boeing 737 family aircraft. Other market segments might require different solutions to reach zero-impacts. It is possible that ZIA-SAF is viable for other size and range specifications while the viability of ZIA-LH_2 for larger aircraft at long range is unclear and further research into alternative airframe configurations such as blended wing bodies are needed and are topics of future work.

Author contributions

(1) Conceptualization: PP, SB, FA, JS, SDE, RLS. (2) Methodology: PP, JE, SI, SZ, JA, CF. (3) Investigation: PP, JE, CG, SI, SZ, JA, CF, TF. (4) Software: PP, JE, CG, SI, SZ, JA, CF, TF. (5) Visualization: PP, JE, CG, SZ. (6) Funding acquisition: FA, JS, SDE, RLS, SB. (7) Project administration: PP, FA, JS, SDE, RLS, SB. (8) Supervision: FA, JS, SDE, RLS, SB. (9) Writing – original draft: PP, JE, CG, SI, SZ, JA, TF. (10) Writing – review & editing: PP, CF, FA, JS, SDE, SB.

Conflicts of interest

There are no conflicts to declare.

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