Airport Infrastructure Planning to Support Sustainable Aviation

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***Abstract*—Decarbonisation of the air transport sector is expected to be delivered through a combination of efficient aircraft and engine designs, low-carbon fuels such as sustainable aviation fuels (SAF), and zero carbon technologies, such as electric and hydrogen propulsion. The move toward low-carbon fuels and technologies is expected to pose a significant challenge to airport infrastructure requirements. The introduction of novel aircraft technologies will require complementary ground infrastructure at airports capable of supporting the transition at pace. Focused on electric flight, this paper proposes a holistic methodology that utilises historic airport logs, technological progression, along with aircraft mission feasibility to assess the airport infrastructure requirements over time. The methodology incorporates technology uncertainty and its effect on sustainable aviation. The main objective within the methodology is to project associated infrastructure requirements and fleet energy costs to enable planning support for decarbonisation transition pathways. The paper demonstrates the use of the proposed methodology using real-world historic flight logs, identifying the progression in energy demand and ground infrastructural requirements in five-year horizons up to 2050. The methodology presented in this paper and associated results will help airport operators, airline operators, and policymakers by providing planning support through such technology pathway projection.**

***Index Terms*—Airport infrastructure, All electric aircraft, Sustainable aviation, Mobile battery charger**

I. INTRODUCTION

Over the last five-decades large strides have been made in reducing the average fuel burn with new aircraft designs reducing fuel burn in designs by over 40% from 1970 to 2019 [1]. However, even with such improvements, within EU aviation, the direct emissions from aviation still account for 4% of total CO2 emissions as well as contributing to 14% of emissions within the transport sector [2].

The British aviation industry has reaffirmed its goal of decarbonisation by 2050, with intermediate targets of 15% reduction by 2030 and 40% reduction by 2040 (relative to 2019) [3]. Similar targets have been set by the FAA for U.S. aviation and mirrored in the EU, with both aiming to achieve net-zero emissions by 2050 [4], [5]. This move towards decarbonisation will be achieved through more efficient aircraft and engine designs, low-carbon fuels such as game-changing SAF, and new low or zero carbon technologies such as All Electric Aircraft (AEA) and Hydrogen powered aircraft [3]. AEA and Hydrogen aircraft propulsion holds the potential to power short to medium haul flights while SAF may enable net zero emissions for long haul flights [7], [8]. However, aviation decarbonisation will only be realized through the commitment and support of airport operators.

The journey towards electrification in aviation has begun with the introduction of Li-ion batteries powering secondary power loads on commercial aircraft More electric aircraft (MEA) use large battery packs for powering secondary loads ranging from kWh (1.9 kWh in Boeing 787) [8]-[10], to MWh for future single-aisle electrified aircraft (60 MWh in Celiner concept) [11]. AEA concept utilises a battery as the sole energy source, which supplies power to converters and propulsion motors to provide thrust [12]. Use of batteries for propulsion, as in AEA, offers a complementary solution to decarbonisation and zero in-flight emissions, particularly if the batteries are charged from renewable energy. Other advantages that electrified aircraft offer are lower noise and higher energy efficiency compared to conventional powered aircraft [7]. However, a key limitation of AEA is the low energy density of batteries compared to kerosene and hydrogen, making them much heavier and restricting the aircraft range.

With major aircraft decarbonisation required to meet aviation targets, aircraft electrification is part of transition pathways to meeting these goals. Challenges for electrification of aviation include battery technology innovation, battery thermal management, electric propulsion integration, reliability, and certification [7], [13]. This is in conjunction with further challenges to reduce energy use through better airframe design such as aerodynamic and advancement in material in order to improveme energy efficiency.

Furthermore, the uncertainty over which technology combination or which technology will be dominant in the future will need to be clarified and coordinated in order to meet decarbonisation goals. However, existing airport infrastructure are broadly not designed for electrified aircraft operations. The airport infrastructure requirements to facilitate AEA will require additional power supply, battery storage facilities and battery charging infrastructure [7], [14]. Battery charger technology will play an important role in allowing electric flights to be adopted with the aim of also having limited disruption to current levels of flight schedules. Furthermore, a larger power

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demand will be placed on the grid to achieve required charging rates, requiring airport owners and operator to plan and facilitate accordingly. The success of aviation decarbonisation will be partly a result of aircraft electrification in parallel with airport infrastructure planning to support sustainable aviation.

Examples of airside and airport simulation tailored for future AEA infrastructure requirements already exist in the literature.

Authors in [15] presented an optimal charging strategy for battery swap and plug-in chargers through a Gatwick airport case study. The authors found battery swapping is only cost effective for low electric aircraft fleet implementation. However, only one type of AEA was used limiting the scope of fleet or airport wide representation. The authors also directly applied an AEA percentage to the overall fleet to simulate fleet change rather than calculating AEA energy demand or the feasibility of such aircraft, which could result in an unrealistic representation of uptake of AEA. Furthermore, the authors assumed on ground time of 30 minutes for all flights, which omits the more detailed scheduling inter-dependencies for battery charger at fleet level which in turn further influences power ratings.

Authors in [16] investigated ground infrastructure impact on turnaround time for AEA. The paper concluded that no delays would occur using current procedures for AEA using assumptions of battery swap times. However this only considers battery swapping, and does not investigate electrical power demand for chargers and only one on ground time was studied.

Authors in [17] as part of the MAHEPA (modular approach to hybrid electric propulsion architecture) project studied ground infrastructure requirements for hybrid electric aircraft at Athens international airport. The aircraft studies used high fidelity modelling for hybrid electric aircraft to calculate battery capacity. Fleet information was captured from Flight Radar 24 and assumed an on ground time of 30 minutes for all flights. Although the authors have stated the study is based on hybrid electric aircraft, there are no corresponding results for fuel requirements or emissions. As part of MAHEPA, [18] also considered the requirements for hybrid electric infrastructure for Athens international airport and found that plug in chargers were not a viable option even for regional aircraft. The studies provided a snapshot in time while it did not explore airport infrastructure upgrade requirements over time. Furthermore, the aircraft type of hybrid electric inherently would require a lower battery charger requirement compared to AEA.

Authors in [19] examined the optimal number of chargers required through queuing theory for the uptake of AEA. A higher uptake in AEA resulted in a higher number of electric chargers fitted at stands, with no investigation into battery swaps or mobile chargers to reduce queuing times. In the studies, only one type of aircraft was used limiting the scope of airport wide evaluation. A constant ground time for aircraft was also implemented along with arbitrary number of stands.

Authors in [20] adapted scheduling theory principles to reduce peak power demand, energy and investment cost for AEA battery recharging and swapping. This methodology was applied to a nine seat commuter aircraft and used in comparison between non-optimised power strategy. However, this paper presents only a snapshot in time results and utilises fixed costs over time. The same authors [21] presents airport operation for the year 2040 for three types of commuter aircraft. This has similar elements to the proposed methodology, in terms of battery technology progression projection.

In summary, current literature on airport infrastructure planning methodologies exist addressing different parts of airport and fleet decarbonisation transition. However, the combined comprehensiveness in terms of horizon progression/transition representation, more detailed fleet energy demand and on ground scheduling representation are limited, with methodologies only presenting snapshot viewpoints in time, not considering multi-year planning of the airport infrastructure, not conducting energy modelling for AEA and more detailed on ground time. All these combined will influence more intricately the airport upgrade requirements and expected operations.

As such, the proposed methodology aims to address these gaps and provide a means to evaluate the required airport infrastructure to facilitate the new aviation emissions goals and to meet net zero emissions with a more comprehensive representation. Within the proposed methodology, aircraft fleet is modelled for both conventional and AEA including the electrification transition over time. The infrastructure requirements are also presented in five years increments over horizon years, providing projections of the fleet decarbonisation achievements, aircraft energy cost, aircraft lateness, power and energy under transition pathways. This is processed in the methodology while also adhering to AEA charging requirements and minimising the number of battery chargers required. The paper demonstrates the use of the proposed methodology using real-world historical flight logs containing on ground time, aircraft type and destination. The fleet analysis incorporates operating cost and in particular fuel and electrical energy required to refuel or recharge the aircraft. This is also an important part of the operations planning as today's cost account for 20-30% operating costs [2], [22] and [23].

The remainder of the paper is organised as follows: Section II presents methodology for assessment of the infrastructure to support aviation decarbonisation. The use of the methodology is demonstrated through a case study in Section III. Section IV concludes the paper.

II. METHODOLOGY FOR PLANNING AIRPORT GROUND INFRASTRUCTURE

The methodology (as shown in Fig. 1) has a number of inputs which facilitate the airside demand modelling for both conventional aircraft and AEA. The airside energy demand modelling is conducted in 5 year increments to allow for technology progression and modelling of fleet transition and fleet composition over time. Associated airside infrastructural requirements are then projected for meeting the modelled fleet demand. This comprehensive approach allows for a more detailed picture of the airside requirements to be modelled. The

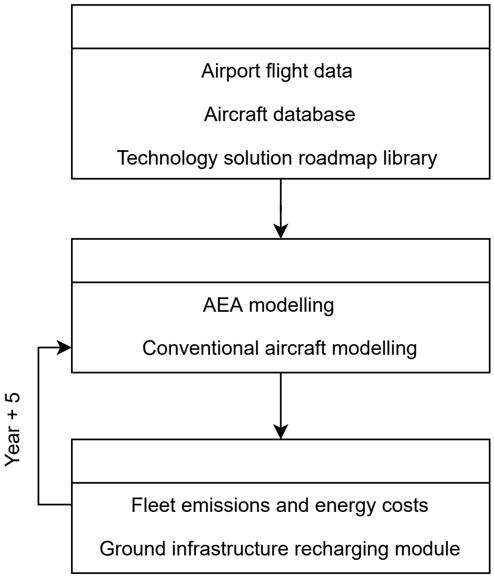


Fig. 1: High level methodology overview

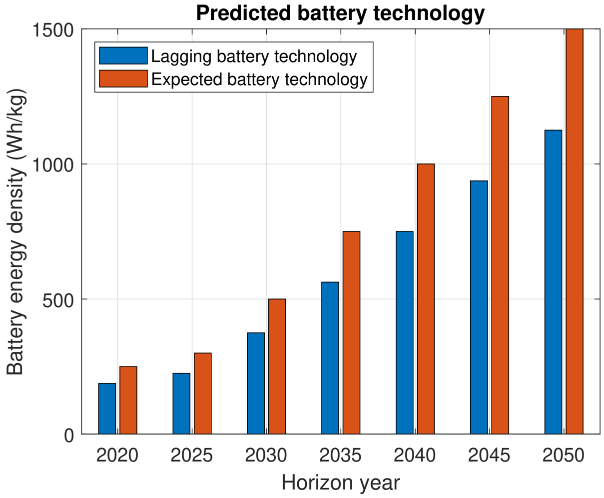


Fig. 3: Battery technology roadmaps

output from methodology is the solution pathway for the future airport infrastructure requirements to support decarbonisation with a viable combination of sustainable technologies.

A. *Inputs*

The methodology has three inputs: airport flight data, aircraft database, and the technology solutions library. Airport flight data is captured from historical flight operations for either an airliner or total flights at an airport. The flight data contain details of arrival and departure times, aircraft type, airliner operator, terminal, and stand number. The second input of the methodology are the aircraft class specifications and performance information. The aircraft database contains all aircraft within the airport flight data and include performance (take-off, climb, cruise velocities), engine efficiency (specific fuel consumption), aircraft weight specifications and aircraft aerodynamics - used in AEA and conventional aircraft flight modelling. The final input into the methodology is the technology solutions roadmap library which contains expected battery technology energy densities, predicted SAF blend ratio, and the energy cost for SAF, jet fuel and electricity over the horizon years.

B. *Airside energy demand modelling*

The first step of the methodology is to derive the airside energy demand. The energy demand is calculated through high fidelity modelling of the aircraft fuel burn and an assessment of the feasibility for AEA flight. The following two sub-sections present the aircraft modelling in detail.

1) AEA modelling: within this, high fidelity modelling of AEA is conducted as shown in Fig. 2 1A. Each flight model assesses energy and MTOW (maximum take-off weight) feasibility of electrification over the different points of the horizon years. Aircraft not meeting the electrification pre-assigned MTOW requirements will not be replaced with an electrical equivalent for the given horizon year. Additionally, fuel burn and emissions reduction is included in the model to represent improvement in future aircraft aerodynamics design. This includes evolutionary upgrades up to 2030 and revolutionary changes towards 2050 [7], [24]. These include optimised aerodynamics in the form of curved wingtips to reduce drag, smoothed wing surfaces, and new materials such as 3D printing and CFRP to reduce airframe weight [25].

The battery technology roadmaps project energy density progression and are presented in Fig. 3 [26]-[30] for both expected values for each horizon year and incorporate different progression rate factor options to explore scenarios with less than expected progression. The baseline roadmap projects Li-ion energy density to reach 400 Wh/kg in the near future and lithium-sulfur at 650 Wh/kg achievable in 15 years. Lithium-air capability is projected to be over 1000 Wh/kg. The future Li-ion technology with predicted enery density of 750 to 1500 Wh/kg makes it viable for electrified aircraft [31]. However, Li-air has many limitations including the limited ability to complete as many charge/discharge cycles as Li-ion [32], [33]. Although, promising research has been presented in addressing this draw back in [34].

Full flight mission profiles are modelled, including climb, cruise, loiter, land, and reserve segments as part of the demand modelling. The Breguet range equation for cruise [26], [35] was adapted for inclusion of state of charge (SoC) limits for AEA. A SoC limit is applied to represent more realistic cycling of the battery and cycle life preservation [36], whereby a constraint for SoC limit of 20 % was used [37]. AEA reserve was modelled in a similar fashion to conventional aircraft with an additional 6 % reserve of the total energy and the descent was assumed to consume no energy. As part of the demand modelling, electrification transition for given aircraft within the fleet will be assigned when the aircraft can complete all expected routes through electric flight. The AEA feasibility

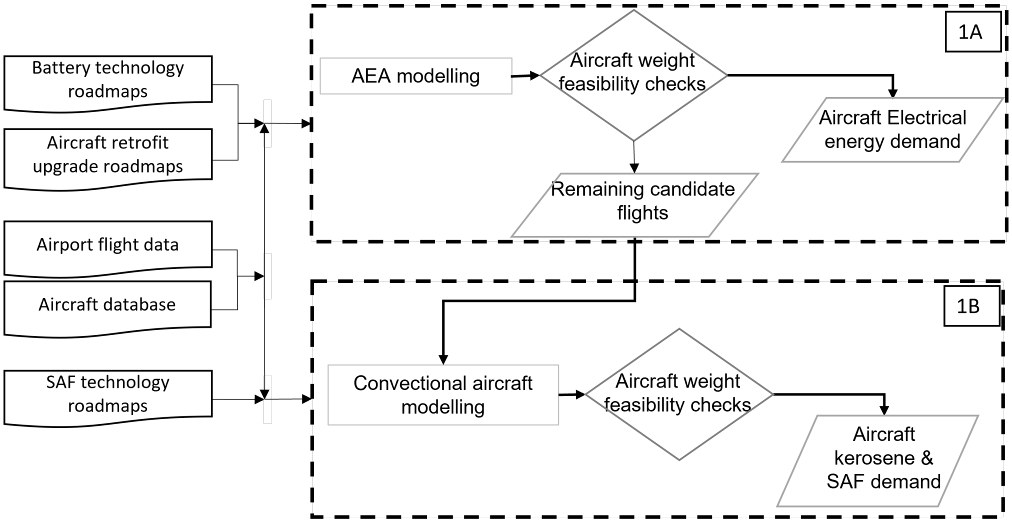


Fig. 2: Airside energy demand modelling methodology

check is performed to ensure the aircraft weight is within the MTOW. The method allows for aircraft that cannot be retrofitted with electric propulsion to remain conventionally powered. Furthermore, an assumption of the model is when a conventional aircraft is converted to AEA, over the life of the aircraft the on board battery technology remains the same in the subsequent horizon years. Providing the output of required battery weight for a given AEA, for a flight route and for a given horizon year. The predicted electricity cost for AEA charging over the horizon years was assumed to be 0.3 (£/kWh) similar to that of the UK in mid-2022. Although grid purchased electricity must be decarbonised with renewable sources such as wind, photovoltaic, and hydropower to allow for net zero emissions.

2) Conventional aircraft modelling: In conjunction to electrification demand modelling, conventional aircraft modelling is also part of the methodology as shown in Fig. 2 1B. The outputs include composition of kerosene and SAF demand to model SAF blend progression over the horizon years. Conventional aircraft modelling was performed for both jet and turboprop aircraft using Breguet range equation for cruise and the Breguet endurance equation utilsing climb and loiter, fuel fractions for landing, and reserve requirements [38]. This provides the output of required fuel weight for a given conventional aircraft, for a flight route and for a horizon year. SAF is produced from non-petroleum derived fuel from a wide variety of feedstock such as waste oils [6]. SAF can contribute to decarbonisation and is considered ”drop-in” fuels due to their similarities in chemical and physical properties to conventional Kerosene Jet-A1 [7]. The main hurdle to large scale application of SAF is the cost which is considerably higher than Kerosene Jet-A1 [7]. Currenly, SAF is blended with Kerosene Jet-A1 and can be used without modification to aircraft, with the first commercial flight using SAF operated by KLM in June 2011 [39]. At present SAF blend percentage is certified up to 50% [40]. SAF blend ratio roadmaps within literature present a number of different SAF percentages trajectories [2],[6] and [40]. Taking into consideration low economic viability, two separate SAF uptake percentages studies give an indication of the variation in future technologies. With high economic viability achieving 75% uptake in 2050, in contrast to low economic viability studies of 30% uptake in 2050 [40].

The cost for SAF was adopted from the predicted price for EU market from 2020 to 2050 [41]. Kerosene Jet-A1 horizon price is modelled as current day price mid- 2022 of 0.9 (£/L).

C. Airside infrastructural assessment

The following two sections presents the airside infrastructure deployment part of the methodology and allows the calculation of fleet annual emissions, energy cost, and the ground infrastructure recharging module requirements.

1) Fleet emissions and energy cost: The quantity of annual net carbon dioxide emitted over a horizon year for all aircraft is calculated based on the assumption that AEA flights are recharged with renewable energy sources and do not produce in-flight emissions. The CO_2 produced per kg of Kerosene Jet-A1 burnt and SAF is the CO_2 produced per kg of SAF was based on [42], [43]. The total energy cost required for all aircraft flights for a given horizon years is also calculated.

2) Ground infrastructure recharging module: The module takes the airport flight operations data from the airport, and evaluates arrival and departure times, enabling the calculation of time of aircraft on the ground. For a given flight, ground time (time between arrival and departure) is assigned as sufficient (without changes to the schedule) in the model if battery charge time is sufficient for the given onward journey energy requirements at the charger power rating. The quantity of chargers required at the airport to service the recharging of the electric fleet for a given horizon year is determined from an optimisation model that minimises the maximum number of chargers required to charge the fleet of AEA during a peak day for a given horizon year as follows:

$$S_t = min(max(\sum N_{h,t})) \tag{1}$$

where $N_{h,t}$ is the sum of the active chargers at any 30-minute time slot, h, within a day. Subject to 2:

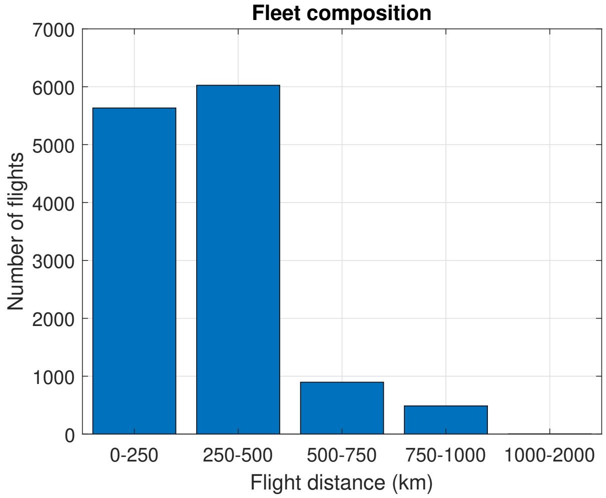


Fig. 4: Sample airliner distance analysis

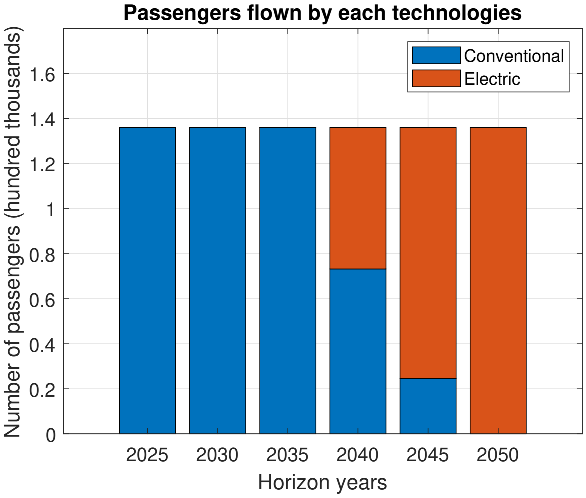


Fig. 5: Passenger flown for a given technology

$$h^c_{a,i} \leq [\frac{h^d_{a,i} - h^l_{a,i}}{30}], \forall q \in A_{long} \tag{2}$$

and

$$h^c_{a,i} \geq [\frac{h^d_{a,i} - h^l_{a,i}}{30}], \forall q \in A_{short} \tag{3}$$

where $h^c_{a,i}$ is the number of 30-minute time slots required to charge an electric aircraft a for a given flight route i. A_{long} are the subset of AEA in the fleet with ground times that are longer than the required charging time. Similarly, A_{short} is the other subset of the AEA fleet with ground time shorter than the required charging times. Arrival time from the flight logs is given by $h^l_{a,i}$ and departure time is $h^d_{a,i}$ in minutes of the day. The number of 30-minute time slots required to charge an aircraft is given by (4).

$$h^c_{a,i,t} = [\frac{2 \times E^{electric}_{a,i,t}}{P_c}] \tag{4}$$

where $E^{electric}_{a,i,t}$ is the energy required by an aircraft a, of flight i, for a given horizon year t, in (MWh) and P_C is the charger capacity in (MW). To date, EV charging infrastructure utilise high power DC fast chargers which have a rating up to 360 kW. With key research focus on producing Megawatt chargers for electric lorries [44] and for aircraft such as Lilium Jet 1 MW chargers have an expected entry into service (EIS) of 2024 [45]. Besides establishing the number of chargers to service the aircraft charging demand on the peak day, the module also evaluates the charging schedule of the AEA flights on the peak day. It also evaluates the utilisation ratio of the chargers on the peak day. In addition, it presents the level of lateness of the aircraft if charging time is longer than the initially planned ground time of the aircraft.

III. CASE STUDY: GLASGOW INTERNATIONAL AIRPORT

A sample airline's flight operations data at Glasgow International Airport for the year 2019 was made available to support the project and to demonstrate net zero emission planning through the use of the methodology. The case study is based on a regional airliner at Glasgow Airport. Commercial aircraft can be classified into three types regional, narrow-body, and wide-body aircraft. The selected airliner operates a number of aircraft over relatively short haul operations as can be seen from Fig. 4, with 43 % of flights serving routes under 250 km, 46 % serving distances between 250-500 km, with less than 11 % of flights serving distances over 500 km. The fleet comprises number of different aircraft including both regional jet (ERJ-135 and ERJ-145) and turboprop (ATR 42, ATR 72, DHC-6, SB20, and SF34) aircraft. For the purpose of this study, the number of passengers flown is assumed to be a constant over the horizon years.

A. Technology progression as expected

The number of passengers flown per aircraft technology over the horizon years and the decarbonisation achieved are presented in Fig. 5 and Fig. 6 respectively. As can be observed, all passengers are flown on a conventional aircraft in initial years, it is not until 2040 that the fleet begins to transition

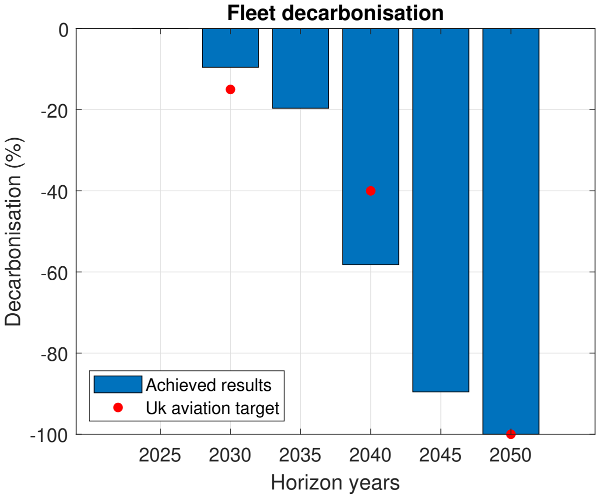


Fig. 6: Fleet decarbonisation

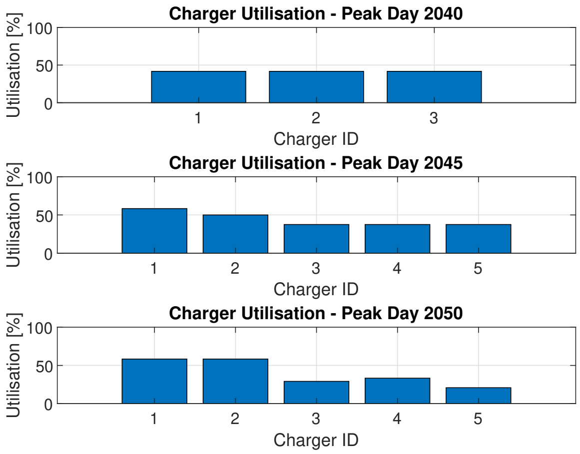


Fig. 7: Mobile charger utilisation

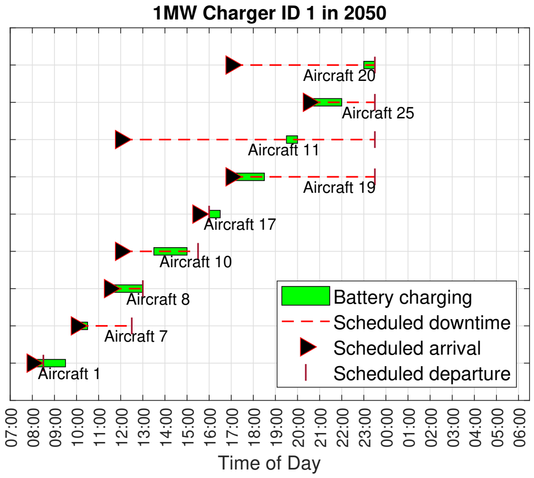


Fig. 8: Mobile charger scheduling

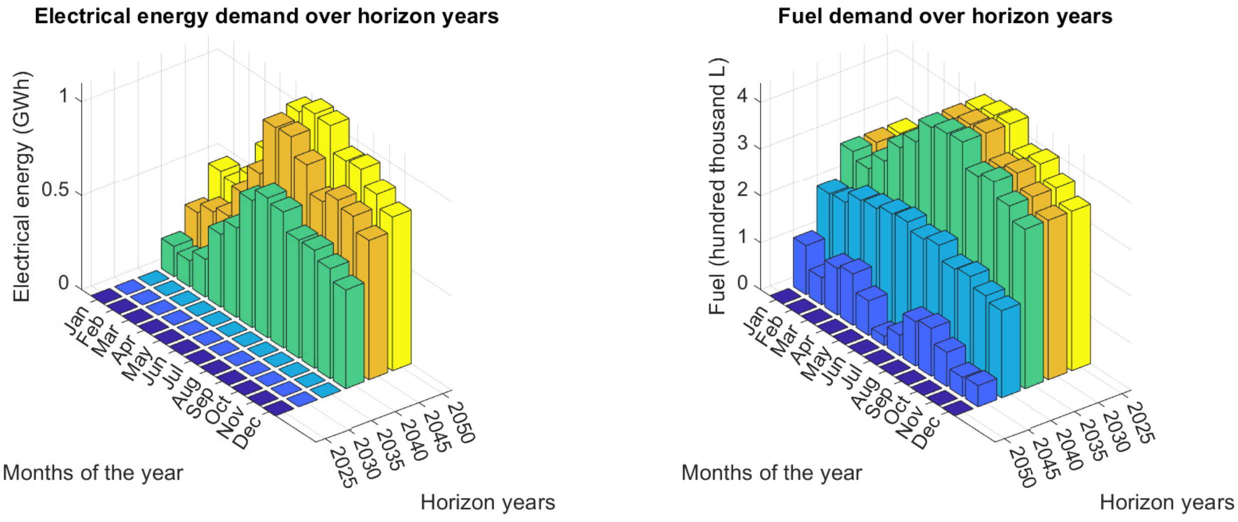
to AEA. The main reason behind this is due to low energy density of battery in the beginning horizon years.

Before 2040, the contribution towards decarbonisation is only through the use of SAF as shown in Fig. 6. It should be noted that although the use of SAF introduces decarbonisation, it is still considered as a conventional aircraft type (Fig. 5). For the initial years up to 2030 the decarbonisation goals are not met (Fig. 6). In 2040, the decarbonisation goals are met through the utilisation of both AEA and conventional aircraft being partly fueled by SAF. In year 2050 net zero emissions are achieved through the replacement of all conventional aircraft with AEA.

In Fig. 7, the number of mobile chargers required to support the electrification of the fleet over the horizon years is presented along with their utilization. The chargers are required to be introduced from 2040 with additional upgrade required in 2045. The change from 2045 to 2050 is minimal with approximately 15% further decarbonisation, however, this marginally impacts the electrical demand as in Fig. 9a.

The detailed charger scheduling can be generated for each of the chargers, an example for one mobile charger presented in Fig. 8. The mobile charger is rated at 1 MW presenting the schedule for the peak day in 2050, indicating the arrival and departure time of AEA, and the time required to charge the battery to fulfill the energy requirements for next flight. A number of aircraft are unable to be charged in time, such as aircraft 1 and 17 in Fig. 8. On the peak day in horizon year 2050, 46 % of flights would be delayed when a 1 MW charger is utilised. The average delay for AEA with 1 MW mobile charger was 1 hour and the maximum delay time of 4 hours was observed. If the mobile charger rating is increased to 2 MW, the percentage of delayed flights is reduced to 19 %, resulting in an average delay time half an hour for AEA.

Fig. 9a shows the monthly electrical demand over the horizon years, with a large increase in electrical demand in 2040 and another leap in the penultimate year. The curvature



(a) Electrical demand

(b) Fuel demand

Fig. 9: Energy and fuel demand over horizon years

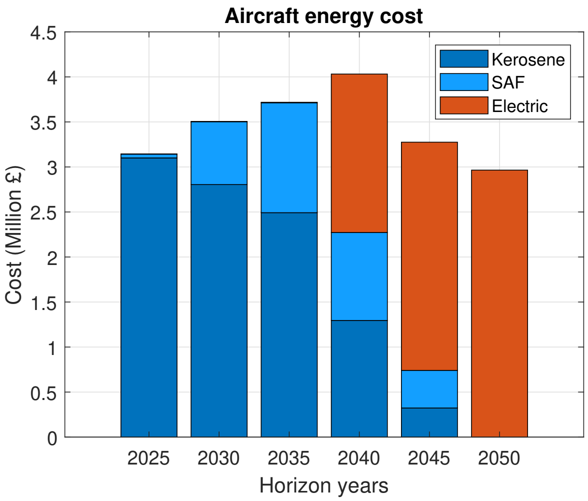


Fig. 10: Aircraft energy cost over horizon years

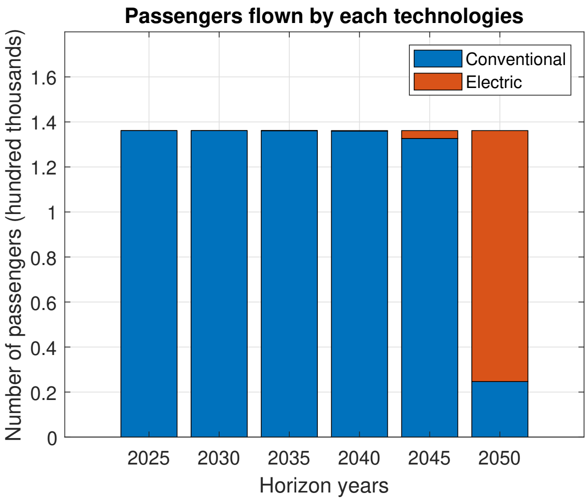


Fig. 11: Passenger flown for slowed technology progression

of the graph reflects the increase flights and passenger demand during the summer months.

Fig. 9b presents the fuel demand which includes both Kerosene Jet-A1 and SAF fuel together. From horizon year 2025 to 2035 there is no change, as there are no aircraft improvements applied to conventional aircraft. In 2040 there is a change due to the introduction of AEA, which then results in zero fuel demand in 2050.

The aircraft energy cost are presented in Fig, 10. As can be observed, the costs increase slightly from 2025 to 2035 due to the introduction of SAF. During these years SAF is considerably more expensive than Kerosene Jet-A1. After the horizon year 2040 the aircraft energy cost reduces due to conventionally powered aircraft being replaced with AEA. Although these are predicted costs, the cost of electricity could be further reduced by onsite renewable energy production.

B. Slowed technology progression

Keeping the uncertainty in technology progression in mind, this section provides findings when the technology roadmaps are hampered. The study presents a case where battery technology progession in terms of achevable power denity is slower than projected within the roadmaps and the uptake of SAF is limited as well. It is assumed that the progression in battery technology is only 75 % of its projected growth in Fig. 3, while the uptake in SAF is 30 % in 2050 instead of 75 % as projected in roadmaps. The lagging battery technology results in a slower adoption of AEA, with a small portion of passenger being flown in 2045 and a large uptake in 2050, see Fig. 11.

As a result, decarbonisation goals are not met in any of the horizon years, as seen in Fig. 12. This implication results in fewer passenger flying on AEA and therefore fewer mobile chargers are required but with the detriment of not being able to meet any decarbonisation goals.

IV. CONCLUSIONS

This paper presents a methodology to inform the power and energy requirements for refuelling infrastructure at airports to enable and support the transition to net-zero emissions flight. The proposed methodology utilises historic airport logs, technological progression roadmaps, along with aircraft mission feasibility to assess the sustainable airport infrastructure transition requirements over horizon years. The novelty is brought through combined comprehensiveness in terms of horizon progression/transition representation, more detailed fleet energy demand and on ground scheduling representation through delay flight analysis. The inclusion of these factors influence more intricately the airport upgrade requirements and expected operations. The methodology was utilised to assess the infrastructure requirements to support the decarbonisation of a sample airliner at Glasgow airport. The paper also explored the implication of slower technology advances to demonstrate the large uncertainty faced in sustainable aviation and the effects on decarbonisation goals. The perceived benefits of the methodology can be summarised as follows. Airport operators will be informed of the progression in infrastructural requirements to enable the operations of AEA, which feeds

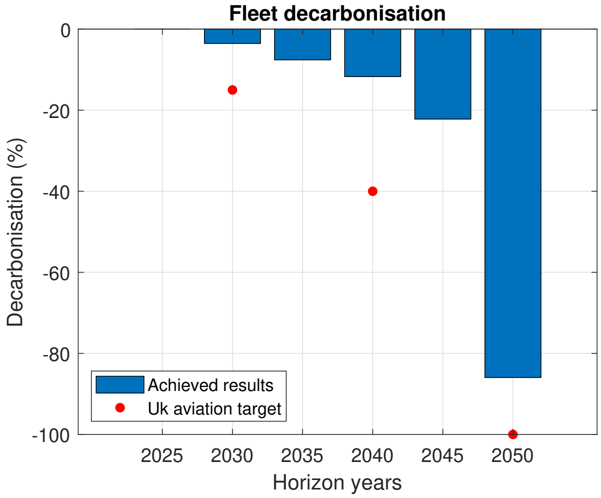


Fig. 12: Decarbonisation for slowed technology progression

into their strategic investment planning. Airline operators will have an idea of when some of their conventional fleet may be ready for retrofitting with electric propulsion. Policymakers will be informed of the role of technology progression in achieving policy targets hence informing associated support that may be required to the industry. Future advancement of this methodology includes incorporation of hydrogen powered aircraft, and future passenger demand increase.

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