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Impact of emerging sustainable aircraft technologies on the existing operating ecosystem

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ABSTRACT

Emerging sustainable aircraft technologies—such as sustainable aviation fuel, electric and hydrogen propulsion—are expected to play a major role in the decarbonization of the aviation sector. Nevertheless, at present, the exact impact that their deployment will have on the existing operating ecosystem is not yet clear. To shed some light on this area, this paper adopts an exploratory research approach based on the collection of impact assessments through semi-structured interviews with domain experts. In particular, we involve 22 individuals affiliated with the most important stakeholders in the European and American aviation industries, including airlines, airports, aircraft and engine manufacturers, fuel producers, government agencies, universities and research centers, and aviation industry experts. Our results, that are presented in the form of spider charts and tables, provide an exhaustive and comprehensive picture of all the impacts that the examined technologies are expected to have on airline operations, airport operations, and airside airport infrastructure. What emerges is that SAF, even if used in high percentages, is anticipated to have a fairly marginal effect. In contrast, electric and hydrogen aircraft propulsion are foreseen to be much more disruptive, having a similar medium-to-high impact on many operations and parts of the airport infrastructure. In light of this finding, we propose the development of multi-technology airport infrastructural assets as a solution not only for the possible onset of lock-in effects but also for the chicken and egg dilemma currently affecting the sector.

1. Introduction

At present, aviation accounts for approximately 12% of carbon dioxide (CO2) emissions from all transportation sources and about 2–3% of human-produced CO2 pollution (ICAO, 2019; Amankwah-Amoah, 2020; Overton, 2022). Besides, the sector is also responsible for a number of highly polluting non-CO2 emissions that include soot particles, particulate matter, unburnt hydrocarbons (HC), nitrogen oxides (NOx), carbon monoxide (CO), and sulfur oxides (SOx) (Modarress and Ansari, 2020). All of these emissions combined cause aviation to have a significant environmental impact, which is roughly twice that of CO2 alone (Gössling, 2020). It should not then come as a surprise that, in recent years, the sustainability of the aeronautical industry has become an ever more important priority on the political agenda of the Western world (Ryley et al., 2020). In Europe, this resulted in the development of ambitious emission-reduction plans, the most relevant ones being ‘Flightpath 2050’ and ‘Destination 2050’ (European Commission, 2011; Van der Sman et al., 2021). According to these plans, by 2050, the European aviation sector will have to achieve: (1) net-zero CO2 emissions; (2) a 90% reduction in NOx emissions; and (3) emission-free aircraft movements on the ground (European Commission, 2011; Van der Sman et al., 2021). Similarly, in the United States, the Federal Aviation Administration recently announced its new ‘Aviation Climate Action Plan’, which is aimed at ensuring that the US aviation sector will reach net-zero greenhouse gas emissions by 2050 (FAA, 2021a,b). Of the many strategies that will have to be implemented simultaneously to achieve these targets, the deployment of new aircraft technologies—such as sustainable aviation fuel (SAF) and alternative aircraft propulsions—appears to be the most promising one (ATAG, 2021; ICAO, 2022). However, since new technologies differ (to different extents) from the currently employed jet fuel, their deployment will inevitably have a certain impact on the existing aviation ecosystem. In this regard, the literature reveals that, while the adoption of SAF is foreseen to be relatively straightforward (Bauen et al., 2020; ATAG, 2021; Van der

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Sman et al., 2021), alternative aircraft propulsions are instead anticipated to be much more disruptive, requiring the implementation of numerous changes in multiple areas (McKinsey, 2020; WSDOT, 2020; Connected Places Catapult, 2022; Postma-Kurlanc et al., 2022). Nevertheless, since they generally have a wider focus, existing studies fail to clearly indicate—in an exhaustive and comprehensive way—how emerging aircraft technologies are expected to impact operations and infrastructure. This is problematic because without a complete and thorough understanding of the exact effect that new technologies will have on the different elements of the current operating environment, it is difficult to grasp the full implications associated with their adoption. As a result, it is challenging to develop well-grounded technology deployment roadmaps. This paper aims to address this gap and poses the following research question:

> How and to what extent are emerging sustainable aircraft technologies expected to impact the existing operating ecosystem?

For the purpose of this study, the 'existing operating ecosystem' is defined as consisting of three contiguous dimensions: airline operations, airport operations, and airside airport infrastructure. Furthermore, this study's scope comprises solely SAF, electric aircraft propulsion, and hydrogen aircraft propulsion. This is because these are the predominant technologies that, according to the existing academic and industrial literature, will lead the decarbonization of the aviation sector in the next decades (ATAG, 2020; Bauen et al., 2020; McKinsey, 2020; Van der Sman et al., 2021; Hoelzen et al., 2022). It is important to note that: (1) when referring to 'electric aircraft propulsion', we exclusively mean the all-electric option (hybrid-electric propulsion is not considered), and (2) when discussing 'hydrogen aircraft propulsion' we refer to liquid hydrogen propulsion only (gaseous hydrogen propulsion is beyond the scope of our research). Finally, this study exclusively focuses on commercial aviation, with an emphasis on the short-haul market segment, which is regarded as the most promising one for the adoption of electric and hydrogen propulsion technologies (Gnadt et al., 2019; Berger, 2020b).

We adopt an exploratory research approach based on the collection of qualitative data through semi-structured interviews with domain experts. We involve 22 professionals affiliated with multiple aviation stakeholders in both the European and American markets, including airlines, airports, aircraft and engine manufacturers, fuel producers, government agencies, universities and research centers, and aviation industry experts.

Based on our results, we draw new insights that policymakers and industrial actors should take into account when making decisions on the deployment of emerging sustainable aircraft technologies, planning investments in infrastructure, or changes to aviation operations. The rest of the paper is organized as follows. Section 2 discusses the limitations of the literature in more detail. Section 3 describes the data collection and analysis processes. Section 4 reports the findings of the study, which are summarized in the form of spider charts and tables. Section 5 discusses the results, while Section 6 concludes the paper.

2. Challenges associated with the deployment of emerging sustainable aircraft technologies

The scientific and professional literature tends to examine emerging sustainable aircraft technologies from a rather technical perspective, concentrating in particular on technological feasibility, specific characteristics, and environmental benefits (e.g., National Academies of Sciences, Engineering, and Medicine, 2016; IATA, 2019; Domone, 2020). Only a minority of studies address the deployment of these technologies and discuss their potential impacts at operational and infrastructural levels. Two main dimensions of analysis can be distinguished: a single technology and the entire industrial sector. The first group of studies examines the deployment of technologies independently, analyzing one technology at a time. The reports focused on SAF (e.g., ATAG, 2017; ICAO, 2018; Holladay et al., 2020; Berger, 2020a) concentrate, in particular, on the challenges associated with their large-scale implementation (e.g., lack of sufficient sustainable feedstock, issues with scaling up production, logistical and supply chain difficulties). The analysis they offer in terms of operational and infrastructural impact is fairly limited, as it exclusively remarks how, up to the blend limit, SAF can be generally considered compatible with the existing operating environment. Studies on electric aircraft (e.g., Schmidt et al., 2014; Gnadt et al., 2019; Schäfer et al., 2019; WSDOT, 2020; Staack et al., 2021) discuss the new infrastructural requirements, such as the need for an energy generation plant, facilities for charging and storing batteries, and battery swap stations. They also highlight the generic operational impact caused by the low energy density of batteries and the battery charging/swapping needs during turnarounds. Finally, the hydrogen aircraft-focused studies (e.g., Rondinelli et al., 2017; McKinsey, 2020; Mangold et al., 2022; Postma-Kurlanc et al., 2022) outline the most significant challenges at both an operational level (e.g., difficulties with the safe handling of LH2, the need to completely redesign the refueling procedure, restrictions on parallel turnaround operations) and an infrastructural one (e.g., LH2 compatibility issues with existing infrastructure, the need to install a completely new fuel delivery system). While it is true that these studies offer a good level of detail, they lack in exhaustiveness. This is because they concentrate on certain areas only, hence failing to comprehensively indicate how new technologies are expected to impact all the key processes, operations, and infrastructural assets in the existing operating environment. The second group of studies analyzes and compares different technological options at the industry level. For example, Kivits et al. (2010) offer an overview of the overall impacts of hydrogen, electricity, and biofuels on the aviation ecosystem, highlighting the high-level challenges connected with their adoption (e.g., incompatibility with existing aircraft design, fuel transport and storage difficulties, and impact on airport planning). Similarly, as part of wider-focus studies that consider multiple technological options, ATAG (2021) and Van der Sman et al. (2021) examine the main systemic issues associated with the implementation of SAF, electric, and hydrogen aircraft propulsion (e.g., current barriers, technological limitations, and new infrastructural requirements). Although these studies enable an effective comparison of emerging technologies in terms of general challenges, requirements, and overall disruption, they do not allow to gain a thorough understanding of their full operational and infrastructural impact due to the lack of a sufficient level of detail.

All things considered, it can be stated that, together, the two identified groups of studies give a good general overview of the problem. However, due to the fact that they have different scopes, they fail to provide a comprehensive and detailed picture of all the impacts that new sustainable aircraft technologies are expected to have at operational and infrastructural levels. Addressing this shortcoming is necessary because without a complete and thorough understanding of the exact disruption that each technology is anticipated to have in each area, policymakers and industrial actors cannot effectively prepare or coordinate for the implementation of the required changes.

3. Methods

3.1. Research approach

Given the exploratory nature of the study, we employed a qualitative research approach. This method allowed us to gain a better understanding of the complexity and uncertainty that accompany the deployment of new sustainable aircraft technologies, as well as their potential impact on aviation operations and infrastructure. Specifically, we opted to follow the interview research method outlined by Ryan et al. (2009) and Bullock (2016).

3.2. Data collection

In terms of geographical boundaries, we limited the focus of our research to the European and American aviation markets. This is because, despite some differences in regulatory, financial, and competitive dynamics, both markets have very similar levels of economic development, modernization, and technological advancement (Vergara, 2019).

To answer our research question, it was crucial to engage the most important stakeholders in the aviation industry, who could provide us with a thorough assessment of the expected impact of new aircraft technologies in the three areas of investigation. Therefore, we identified the following key categories of stakeholders: airlines, airports, aircraft and engine manufacturers, fuel producers, government agencies, universities and research centers, and aviation industry experts. Within each category, we selected potential interviewees based on their responsibility and expertise in aviation sustainability and/or new aircraft technologies. In total, we interviewed 22 individuals (Table 1).

All interviews were conducted by the first author of this paper between August 2021 and October 2022. They ranged from 20 to 60 min in length and resulted in a total of 768 min of interview time. The vast majority of interviews were conducted remotely using Microsoft Teams, Zoom, or Google Meet. However, one interview (respondent H) was conducted in person. Regardless of the format, all interviews were recorded with the interviewee's consent.

The interview protocol was based on the 'research framework' described in Appendix A, which lists the key activities and assets in the three areas—airline operations, airport operations, and airside airport infrastructure—that shape the industry ecosystem. The interviewees were asked to provide precise assessments of the expected operational and infrastructural impacts associated with the adoption of new aircraft technologies. Experts' assessments were collected in terms of relative magnitude, according to the impact assessment grading scale shown in Table B1 (Appendix B). Considering the breadth of the topic, the interviews were concentrated on the specific area(s) of expertise of each respondent. All interviewees were informed that the fundamental assumption is that future hydrogen and electric aircraft will continue to have a conventional tube-and-wing configuration, such as that of the Airbus ZEROe turbofan aircraft, the FlyZero narrow-body concept aircraft, and the Wright Spirit electric plane (Airbus, 2022; Postma-Kurlanc et al., 2022; Wright Electric, 2022).

3.3. Data analysis

After each interview, an accurate transcript was elaborated with the help of automatic transcription software. All transcripts, together with the interview notes, were examined using ATLAS.ti, a qualitative data analysis program. The comments provided by the interviewees were coded in terms of 'nature of impact' (WHAT), 'reason behind the impact' (WHY), and 'justification for the suggested impact assessment'. Then, we converted the color-based impact assessments into numeric values according to the impact assessment grading scale (Table B1, Appendix B). In the vast majority of cases, the obtained values were simply a transformation of the color-coded impact assessments recorded during the interviews into numbers. However, in the few cases where no explicit impact assessments were provided by the interviewee but sufficient secondary data was available (e.g., comments, remarks, and observations), we derived an estimated impact assessment ourselves. It has to be stressed that this extrapolation was performed exclusively when the collected data were enough to ensure a high confidence level. When this could not be guaranteed, the response was dismissed. A color-coded summary of all the impact assessments included in the study after the coding process, that clearly shows the contribution of each interviewee in each area, is provided in Appendix B (Tables B2–B4).

To minimize biases, the co-authors performed the coding of selected interviews independently and then analyzed the results together. This allowed not only to refine the coding process, but also to validate its reproducibility and replicability. After this initial step, the first author continued the coding of the rest of the interviews autonomously. Once the coding was concluded, the average impact assessment value for each operation and infrastructural asset was calculated as the geometric mean of the collected assessments in accordance with the following formula:

$$\left(\prod_{i=1}^{n} x_i\right)^{\frac{1}{n}} = \sqrt[n]{x_1 \bullet x_2 \bullet x_3 \bullet \cdots \bullet x_n}$$

where i = 1, …, n is the number of collected experts' assessments for each item.

This was done because the geometric mean is generally regarded as the best method for aggregating experts' judgments when such experts are considered equally knowledgeable on the subject (Cooke, 1991).

Table 1
List of aviation stakeholders included in the study.

Type of stakeholder	Reference market	Interviewee's job title (and background)	Interviewee ID
Airline	European	Director of Flight Operations (Airline Captain)	A
		Sustainability Manager (Environmental Specialist)	B
Airline	American	Sustainability Manager (Aviation Manager)	C
Airport	European	Environment Director (Mechanical Engineer)	D
Airport	European	Head of Environmental Affairs Unit (Airport Manager)	E
Airport	European	Head of Sustainability and Environment (Airport Manager)	F
Airport	American	Chief Innovation Officer (Aeronautical Scientist)	G
Aircraft manufacturer	American	Chief Executive Officer (MBA graduate)	H
Aircraft manufacturer	European	Environmental Engineer (Aeronautical Engineer)	I
		Hydrogen System Engineer (Mechanical Engineer)	J
Engine manufacturer	Global	Performance Engineer (Aerospace Engineer)	K
Fuel producer	Global	Technical Services Manager (Mechanical Engineer)	L
Government agency	European	Sustainability Expert (Environmental Specialist)	M[a]
Government agency	American	Program Manager (Aerospace Engineer)	N
University	European	Professor (Aerospace Engineer)	O
University	European	Senior Researcher (Industrial Engineer)	P
University	American	Researcher (Aeronautical Engineer)	Q
Research center	European	Head of Transportation (Aeronautical Engineer)	R
		Researcher (Sustainability Specialist)	S
Research center	European	Airport Operations Specialist (Aviation Manager)	T
Aviation industry expert	European	Consultant and Researcher (Electrical Engineer)	U
Aviation industry expert	American	Director and Senior Technical Fellow (Aerospace Engineer)	V

[a] Due to unavailability for a live interview, respondent M provided a detailed written response instead.

These geometric means, together with the minimum and maximum impact ratings, were finally used to create the spider charts presented in the following section.

4. Results

This section reports the expected impacts of each technology on airline operations, airport operations, and airside airport infrastructure. The spider charts (Figs. 1–3), whose scales range from no impact (1) to high impact (4), depict the minimum, maximum, and average values of the impacts indicated by the interviewees. They also show the areas of higher disagreement among experts, which are represented as the distance between the minimum and maximum values of the same impact category. The tables (Tables 2–10) summarize the nature and cause of the impacts.

4.1. SAF

All interviewees agreed that SAF is expected to have no impact on airline operations, even if used in high percentages (Fig. 1a and Table 2). This is because, as reported by multiple respondents (C, F, L, P), the maximum SAF blend limit, currently set at 50% for most feedstocks, will be increased by competent authorities only once it is clearly demonstrated that aircraft performance is not affected in any way. When looking at the average line in Fig. 1b, it can instead be noticed that the only airport operation expected to be impacted, in a minor way, is aircraft maintenance. Specifically, numerous interviewees (D, L, N, P, S) highlighted how, due to low aromatics and potentially different chemical properties, high percentages of SAF may have a negative effect on the engine seals, filters, fuel pumps, and fuel systems of older aircraft. Since these parts would then most likely have to be inspected more frequently, there could be a slight change in the maintenance process. Interviewees L and M remarked that a low impact may also be expected in the hydrant system refueling operation, as there will be a need to perform extra safety checks.

In terms of airport infrastructure, both the hydrant refueling system and fuel depot are expected to be marginally impacted (Fig. 1c and Table 4). More specifically, three interviewees (D, N, S) remarked that high quantities of SAF may have a detrimental effect on certain parts of the hydrant refueling system (e.g., seals, pumps), similarly to what is expected for the engines and fuel systems of older aircraft. Interviewees D and P also highlighted how the use of the hydrant system will result in a reduced fuel supply flexibility at airports. In particular, as explained by respondent D:

> *"All airlines, irrespective of their individual requests, will receive the specific SAF blend chosen by the airport operator."*

This is due to the fact that the hydrant system, not having segregated pipelines, is unable to handle different fuel blends simultaneously. In terms of fuel depot, the impact assessment evaluations are more varied: while most respondents gave a 'no impact' rating, interviewees L and M expressed the view that a low-to-medium impact may be expected. This is because, being necessary to store SAF blends in segregated fuel tanks, some infrastructural changes may be required (unless effective accounting solutions—such as 'Mass Balance' and 'Book & Claim'—are implemented).

4.2. Electric aircraft propulsion

As shown in Fig. 2, the interviewees provided rather dispersed evaluations in terms of expected impacts of electric aircraft propulsion. The minimum and maximum impact assessment lines are pretty far apart, denoting a relatively lower level of agreement among the experts compared to SAF. This is likely due to the fact that the electric aircraft propulsion technology is still under development, and thus deeper uncertainties exist at present.

4.2.1. Impact on airline operations

The expected average impact of electric propulsion on airline operations (Fig. 2a and Table 5) ranges from low to medium in most areas. For aircraft preparation procedures, the impact varies from none-to-low (with swappable batteries) to high (for plug-in aircraft). In the first case, the turnaround time should not change significantly, meaning that aircraft preparation procedures would remain mainly unchanged in terms of timing and format (respondents H, O, S). In the second case instead, the required battery recharge time would considerably elongate the turnaround time (respondents M, Q). In turn, this would result in a major change in the aircraft preparation process, which at present is normally calibrated for a 30 to 35-min turnaround. Regarding push-back and taxi procedures, while three interviewees (M, O, Q) foresee minimal impacts, experts H and N expect more substantial changes. In particular, respondent H stated:

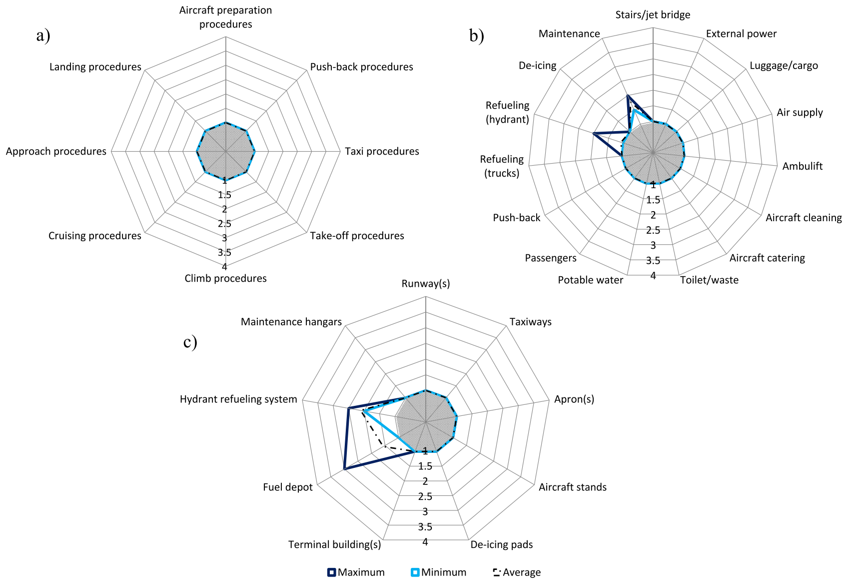

Fig. 1. Impact of SAF on: (a) airline operations; (b) airport operations; and (c) airport infrastructure (detail).

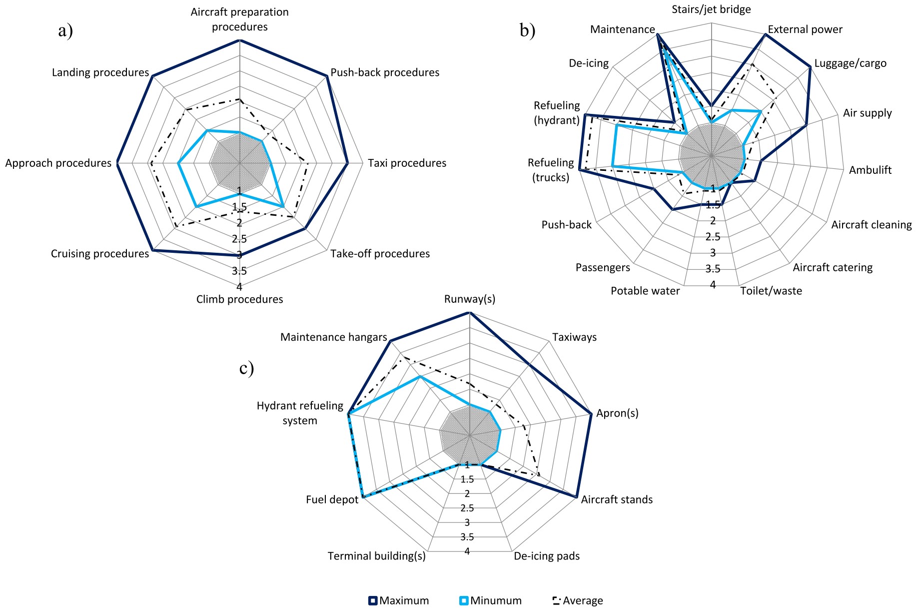

Fig. 2. Impact of electric propulsion on: (a) airline operations; (b) airport operations; and (c) airport infrastructure (detail).

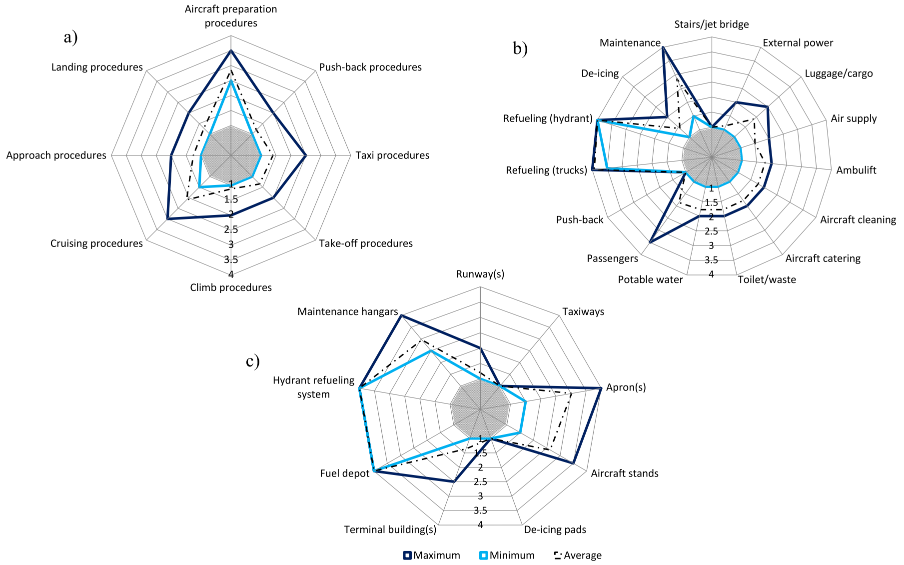

Fig. 3. Impact of hydrogen propulsion on: (a) airline operations; (b) airport operations; and (c) airport infrastructure (detail).

> "Push-back and taxi procedures will be different because we will switch to an electric tug. You know how today sometimes you have to taxi for 20 or 30 minutes? We do not have the energy capacity for that. So there is an expectation that there will be some sort of an electric tug that, after push-back, will pull you all the way to the runway holding point or thereabouts."

Respondent N provided even further details on how the taxi operation may be affected:

> "There has to be some accommodation for an electric aircraft to be able to preserve its energy, either by shutting down [its engines] in the event of a delay or by having a different way to move from the gate to the runway. This is because it cannot waste a lot of its energy just taxiing out and sitting there [at the holding point] waiting to get on with its departure."

Interviewees O and Q highlighted how, thanks to reduced engine noise, electric aircraft could fly more direct departures, which would have a certain impact on both take-off and climb procedures. The average impact on cruising procedures is expected to be fairly high due to: i) the low energy density of batteries, which results in a significantly reduced aircraft range (respondents O and Q); ii) the need for cruising at the most efficient altitude for battery cooling (respondent N). Finally, since the weight of electric aircraft will not change during flight, the approach and landing speeds may be higher (interviewee Q). Furthermore, just like for the take-off and climb phases, there was a shared view that the approach path could be much more direct due to lower engine noise. Interviewee O also remarked that:

> "The descent and approach procedures could be different because the descent angle and speed may be changed to exploit the windmilling

Table 2
Impact of SAF on airline operations (detail).

AIRLINE OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Aircraft preparation procedures	8	No impact	No impact
Push-back procedures	8	No impact	No impact
Taxi procedures	8	No impact	No impact
Take-off procedures	8	No impact	No impact
Climb procedures	8	No impact	No impact
Cruising procedures	8	No impact	No impact
Approach procedures	8	No impact	No impact
Landing procedures	8	No impact	No impact

Table 3
Impact of SAF on airport operations (detail).

AIRPORT OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Stairs/jet bridge connection/disconnection	9	No impact	No impact
External power connection/disconnection	9	No impact	No impact
Luggage/cargo loading/unloading	9	No impact	No impact
Air supply connection/disconnection	9	No impact	No impact
Ambulift connection/disconnection	9	No impact	No impact
Aircraft cleaning	9	No impact	No impact
Aircraft catering	9	No impact	No impact
Toilet servicing/waste drainage	9	No impact	No impact
Potable water servicing	9	No impact	No impact
Passenger embarking/disembarking	9	No impact	No impact
Push-back	9	No impact	No impact
Refueling via trucks	9	No impact	No impact
Refueling via hydrant system	9	Slight change in process (additional safety checks)	Need to ensure that receiving aircraft (a/c) is compatible with the percentage of saf in the fuel
Aircraft de-icing/anti-icing	9	No impact	No impact
Aircraft maintenance	7	Slight change in process (more frequent inspection of certain parts)	Possible impact of high percentages of saf on: engine seals, filters, fuel pumps, and fuel systems of older a/c

> effect of the electric motor propellers – this would allow for partial recharging of the batteries."

All these factors will inevitably affect both the approach and landing procedures, which are expected to be subject to an average low-to-medium impact.

Table 4
Impact of SAF on airport infrastructure (detail).

AIRPORT INFRASTRUCTURE	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Runway(s)	8	No impact	No impact
Taxiways	8	No impact	No impact
Apron(s)	8	No impact	No impact
Aircraft stands	8	No impact	No impact
De-icing/anti-icing pads	8	No impact	No impact
Terminal building(s)	8	No impact	No impact
Fuel depot	6	Need to have multiple, segregated fuel tanks	Different saf blends have to be stored separately
Hydrant refueling system	4	Possible impact on certain parts (if SAF is used in high percentages) Reduced fuel supply flexibility	Low aromatics and potentially different chemical properties of SAF Unable to handle different fuel blends simultaneously
Maintenance hangars	8	No impact	No impact

4.2.2. *Impact on airport operations*

As reported in Fig. 2b and Table 6, the average impact on airport operations is expected to be considerably variable, affecting some processes significantly (such as refueling and maintenance) while leaving others nearly unchanged. Interviewees N, O, Q emphasized that, for plug-in aircraft, the primary constraint for many operations would be maintaining a safe distance from the high-power battery recharging connector at all times. The external power connection/disconnection process is expected to be significantly impacted because, in the case of plug-in aircraft, the external power connector is also going to be used for the purpose of recharging the aircraft batteries during turnaround. Since high voltages and currents will be flowing through the external power cables, a whole new range of safety procedures will have to be designed and implemented (respondents N, O, Q). In the case of swappable-battery aircraft, some changes to luggage/cargo loading/unloading operations will be required since, in addition to luggage and cargo, ground handlers will also have to load/unload the aircraft batteries (respondents H, N, O). Interviewee R remarked that, due to battery weight, new ground support equipment will probably have to be used during this process. While three out of four experts (H, M, O) reported that no impact is expected on the air supply connection/disconnection operation, interviewee N highlighted that:

> "There may be a new demand for air supply for cooling, especially in warm climates. If you are using electrics, you would have to keep the batteries cool and be very aware of their temperature. That might put a big additional load on the cooling for air supply, and also affect the procedures and equipment."

The push-back operation is expected to remain largely unchanged, with the only consideration being the potential increased aircraft weight due to the extra batteries (respondent M). Refueling will undergo a total change in the process since, instead of liquid fuel, the refueler will have to handle electricity. For swappable-battery aircraft, the refueling operation will involve replacing discharged batteries with new ones, while plug-in aircraft will require fast-charging via high-voltage connectors and cables. In both cases, new safety measures and procedures will have to be designed and implemented (respondents H, M, N, O, Q). No impact is expected on the de-icing/anti-icing operation, except for the fact that, as reported by respondent N:

> "Extra caution will have to be used to avoid inadvertent spraying of the de-icing/anti-icing fluid into the extra vents and intakes that will

Table 5
Impact of electric propulsion on airline operations (detail).

AIRLINE OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Aircraft preparation procedures	6	(swappable-battery a/c) – no significant impact (plug-in a/c) – having to be performed at a different time	turnaround time mainly unchanged turnaround time significantly elongated
Push-back procedures	5	complete redesign of procedures	a/c will be pulled all the way to the runway holding point to save battery energy
Taxi procedures	5	requiring implementation of new engine start/shut down procedures	• a/c will be pulled all the way to the runway holding point to save battery energy • taxiing will be on one engine; other engine(s) to be started in the proximity of the runway holding point to save battery energy • in the event of extended delays: taxiing engine to be shut down to save battery energy
Take-off procedures	3	different a/c handling	more direct departure routes due to lower noise
Climb procedures	4	different a/c handling	more direct departure routes due to lower noise
Cruising procedures	4	having to be performed at a different time (significantly shorter cruise phase)	•reduced range due to low energy density of batteries •cruising at the most efficient altitude for battery cooling
Approach procedures	3	different a/c handling	•higher approach speed due to higher landing weight •more direct approach routes due to lower noise •steeper descent angle to exploit windmilling effect
Landing procedures	4	selection of higher autobrake settings and reverse thrust by the pilots	•higher landing speeds due to higher landing weight •longer landing distance requirements due to higher landing weight and faster speeds

be present on electric aircraft to eject heat and suck in cool air from/to the batteries."

Finally, substantial changes are anticipated in the maintenance process due to differences in aircraft systems (respondents H, M, N, O, Q, R). Interviewee N also suggested that maintenance may be performed directly by aircraft manufacturers with their own personnel and procedures.

Table 6
Impact of electric propulsion on airport operations (detail).

AIRPORT OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Stairs/jet bridge connection/disconnection	5	(plug-in a/) – ensuring that sufficient distance is maintained from high-power battery-recharging connector	safety risks due to high voltages and currents
External power connection/disconnection	4	(plug-in a/c) – complete redesign of the operation due to new safety procedures	external power connector to be used to recharge a/c batteries during turnaround
Luggage/cargo loading/unloading	4	(plug-in a/c) – ensuring that sufficient distance is maintained from high-power battery-recharging connector (swappable-battery a/c) – requiring implementation of new procedures to load/unload a/c batteries	safety risks due to high voltages and currents a/c batteries to be loaded/unloaded using new ground support equipment
Air supply connection/disconnection	4	(plug-in a/c) – ensuring that sufficient distance is maintained from high-power battery-recharging connector requiring implementation of new procedures to connect multiple air hoses	safety risks due to high voltages and currents new air supply demand to keep a/c batteries cool
Ambulift connection/disconnection	5	(plug-in a/c) – ensuring that sufficient distance is maintained from high-power battery-recharging connector	safety risks due to high voltages and currents
Aircraft cleaning	5	ensuring that only standard cleaning procedures are adopted	certain special procedures – such as warming up the a/c cabin to kill bacteria – may damage the electrical system
Aircraft catering	5	no impact	no impact
Toilet servicing/waste drainage	5	special caution in the event of leaks or spillages	a/c electrical system may otherwise be damaged
Potable water servicing	5	special caution in the event of leaks or spillages	a/c electrical system may otherwise be damaged
Passenger embarking/disembarking	4	(in the case of plug-in a/c and passenger boarding-de-boarding through stairs) – ensuring that sufficient distance is maintained from high-power battery-recharging connector ensuring that passengers do not interfere with electric system controls	safety risks due to high voltages and currents emergency shut offs may be in relatively easy-to-access locations (because crew may have to action them quickly)
Push-back	5	use of different tugs may be required	a/c may be heavier
Refueling via trucks	6	complete redesign of the operation	• new safety procedures

(*continued on next page*)

Table 6 (*continued*)

AIRPORT OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
			•(swappable-battery a/c) – batteries will have to be swapped •(plug-in a/c) – fast charging of the batteries through high voltage cables
Refueling via hydrant system	5	complete redesign of the operation	•new safety procedures •(swappable-battery a/c) – batteries will have to be swapped •(plug-in a/c) – fast charging of the batteries through high voltage cables
Aircraft de-icing/anti-icing	4	ensuring that de-icing/anti-icing fluid is not inadvertently sprayed into vents and intakes	a/c will have extra vents and intakes to eject heat and suck in cool air from/to the batteries
Aircraft maintenance	6	complete redesign of the operation	•most a/c systems will be different •(swappable-battery a/c) – machine assistance required to remove batteries •maintenance to be (possibly) performed directly by a/c manufacturers •need to have new procedures to proactively data monitor the state of health of the a/c batteries •more complex engine prognostics

4.2.3. *Impact on airport infrastructure*

As reported in Fig. 2c and Table 7, the average impact on airport infrastructure is expected to be quite significant, with a number of changes required in multiple areas. Interviewees H and O reported that the impact on runways should be none. Respondents N and Q remarked instead that, because electric aircraft will probably be heavier at landing and require longer landing distances, runways may have to be reinforced with stress-resistant materials and be elongated at certain smaller airports – in this case there would obviously be a high impact. Three out of four experts (N, O, Q) foresaw no impact on taxiways, but interviewee H argued that partial modifications may be required to accommodate aircraft tug movements. On average, aprons and aircraft stands are expected to experience a low-to-medium impact. For plug-in aircraft, new infrastructure (e.g., power distribution networks, fixed chargers, high voltage cables and connectors) will have to be installed at aircraft stands to fast charge the batteries during turnaround (respondents M, N, O, Q). In the case of swappable batteries, new spaces will have to be allocated for the ground equipment that will be used to support the battery swap process (respondents N, O). Interviewee O also reported that:

> “The high currents and voltages occurring on board electric aircraft parked next to each other are a concern. Because of this, a wider minimum distance between aircraft stands may be imposed to minimize the risk of electric arcs forming.”

All experts agreed on an expected high impact on both the fuel depot (respondents E, H, M, N, O, Q, R, S) and hydrant refueling system (respondents M, N, O, Q) since the use of electricity instead of liquid fuel will require different infrastructure. In particular, the fuel depot area will have to host a power generation plant or a dedicated electrical substation. Also, the existing hydrant refueling system will no longer be useable since electricity will have to be transported via high voltage cables to either the aircraft stands (for plug-in aircraft) or the battery charging facilities (in the case of swappable batteries). Interviewee S stressed that, in the latter case, new risks will arise:

> “From an airport infrastructure perspective, you have some important safety issues. This is because recharging and storing gigawatt hours of battery capacity somewhere [around the airport] brings some safety concerns with it.”

Maintenance hangars are expected to be subject to a medium-high impact, necessitating new battery maintenance equipment (respondents M, N, O, Q) and potential structural adjustments to meet the new safety standards (respondent N).

Table 7
Impact of electric propulsion on airport infrastructure (detail).

AIRPORT INFRASTRUCTURE	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Runway(s)	4	need to elongate runways at smaller airports and reinforce them with stress resistant materials	a/c will require longer landing distances because they will be heavier at landing
Taxiways	4	partial modifications to allow tug movements to/from runway	a/c will be pulled all the way to the runway holding point by tugs
Apron(s)	4	(plug-in a/c) – new infrastructure required more space required between aircraft stands	need to have new electric power distribution network safety risks (possible formation of electric arcs)
Aircraft stands	5	(plug-in a/c) – new infrastructure required	need to have new infrastructure to fast charge the a/c batteries during turnaround
		(swappable-battery a/c) – extra space required	new spaces to be allocated to the ground support equipment used during the battery swap process
De-icing/anti-icing pads	4	no impact	no impact
Terminal building(s)	5	no impact	no impact
Fuel depot	8	complete redesign	power generation plant and/or electrical substation to be installed
Hydrant refueling system	4	complete redesign	electricity to be transported via cable to either aircraft stands (for plug-in a/c) or battery charging facilities (for swappable battery a/c)
Maintenance hangars	4	possible structural modifications required	• new maintenance equipment required to handle a/c batteries • new structural safety standards

Table 8
Impact of hydrogen propulsion on airline operations (detail).

AIRLINE OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Aircraft preparation procedures	4	to be redesigned in light of new operational requirements, and be performed at different times	• possibly longer turnaround due to restrictions on parallel operations during refueling •possible restrictions on how an a/c can be approached multiple hours after refueling due to hydrogen boil-off and associated venting issues
Push-back procedures	6	slight changes in procedures	•more complex a/c systems •possibly different engine start timing
Taxi procedures	6	wider safety distance to be maintained between taxiing a/c	•a/c may vent at any time (safety risks for following a/c) •(fuel-cell a/c) – may have to pour water produced by fuel cells onto taxiways (potential issues for following aircraft, especially in cold weather conditions)
Take-off procedures	6	slight changes in procedures	possible minor changes in take-off performance
Climb procedures	6	slight changes in procedures	possible minor changes in climb performance
Cruising procedures	7	cruising at different altitudes and/or avoiding climate sensitive areas	need to minimize the formation of contrails and aviation-induced cirrus clouds
		fewer step climbs	optimum cruising altitude remains mainly unchanged due to lower weight variation in flight
		(fuel-cell a/c) – possibly cruising at lower altitudes	need to cruise at most efficient altitude for fuel cell cooling
Approach procedures	6	different a/c handling	higher approach speeds caused by heavier a/c (due to the extra weight of the LH2 tanks)
Landing procedures	6	having to select higher autobrake settings and reverse thrust	higher landing speeds caused by heavier a/c (due to the extra weight of the LH2 tanks)

Table 9
Impact of hydrogen propulsion on airport operations (detail).

AIRPORT OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Stairs/jet bridge connection/ disconnection	5	no impact	no impact
External power connection/ disconnection	5	having to pull and connect a longer external power cable	external power unit may be further away from a/c (due to safety concerns in the event of hydrogen leaks)
Luggage/cargo loading/ unloading	5	requiring implementation of new procedures and different timing	•cargo compartments may be in a different location (since part of the fuselage will be occupied by LH2 tanks) •extra training required for personnel •extra caution due to proximity to LH2 tanks •restrictions on parallel operations during refueling
Air supply connection/ disconnection	6	same operation but different timing	restrictions on parallel operations during refueling
		extra caution not to generate any sparks during connection	safety concerns (higher flammability of hydrogen)
Ambulift connection/ disconnection	6	same operation but different timing	restrictions on parallel operations during refueling
Aircraft cleaning	6	same operation but different timing	restrictions on parallel operations during refueling
Aircraft catering	6	same operation but different timing	restrictions on parallel operations during refueling
Toilet servicing/ waste drainage	6	same operation but different timing	•restrictions on parallel operations during refueling •could not be performed during refueling in any case due to space issues (the area around the tail of the a/c will already be occupied by the fuel truck(s))
Potable water servicing	6	same operation but different timing	•restrictions on parallel operations during refueling •could not be performed during refueling in any case due to space issues (the area around the tail of the a/c will already be occupied by the fuel truck(s))
Passenger embarking/ disembarking	6	same operation but different timing	restrictions on parallel operations during refueling
Push-back	6	no impact	no impact
Refueling via trucks	8	complete redesign of the operation	•LH2 to be kept below −252.9 °C to avoid boil-off •use of automated or semi-automated equipment (due to cryogenic temperatures)

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4.3. Hydrogen aircraft propulsion

Compared to electric propulsion, a higher level of agreement among the interviewees was observed in the hydrogen propulsion scenario (Fig. 3) – i.e., the minimum and maximum impact assessment lines are closer. This is probably because, having hydrogen propulsion for commercial airliners received growing attention in recent years, the experts in the field have a higher degree of shared knowledge.

4.3.1. Impact on airline operations

As reported in Fig. 3a and Table 8, the average expected impact of hydrogen propulsion on airline operations is rather low. This is mainly because, as suggested by multiple interviewees (F, J, K, T, U), hydrogen airplanes will probably be designed to perform similarly to existing ones

Table 9 (*continued*)

AIRPORT OPERATIONS	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
			•a/c refueling point in a different location (instead of being on the right wing, it will probably be at the rear of the a/c, in proximity of the LH2 tanks) •connection/disconnection of multiple refueling hoses (to minimize refueling time) •new procedures to collect boiled-off hydrogen (to minimize safety risks) •new procedures to avoid tipping over the a/c •timing restrictions (refueling to occur close to departure time due to the limited dormancy time of LH2 tanks) •extra steps required before/after refueling hose connection/disconnection (hoses to be purged with inert gas to prevent contamination) •whole new range of strict safety-related procedures
Refueling via hydrant system	7	complete redesign of the operation	•LH2 to be kept below −252.9 °C to avoid boil-off •use of automated or semi-automated equipment (due to cryogenic temperatures) •a/c refueling point in a different location (instead of being on the right wing, it will probably be at the rear of the a/c, in proximity of the LH2 tanks) •connection/disconnection of multiple refueling hoses (to minimize refueling time) •new procedures to collect boiled-off hydrogen (to minimize safety risks) •new procedures to avoid tipping over the a/c •timing restrictions (refueling to occur close to departure time due to the limited dormancy time of LH2 tanks) •extra steps required before/after refueling hose connection/disconnection (hoses to be purged with inert gas to prevent contamination) •whole new range of strict safety-related procedures
Aircraft de-icing/anti-icing	5	slight change in the operation	•unsure if operation can be carried out with engines running (to be determined) •need to take into account the fact that a/c will be slightly bigger than existing ones
Aircraft maintenance	6	requiring implementation of new procedures, and possible change in location	•extra maintenance checks to be performed during turnaround (to ensure there are no hydrogen leaks) •more complex a/c systems (higher level of maintainability) •need to move a/c to a ‘clean environment’ (i.e., maintenance hangar) in many more cases •in case of LH2-tank related intervention: i) need to completely empty tanks and the fuel system; ii) (after repair) need to cool tanks back to cryogenic temperatures before refueling them again •new stringent safety requirements

– this was generally agreed to be one of the prerequisites for these new aircraft to be considered as a viable alternative. Aircraft preparation procedures are expected to be the most impacted area since, due to possible restrictions on parallel operations during LH2 refueling and the longer refueling time, turnarounds may exceed the current 30 to 35-min standard (respondents F, J, K, T). Thus, these procedures will require redesign to align with the new operational requirements and may have to be performed at different times. Push-back procedures are expected to remain largely unaffected, except for minor adjustments due to more complex aircraft systems (respondent F). On average, a none-to-low impact is expected on taxi procedures as well. However, two interviewees (J, T) reported that safety-driven changes may be required, suggesting the potential need for wider safety distances between taxiing aircraft. This is because, as stated by respondent J:

> “In case of failure, you will have to vent hydrogen overboard in significant quantities. The direction in which you will vent is not yet defined, but there is a good chance it will be from the tail backwards. This may pose a direct safety risk for the following aircraft.”

Referring specifically to a fuel cell-powered aircraft, respondent T mentioned:

> “Fuel cells produce water, and this water may have to be poured onto the ground. The amount would be no more than if you had a heavy rain shower. However, especially in cold, icy weather, this could cause potential issues [for the following aircraft].”

Table 10
Impact of hydrogen propulsion on airport infrastructure (detail).

AIRPORT INFRASTRUCTURE	Number of respondents	TYPE OF IMPACT	
		WHAT	WHY
Runway(s)	6	longer runways may be required at certain smaller airports	possibly longer landing distance requirements due to heavier a/c (caused by the extra LH2 tank weight)
Taxiways	6	no impact	no impact
Apron(s)	5	complete redesign required	•taxiways to be moved further away from parked a/c (due to larger FSZ) •distance between a/c stands to be widened (due to safety concerns and regulatory restrictions) •a/c to be parked in more remote areas away from terminal buildings (due to safety concerns associated with the high explosiveness of hydrogen) •necessary to install leak detection system (since hydrogen is odorless and colorless) •may be necessary to build 'ventilation chimneys' (to quickly disperse large amounts of gasified hydrogen in case of leaks or structural failures)
Aircraft stands	6	elongation may be required at ordinary narrow-body a/c stands	LH2 a/c may be longer than their existing equivalent, and may not fit in ordinary narrow-body a/c stands
		installation of new infrastructural assets	•necessary to install leak detection system (since hydrogen is odorless and colorless) •may have to install gaseous hydrogen collection system
De-icing/anti-icing pads	5	no impact	no impact
Terminal building (s)	6	may be necessary to reinforce terminals with blast walls and/or blast resistant gazing	safety concerns (high explosiveness of LH2)
Fuel depot	10	brand new infrastructure required	•totally different fuel supply system → need to build (depending on the size of the LH2 aircraft operation): LH2 storage facilities; a liquefaction plant (if hydrogen is transported to the airport in a gaseous format); an electrolyzer (if hydrogen is produced on site) •necessary to install leak detection system •necessary to install hydrogen fire suppression system
Hydrant refueling system	8	brand new system to be built and installed (only once LH2 aircraft operations reach a certain level)	•existing system is not compatible with LH2 •hydrant's fuel pit to be moved closer to the aircraft tail (which is where LH2 tanks will be located)
Maintenance hangars	6	structural modifications required	•need to have venting system for rapid gasified hydrogen dispersion •need to install multiple hydrogen leak detectors •higher structural stability and blast resistance may be required (due high explosiveness of LH2) •new LH2-handling equipment required

Some changes may be required in cruising procedures as well: to minimize the formation of contrails and aviation-induced cirrus clouds, hydrogen aircraft may have to cruise at different altitudes and/or avoid climate-sensitive areas (respondents F, J, M, S, T). Interviewee K also remarked that:

> "You would cruise at a higher altitude because your aircraft would be lighter than its kerosene equivalent [at that stage of flight]. Since your optimum cruise altitude would not change very much, you would not need to do as many step climbs."

Regarding approach and landing procedures, the potential impact is expected to be induced by the higher approach and landing speeds (respondent K), which may require pilots to select higher autobrake settings and reverse thrust.

4.3.2. *Impact on airport operations*

As shown in Fig. 3b and Table 9, on average, most airport operations are expected to be subject to a relatively low impact, primarily caused by possible restrictions during the LH2 refueling process. Refueling and maintenance are the only two operations where the average impact is instead expected to be medium-high. External power connection/disconnection will be minimally affected, as safety regulations may require the external power unit to be farther away from the aircraft (respondent K). Air supply connection/disconnection, ambulift connection/disconnection, cleaning, catering, toilet servicing/waste drainage, potable water servicing, and passenger embarking/disembarking will all be subject to a limited impact: while the operations themselves should not change significantly, they will probably have to be performed either before or after the refueling operation (respondents F, J, K, M, T, U). This is because, due to safety concerns, LH2 will necessitate a much wider Fuel Safety Zone (FSZ), that is expected to be approximately 20 m for refueling hose connection/disconnection and 10 m for actual refueling – as a comparison, at present, the FSZ for a narrow-body kerosene-powered aircraft is 3 m in radius (IATA, 2020). A slightly higher impact is expected on the luggage/cargo loading/unloading operation since, apart from timing restrictions caused by refueling limitations, the proximity of the cargo compartment to LH2 tanks may require procedural changes and heightened caution (respondents J, U). As already anticipated, a high impact is expected for both refueling via trucks and the hydrant refueling system, as the refueling operation will need a complete redesigned due to the significantly different handling characteristics and safety requirements of LH2 (respondents A, F, J, K, M, T, U). The extent of this impact was effectively summarized by interviewee D:

> "With hydrogen everything changes in the refueling operation, as you will have completely different procedures and safety requirements. And these will all be highly dependent on the actual regulations."

The maintenance operation is expected to be subject to an average medium impact due to a diverse set of factors, ranging from the necessity of conducting extra checks for hydrogen leaks during turnarounds to the requirement of complying with new, rigorous safety standards (respondents J, K, M, T, U).

4.3.3. *Impact on airport infrastructure*

The impact of hydrogen propulsion on airport infrastructure is expected to be significant in several areas (Fig. 3c and Table 10). Five out of six interviewees (F, J, M, T, U) predicted no impact on runways. However, respondent K noted that hydrogen aircraft, being possibly heavier at landing due to the extra weight of the LH2 tanks, might need slightly longer landing distances – this may cause some issues at smaller airports with reduced runway lengths. An average medium impact is expected on aprons and aircraft stands, that will necessitate a number of modifications primarily caused by safety concerns and regulatory restrictions (respondents F, J, K, M, T, U). While four experts (J, K, M, U) foresaw no impact on terminal buildings, interviewees F and T suggested that, due to safety concerns, it may be necessary to reinforce passenger terminals with blast walls and blast-resistant glazing. All experts agreed that a high impact is expected on the fuel depot since completely new infrastructure will be required – the exact type of infrastructure and its size will largely depend on the number of LH2 aircraft handled by the airport. Specifically, as effectively explained by respondent T:

> "For as long as you have only a few [LH2] aircraft operating, the changes [to the fuel depot] will be relatively limited. But as the operations increase, you would need to have those circular refueling storage areas like the ones you see at NASA at the moment."

A complete consensus was also recorded on the expected high impact on the hydrant refueling system, since the existing one is not compatible with LH2 and will have to be completely redesigned. On average, a medium impact is expected on maintenance hangars, as they will have to be equipped with multiple hydrogen leak detectors (respondent T) and an effective venting system to allow rapid gasified hydrogen dispersion (respondents F, J, K, T).

5. Discussion

5.1. *How emerging sustainable aircraft technologies will affect aviation operations and infrastructures: locus and expected impact*

The results section highlighted that the level of convergence among interviewees' impact assessments varies with the technology: while there is general agreement among experts regarding SAF, the impact evaluations for electric and hydrogen propulsion are significantly more varied. One reason for this difference may be the varying technology readiness level. Specifically, while SAF has not yet been deployed on a wide commercial scale, it is an existing and currently used technology. This facilitates expert predictions of the expected impacts associated with its increased usage. Conversely, electric and hydrogen aircraft propulsion are still in development. As a result, their potential impacts on the operating ecosystem can only be envisioned at this time, which leads to greater uncertainties.

With regard to the generic impact on airline operations (Fig. 4a), our findings show that deployment of SAF is not expected to lead to any significant disruption (i.e., no impacts). This is totally in line with the existing literature that repeatedly remarks that, up to the blend limit, the use of SAF is not expected to have any effect on operations (ATAG, 2017; ICAO, 2018). Our results, however, also show that the experts in the field do not envision major difficulties even for richer SAF blends (once these will be certified by the competent authorities) – this was never fully clarified by the literature. Electric propulsion is expected to have a low-to-medium impact in most areas. This is not surprising, as previous studies (e.g., Gnadt et al., 2019; Schäfer et al., 2019) already revealed that, due to battery technology limitations, all-electric airliners are expected to have poorer performance compared to existing aircraft. Nonetheless, our results provide a new level of detail, clearly showing how current airline procedures are anticipated to be affected in each phase of flight. Hydrogen propulsion is expected to impact aircraft preparation and cruising procedures in particular. While it is true that this could already be indirectly inferred from the reports produced by McKinsey (2020) and Postma-Kurlanc et al. (2022), our results make this explicit, and provide an assessment of the relative impact in both areas.

In terms of airport operations (Fig. 4b), our study shows that if SAF is used in high percentages, it may have a potential impact on the maintenance procedure, possibly requiring a more frequent inspection of certain parts. This can be considered an expansion of the literature, given that existing studies only hint at the possible negative effects of rich SAF blends on the fuel systems of older aircraft and the seals of older engines (CAAFI, 2021; Kramer et al., 2022). Electric propulsion is expected to have a medium-to-high impact in multiple areas, including refueling, maintenance, external power connection/disconnection, and luggage/cargo loading/unloading. While a few of these impacts were already—partially and indirectly—mentioned by Schmidt et al. (2014) and WSDOT (2020), our results clarify the extent to which they affect ground turnaround operations and provide precise explanations for the reasons behind them. Hydrogen propulsion is expected to have a significant impact on both refueling and maintenance. In principle, this is in line with the studies produced by McKinsey (2020) and Mangold et al. (2022), that highlight the existence of a certain impact in both areas. Our results, however, further expand the understanding of this impact by providing an assessment of the degree to which these two operations are going to be affected.

As for airport infrastructure (Fig. 4c), our results show that SAF is expected to have a certain impact on both the fuel depot and the hydrant refueling system. This can be considered a new result, given that it was not previously reported in the literature. Electric propulsion is anticipated to significantly affect a number of existing infrastructural assets, including the fuel depot, the hydrant refueling system, maintenance hangars, and, to a lesser extent, aircraft stands. While WSDOT (2020) and Connected Places Catapult (2022) indirectly implied the existence of a certain impact in most of these areas, our results provide a new level of detail. Hydrogen propulsion is instead expected to have a medium-to-high impact on the fuel depot, the hydrant refueling system, maintenance hangars, aprons, and aircraft stands. This falls in agreement with both Connected Places Catapult (2022) and Postma-Kurlanc et al. (2022) who, in a less specific way, anticipated the very significant changes required in these areas.

Finally, it is important to remark that, as highlighted by a number of interviewees, the timing and scale of the identified impacts are expected

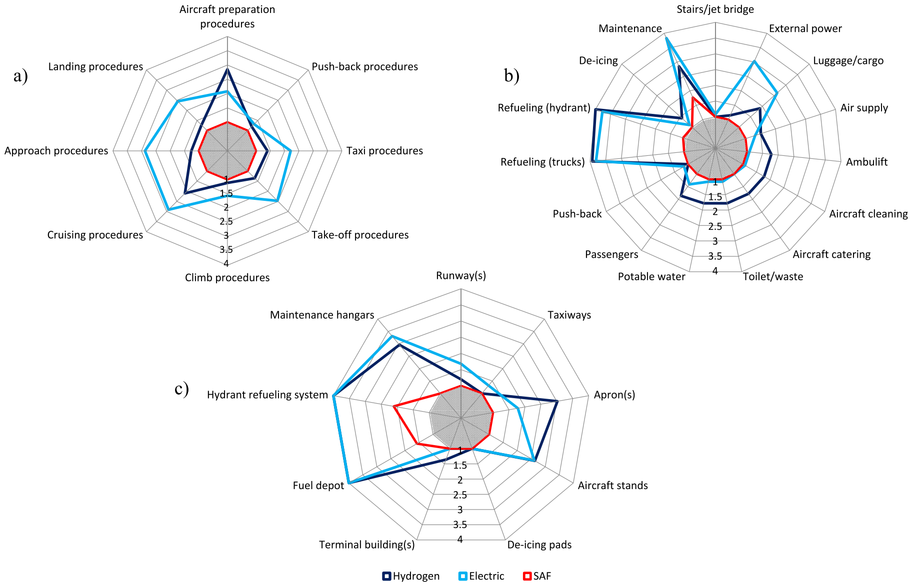

Fig. 4. Comparison of the average impact that the three technologies are expected to have on: (a) airline operations; (b) airport operations; and (c) airport infrastructure. Values from 1 (min) to 4 (max) are the geometric means of the experts' independent judgements.

to differ. For example, the widespread use of LH2 aircraft is unlikely to occur for a decade or more, and even then, storage infrastructure may not need to be permanent for some time. Similarly, a significant presence of all-electric aircraft at large airports in the short to medium term is quite improbable, as this type of alternative propulsion is likely to have limited roles beyond very short journeys and niche applications (such as short regional flights and island hopping). Nonetheless, new infrastructure development and operational adjustments require time, so it is important to carefully plan the transition process balancing the changing mix of technologies.

5.2. *Implications for the sustainable transition of the aviation sector*

Fig. 4 compares the average impact lines of the three technologies in all dimensions of analysis. The results show that SAF, even if used in high percentages, is anticipated to have a marginal effect on the operating environment. In contrast, electric and hydrogen aircraft propulsion are expected to be much more disruptive, significantly affecting numerous of the existing procedures, operations, and infrastructural assets. In particular, as shown in Fig. 4b and c electric and hydrogen propulsion are foreseen to have a similar medium-to-high impact on many airport operations (refueling and maintenance) and parts of the airport infrastructure (fuel depot, hydrant refueling system, maintenance hangars, and aircraft stands). This is because electricity and LH2 are very different from jet fuel and will require major changes in all those processes and infrastructural assets related to their supply, distribution, and handling. However, since the nature of their impacts is very diverse (as discussed in Section 4), the operational and infrastructural requirements of these two technological options will be significantly dissimilar. Institutions and policymakers should carefully take these differences into account when making long-term strategic decisions about infrastructure reconversion plans. This is because, to adapt the airport ecosystem to the new technological needs, considerable economic investment and time will be required. Consequently, once major infrastructural changes are implemented, the airport operating environment will tend to remain unchanged in the long term. In light of this, new design solutions should be explored, such as the development of 'multi-technology infrastructural assets'. These can be defined as infrastructural assets that have the potential to simultaneously satisfy the operational and safety requirements of multiple technologies. While this concept is relatively novel in the aviation sector, it has established precedents and serves as a strategic model in various other industries. Examples from other sectors where multi-technology infrastructural assets have proven effective include:

1. Multi-Fuel Vehicle Refueling Stations: Most modern gas stations are designed to dispense various types of fuels (e.g., petrol, diesel, methane, LPG) to a wide range of different vehicles (e.g., motorcycles, cars, vans, buses, trucks), effectively showcasing that multiple energy sources can be safely handled concurrently.
2. Intermodal Transportation Hubs: Intermodal transportation terminals effectively accommodate the different safety and operating requirements of multiple ground transportation modes, ranging from electric trains and subways to fossil fuel-powered buses and cars.
3. Substations in Energy Grids: Within the energy sector, multi-technology substations integrate diverse sources of energy generation, such as solar, wind, and traditional fossil fuels, into a unified distribution network. These substations manage energy flow and ensure compatibility, making the grid adaptable to various energy sources.

Drawing insights from these sectors, the aviation industry can adopt the concept of multi-technology infrastructural assets and apply it to airports. Here, infrastructure could be designed to accommodate both traditional and alternative aircraft technologies simultaneously, ensuring flexibility and adaptability in the face of technological advancements. Practical implementations could involve:

i. Adaptive Aircraft Stands: Designing new aircraft stands that are adequately long and wide (to accommodate larger LH2 aircraft), sufficiently spaced from one another (to comply with the safety and regulatory requirements of kerosene, electricity, and LH2), and positioned far enough from taxiways (to avoid possible movement restrictions for taxing aircraft while parked LH2 aircraft are refueling). Such stands could be equipped with ground support equipment—such as jet bridges, stairs, power supply systems, belt loaders, and tugs—that is versatile and compatible with different aircraft propulsion technologies.
ii. Flexible Maintenance Hangars: Developing maintenance hangars with adaptable configurations that conform to the traditional standards of kerosene aircraft while also meeting evolving safety standards for both electric and hydrogen aircraft. This could

involve redesigning the hangars to include, for example, higher structural stability, new electric fire/hydrogen leak detection systems, and venting chimneys (for rapid gasified hydrogen dispersion).

iii. Integrated Fuel Depot: Establishing a unified fuel depot area capable of securely housing a diverse range of energy sources, including Jet A-1, SAF, electricity, and LH2. This adaptable, integrated facility would serve as a central hub for energy distribution, ensuring efficient supply, storage, and transfer processes tailored to the distinct requirements of each fuel.

Although the implementation of multi-technology airport infrastructural assets would require higher investments in infrastructure renovation, it would allow the aviation industry to keep its options open and avoid the possible onset of technological lock-in effects. It could also help overcome the "chicken and egg" dilemma currently affecting the sector. This is causing, on one side, airlines to be waiting for new technological developments and the operating ecosystem to adapt before committing themselves to one (or more) alternative aircraft propulsion option(s). And, on the other side, aircraft manufacturers to be delaying the multi-billion-dollar investments required to develop new aircraft technologies at an industrial scale until there will be a strong business case for doing so. This industrial stall is currently causing institutions and policymakers to postpone crucial airport infrastructure reconversion decisions until there is a clearer picture of which technological solutions will prevail in commercial aviation. The implementation of multi-technology airport infrastructural assets, though less efficient in the short term, could help to get out of this impasse, and act as the main driver for a faster transition of the aviation sector with higher environmental, social, and economic benefits in the long term.

Nevertheless, as highlighted by the rather divergent experts' judgments presented in the previous section, multiple uncertainties still exist regarding what will be the exact impact of electric and hydrogen aircraft propulsion in a number of areas. Consequently, before being able to concretely evaluate the feasibility of multi-technology airport infrastructural assets and assess the related benefits, the aviation sector needs to invest in coordinated and well-planned R&D initiatives aimed at generating more evidence and reducing current uncertainties.

6. Conclusions

Despite the fact that emerging sustainable aircraft technologies are assigned a central role in the sustainability transition of the aviation industry, the exact level of disruption that they are expected to have on the existing operating ecosystem is not yet clear. Specifically, at this time, industrial actors and policymakers do not seem to have an accurate understanding of all the operational and infrastructural impacts associated with their deployment. This paper attempted to address this gap by interviewing the most important and knowledgeable stakeholders in the European and American aviation industries and asking them to provide detailed impact assessments.

Our results provide a clear and comprehensive picture of all the impacts that the examined technologies are expected to have on the different activities, operations, and infrastructural assets that are currently part of the commercial operating ecosystem. Compared to previous studies, our work presents four elements of novelty that provide original results and insights. First, it offers a more detailed and systematic analysis of the expected operational and infrastructural impacts based on the developed framework of processes and airport assets. Such an analysis not only complements the existing body of knowledge (by providing a precise summary of all the impacted areas) but also expands it (by adding new information about the specific type and nature of the impacts). Second, this paper provides an estimate of the expected magnitude of the impacts based on expert opinions. This is completely novel, as no previous study has ever produced such a result. The added value of this type of information is that it quantifies the level of disruption that each technology is anticipated to have in each area, hence clearly pointing out the operations and infrastructural assets that will be most affected by changes. Third, this study indicates the areas of most uncertain impact. Again, this is something that the existing literature never addressed, but it is important because it permits to identify the areas where further research is more urgently needed (in order to reduce the existing levels of uncertainty). Finally, this work offers a comparative analysis of the technologies. This is because, unlike those of previous studies, our results are presented in a standardized format which allows to directly compare the expected impact of the three technologies on every activity, operation, and infrastructural asset. Regarding the practical contribution, this paper provides insights for policy and industrial decision-makers on how best to prepare for the future implementation of the changes that will be required by the deployment of new aircraft technologies. Specifically, this study proposes the development of multi-technology airport infrastructural assets as a solution not only for the possible onset of lock-in effects but also for the chicken and egg dilemma currently affecting the sector. In terms of limitations, while the interviewed experts represent several key actors in the industry, not all stakeholders were engaged. Therefore, in future studies, it would be valuable to reach out to a broader community through survey methodology, for example. This would allow to differentiate the expected impacts among distinct groups of stakeholders and to establish interconnections and interdependencies between the impacts – both of these aspects fall outside the scope of this paper. Furthermore, while this study provides a good overview of the nature and causes of the operational and infrastructural impacts, further research is required to delve deeper into their timing, scale, and contextual nuances, which is of primary importance for effectively designing and managing the aviation industry's sustainability transition.

Disclaimer

Any opinions, findings, conclusions, or recommendations expressed in this publication are solely those of the authors, and do not necessarily represent those of their affiliated organizations.

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Declaration of competing interest

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Appendix A. Research framework

Relying on the existing literature, we developed a 'research framework' that coherently integrates: (1) the key airline operations occurring during a standard flight; (2) the key airport operations and processes occurring during the normal turnaround of a commercial airliner; and (3) the key airside infrastructural assets that can be found at a typical commercial airport. Such a framework, which is the result of the integration of multiple literature sources, is arranged into three combined lists of items (i.e., operations, activities, and infrastructural assets). Table A1 summarizes the main airline operations and procedures that normally occur during a standard commercial flight (in the right column). These have been divided in accordance with the flight phase in which they are performed (in the left column) – the classification of the different flight phases has been based on the studies published by Midkiff et al. (2004), ICAO (2013), and IATA (2015).

Table A.1
Key airline operations occurring during a standard commercial flight.

AIRLINE OPERATIONS	
Flight phase	Airline operation
Standing	Aircraft preparation procedures
Push-back	Push-back procedures
Taxi	Taxi procedures
Take-off	Take-off procedures
Climb	Climb procedures
En route	Cruising procedures
Approach[1]	Approach procedures
Landing	Landing procedures

[1] Given the relative similarity between the descent and approach phases, and considering the fact that ICAO (2013) does not classify descent as an independent phase, we decided not to include descent in Table 1.

Table A2 outlines the standard airport operations that can occur during a typical narrow-body aircraft turnaround. This list of operations and activities is the result of the re-elaboration of the work produced by Balk (2008), Fitouri-Trabelsi et al. (2014), National Academies of Sciences, Engineering, and Medicine (2015), and Tabares and Mora-Camino (2017). As it can be clearly noticed, the various activities (in the right column) have been grouped in accordance with the general 'type of operation' (in the left column). It is important to highlight that not all the activities/operations reported in this table are necessarily performed during each aircraft turnaround, as the operational needs and environmental conditions differ from flight to flight. Furthermore, it has to be remarked that the aircraft maintenance that can take place during turnaround represents only a fraction of the whole maintenance process, which is generally performed at night.

Table A.2
Key airport operations that can occur during the turnaround of a commercial airliner.

AIRPORT OPERATIONS	
Type of operation	Specific activity
Ground handling	Stairs/jet bridge connection/disconnection External power connection/disconnection Luggage/cargo loading/unloading Air supply connection/disconnection (if required) Ambulift connection/disconnection (if required) Aircraft cleaning (if required) Aircraft catering (if required) Toilet servicing/waste drainage (if required) Potable water servicing (if required) Passenger embarking/disembarking Push-back
Aircraft refueling	Refueling via trucks Refueling via hydrant system
De-icing/anti-icing	Aircraft de-icing/anti-icing (if required)
Maintenance	Aircraft maintenance (if required)

Finally, Table A3 provides a list of the main infrastructural assets that are generally part of the airside infrastructure at a typical commercial airport. This summary list has been derived from the much more detailed airport infrastructure studies produced by Janić (2009), Bradley (2010), Horonjeff et al. (2010), and EASA (2021).

Table A.3
Key airside airport infrastructure at a typical commercial airport.

AIRSIDE AIRPORT INFRASTRUCTURE
Infrastructural asset
Runway(s)
Taxiways
Apron(s)

(continued on next page)

Table A.3 (*continued*)

AIRSIDE AIRPORT INFRASTRUCTURE
Infrastructural asset
Aircraft stands De-icing/anti-icing pads Terminal building(s) Fuel depot Hydrant refueling system (if present) Maintenance hangars

Appendix B. Experts' Impact Assessments

Table B.1
Impact assessment grading scale.

LEGEND		
S	= SAF	
E	= Electric aircraft propulsion	
H	= Hydrogen aircraft propulsion	
Color	**Type of impact**	**Corresponding numeric value**
░	= no response (i.e., item not discussed because outside of the interviewee's area of expertise)	N/A
	= 'do not know' (i.e., item discussed but no impact assessment recorded due to lack of knowledge and/or uncertainty)	N/A
🟩	= no impact	**1**
🟩⬜	= none-to-low impact	**1.5**
🟨	= low impact	**2**
🟨🟧	= low-to-medium impact	**2.5**
🟧	= medium impact	**3**
🟧🟥	= medium-to-high impact	**3.5**
🟥	= high impact	**4**

Table B.2
Color-coded summary of all the impact assessments relating to airline operations that were included in the study after the coding process (only relevant columns are shown).

AIRLINE OPERATIONS	**Interviewee A**	**Interviewee C**	**Interviewee D**	**Interviewee F**		**Interviewee H**	**Interviewee J**	**Interviewee K**	**Interviewee L**	**Interviewee M**			**Interviewee N**	**Interviewee O**	**Interviewee P**	**Interviewee Q**	**Interviewee S**		**Interviewee T**	**Interviewee U**
	S	S	S	S	H	E	H	H	S	S	E	H	E	E	S	E	S	H	H	H
Aircraft preparation procedures	🟩	🟩	🟩	🟩	🟧🟥	🟩	🟧	🟨🟧	🟩	🟩	🟥		🟨🟧	🟨	🟩	🟥	🟩	░	🟨🟧	
Push-back procedures	🟩	🟩	🟩	🟩	🟨	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	░	🟩⬜	🟩
Taxi procedures	🟩	🟩	🟩	🟩	🟨	🟧🟥	🟨🟧	🟩	🟩	🟩	🟧	🟩	🟨🟧	🟩	🟩	🟨	🟩	░	🟩⬜	🟩
Take-off procedures	🟩	🟩	🟩	🟩	🟩		🟩⬜	🟨	🟩	🟩	🟧	🟨		🟨	🟩	🟨🟧	🟩	░	🟩	🟩
Climb procedures	🟩	🟩	🟩	🟩	🟩		🟩	🟩	🟩	🟩	🟧	🟨	🟩	🟩	🟩	🟨	🟩	░	🟩	🟩
Cruising procedures	🟩	🟩	🟩	🟩	🟨		🟨	🟨	🟩	🟩	🟧	🟧	🟧	🟨	🟩	🟥	🟩	🟨🟧	🟨	🟩⬜
Approach procedures	🟩	🟩	🟩	🟩	🟩		🟩	🟨	🟩	🟩	🟧	🟨		🟨	🟩	🟥	🟩	░	🟩	🟩
Landing procedures	🟩	🟩	🟩	🟩	🟩⬜		🟩	🟩⬜	🟩	🟩	🟧	🟨	🟨	🟩⬜	🟩	🟥	🟩	░	🟩	🟩

Table B.3
Color-coded summary of all the impact assessments relating to airport operations that were included in the study after the coding process (only relevant columns are shown).

AIRPORT OPERATIONS	Interviewee A		Interviewee C	Interviewee D	Interviewee F		Interviewee H	Interviewee J	Interviewee K	Interviewee L	Interviewee M			Interviewee N		Interviewee O	Interviewee P	Interviewee Q	Interviewee R	Interviewee S		Interviewee T	Interviewee U
	S	H	S	S	S	H	E	H	H	S	S	E	H	S	E	E	S	E	E	S	H	H	H
Stairs/jet bridge connect./discon.	🟩	▒	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬜	🟩	🟩⬜	🟩	🟩	🟩	▒	🟩	▒	🟩	🟩
External power connect./discon.	🟩	▒	🟩	🟩	🟩	🟩	🟥	🟩	🟨	🟩	🟩	⬜	⬜	🟩	🟥🟧	🟩⬜	🟩	🟥	▒	🟩	▒	🟩	🟩
Luggage/cargo loading/unloading	🟩	▒	🟩	🟩	🟩	🟨	🟧	🟨	🟩	🟩	🟩	⬜	⬜	🟩	🟥	🟨	🟩	🟨	▒	🟩	▒	🟨🟧	🟨🟧
Air supply connect./discon.	🟩	▒	🟩	🟩	🟩	🟨	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟧	🟩	🟩	⬜	▒	🟩	▒	🟩⬜	🟨
Ambulift connect./discon.	🟩	▒	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩⬜	🟩	🟩	🟩	▒	🟩	▒	🟨	🟨
Aircraft cleaning	🟩	▒	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩⬜	🟩	🟩	🟩	▒	🟩	▒	🟨	🟨
Aircraft catering	🟩	▒	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	▒	🟩	▒	🟨	🟨
Toilet servicing/waste drainage	🟩	▒	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩⬜	🟩	🟩	🟩	▒	🟩	▒	🟨	🟨
Potable water servicing	🟩	▒	🟩	🟩	🟩	🟨	🟩	🟨	🟨	🟩	🟩	🟩	🟩	🟩	🟩⬜	🟩	🟩	🟩	▒	🟩	▒	🟨	🟨
Passenger embarking/disembarking	🟩	▒	🟩	🟩	🟩	🟩⬜	🟩	🟨	🟨	🟩	🟩	⬜	🟩	🟩	🟨	🟩	🟩	🟨	▒	🟩	▒	🟥🟧	🟨
Push-back	🟩	▒	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	▒	🟩	▒	🟩	🟩
Refueling via trucks	🟩	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟩	🟥	🟥	🟩	🟥	🟧	🟩	🟥	🟥	🟩	🟥	🟥🟧	🟥
Refueling via hydrant system	🟩	🟥	🟩	🟩	🟩	🟥	🟥	🟥	🟥	🟩	🟨	🟥	🟥	🟩	🟥	🟧	🟩	🟥	⬜	🟩	▒	🟥	🟥
Aircraft de-icing/anti-icing	🟩	▒	🟩	🟩	🟩	🟩⬜	⬜	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩⬜	🟩	🟩	🟩	▒	🟩	▒	⬜	🟩
Aircraft maintenance	⬜	▒	🟨	🟩⬜	🟩⬜	🟩⬜	🟥	🟥	🟧	🟨	🟨	🟥	🟥	⬜	🟥	🟥🟧	🟩⬜	🟥🟧	🟥	🟨	▒	🟨🟧	🟧

Table B.4
Color-coded summary of all the impact assessments relating to airside airport infrastructure that were included in the study after the coding process (only relevant columns are shown).

AIRSIDE AIRPORT INFRASTRUCTURE	Interviewee A	Interviewee C	Interviewee D		Interviewee E		Interviewee F		Interviewee H	Interviewee J	Interviewee K	Interviewee L	Interviewee M			Interviewee N		Interviewee O	Interviewee P	Interviewee Q	Interviewee R	Interviewee S			Interviewee T	Interviewee U
	H	S	S	H	E	H	S	H	E	H	H	S	S	E	H	S	E	E	S	E	E	S	E	H	H	H
Runway(s)	▒	🟩	🟩	▒	▒	▒	🟩	🟩	🟩	🟩	🟩⬜	🟩	🟩	⬜	🟨	🟩	🟨	🟩	🟩	🟥	▒	🟩	▒	▒	🟩	🟩
Taxiways	▒	🟩	🟩	▒	▒	▒	🟩	🟩	🟧	🟩	🟩	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟩	🟩	▒	🟩	▒	▒	🟩	🟩
Apron(s)	▒	🟩	🟩	▒	▒	▒	🟩	🟥🟧	⬜	🟥	🟩⬜	🟩	🟩	🟥	⬜	🟩	🟩	🟨🟧	🟩	🟩	▒	🟩	▒	▒	🟥	🟧
Aircraft stands	▒	🟩	🟩	▒	▒	▒	🟩	🟥🟧	🟩	🟧	🟩⬜	🟩	🟩	🟥	🟨	🟩	🟧	🟨🟧	🟩	🟥	▒	🟩	▒	▒	🟥🟧	🟧
De-icing/anti-icing pads	▒	🟩	🟩	▒	▒	▒	🟩	🟩	⬜	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	▒	🟩	▒	▒	⬜	🟩
Terminal building(s)	▒	🟩	🟩	▒	▒	▒	🟩	🟨🟧	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩	🟩	🟩	🟩	🟩	▒	🟩	▒	▒	🟨🟧	🟩
Fuel depot	🟥	🟩	🟩	🟥	🟥	🟥	⬜	🟥	🟥	🟥	🟥	🟨🟧	🟧	🟥	🟥	⬜	🟥	🟥	🟩	🟥	🟥	🟨	🟥	🟥	🟥	🟥
Hydrant refueling system	▒	⬜	⬜	🟥	⬜	⬜	⬜	🟥	⬜	🟥	🟥	🟨	🟨	🟥	🟥	⬜	🟥	🟥	🟨🟧	🟥	▒	🟨	▒	🟥	🟥	🟥
Maintenance hangars	▒	🟩	🟩	▒	▒	▒	🟩	🟥	⬜	🟧	🟨🟧	🟩	🟩	🟥	🟧	🟩	🟥	🟨🟧	🟩	🟧	▒	🟩	▒	▒	🟧	🟨🟧

References

Airbus, 2022. ZEROe – towards the world's first zero-emission commercial aircraft. https://www.airbus.com/en/innovation/zero-emission-journey/hydrogen/zeroe.

Amankwah-Amoah, J., 2020. Stepping up and stepping out of COVID-19: new challenges for environmental sustainability policies in the global airline industry. J. Clean. Prod. 271, 1–8. https://doi.org/10.1016/j.jclepro.2020.123000.

ATAG, 2017. Beginner's Guide to Sustainable Aviation Fuel, third ed. Air Transport Action Group, pp. 1–24. November 2017. https://aviationbenefits.org/media/166152/beginners-guide-to-saf_web.pdf.

ATAG, 2020. Aviation Benefits beyond Borders. Powering Global Economic Growth, Employment, Trade Links, Tourism and Support for Sustainable Development through Air Transport, Despite Global Crisis, first ed. Air Transport Action Group, pp. 34–44. September 2020. https://aviationbenefits.org/media/167517/aw-oct-final-atag_abbb-2020-publication-digital.pdf.

ATAG, 2021. Balancing Growth in Connectivity with a Comprehensive Global Air Transport Response to the Climate Emergency: a Vision of Net-Zero Aviation by Mid-century, second ed. Air Transport Action Group, pp. 40–91. September 2021. https://aviationbenefits.org/media/167417/w2050_v2021_27sept_full.pdf.

Balk, A.D., 2008. Safety of ground handling. National Aerospace Laboratory (NLR). Report n. NLR-CR-2007-961. January 2008. 1-44. https://www.easa.europa.eu/sites/default/files/dfu/NLR-CR-2007-961.pdf.

Bauen, A., Bitossi, N., German, L., Harris, A., Leow, K., 2020. Sustainable Aviation Fuels. Status, challenges and prospects of drop-in liquid fuels, hydrogen and electrification in aviation. Johnson Matthey Technol. Rev. 64 (3), 263–278. https://doi.org/10.1595/205651320X15816756012040.

Berger, Roland, 2020a. Sustainable aviation fuels - the best solution to large sustainable aircraft? https://www.rolandberger.com/publications/publication_pdf/roland_berger_sustainable_aviation_fuels.pdf.

Berger, Roland, 2020b. Hydrogen – a fuel for future aviation? https://www.rolandberger.com/publications/publication_pdf/roland_berger_hydrogen_the_future_fuel_for_aviation.pdf.

Bradley, A.L.W., 2010. The Independent Airport Planning Manual, first ed. Woodhead publishing, Cambridge.

Bullock, A., 2016. Conduct one-to-one qualitative interviews for research. Educ. Prim. Care 27 (4), 330–332. https://doi.org/10.1080/14739879.2016.1176874.

CAAFI, 2021. 100% SAF – highlighting and exploring open questions. Commercial Aviation Alternative Fuels Initiative. October 2021. 1-17. https://caafi.org/resources/pdf/100percent_SAF_CAAFI_Webinar_10-06-21final.pdf.

Connected Places Catapult, 2022. Blueprint for zero emission flight infrastructure. https://cpcatapult.wpenginepowered.com/wp-content/uploads/2022/03/Blueprint_for_Zero_Emission_Flight_Infrastructure.pdf?utm_campaign=zefi&utm_source=website&utm_medium=download-zefi-blueprint.

Cooke, R.M., 1991. Experts in Uncertainty: Opinion and Subjective Probability in Science. Oxford University Press on Demand.

Domone, J., 2020. Sustainability in Aerospace: Exploring Alternative Fuels, first ed. ATKINS, pp. 1–30 https://www.atkinsrealis.com/~/media/Files/S/SNC-Lavalin/documents/beyond-engineering/sustainability-in-aerospace-2020.pdf.

EASA, 2021. Easy Access Rules for Aerodromes (Regulation (EU) No 139/2014). European Union Aviation Safety Agency. June 2023. 490-568. https://www.easa.europa.eu/downloads/98016/en.

European Commission, 2011. Flightpath 2050: europe's Vision for Aviation. Maintaining global leadership and serving society's needs. In: Report of the High Level Group on Aviation Research. https://data.europa.eu/doi/10.2777/50266.

FAA, 2021a. United States 2021 Aviation Climate Action Plan, first ed. Federal Aviation Administration, pp. 1–37. November 2021. https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf.

FAA, 2021b. Aviation Climate Action Plan. Federal Aviation Administration [online]. https://www.faa.gov/sustainability/aviation-climate-action-plan.

Fitouri-Trabelsi, S., Cosenza, C.A.N., El Moudani, W., Mora-Camino, F., 2014. Managing uncertainty at airports ground handling. Apr 2014, Paris. In: Airports in Urban Networks. Service Technique de l'Aviation Civile (STAC), pp. 1–9. https://hal-enac.archives-ouvertes.fr/hal-00990083.

Gnadt, A.R., Speth, R.L., Sabnis, J.S., Barrett, S.R.H., 2019. Technical and environmental assessment of all-electric 180-passenger commercial aircraft. Prog. Aero. Sci. 105, 1–30. https://doi.org/10.1016/j.paerosci.2018.11.002.

Gössling, S., 2020. Risks, resilience, and pathways to sustainable aviation: a COVID-19 perspective. J. Air Transport. Manag. 89, 1–4. https://doi.org/10.1016/j.jairtraman.2020.101933.

Hoelzen, J., Silberhorn, D., Zill, T., Bensmann, B., Hanke-Rauschenbach, R., 2022. Hydrogen-powered aviation and its reliance on green hydrogen infrastructure – review and research gaps. Int. J. Hydrogen Energy 47 (5), 3108–3130. https://doi.org/10.1016/j.ijhydene.2021.10.239.

Holladay, J., Abdullah, Z., Heyne, J., 2020. Sustainable Aviation Fuel – Review of Technical Pathways. U.S. Department of Energy. Report n. DOE/EE–2041. September 2020. 1-81. https://www.energy.gov/sites/prod/files/2020/09/f78/beto-sust-aviation-fuel-sep-2020.pdf.

Horonjeff, R., McKelvey, F.X., Sproule, W.J., Young, S.B., 2010. Planning and Design of Airports, fifth ed. McGraw-Hill publishing.

IATA, 2015. Safety report 2014. In: International Air Transport Association, 51st Edition. Annex 1, pp. 101–102. https://cdn.aviation-safety.net/airlinesafety/industry/reports/IATA-safety-report-2014.pdf.

IATA, 2019. Aircraft technology roadmap to 2050. In: International Air Transport Association. https://www.iata.org/contentassets/8d19e716636a47c184e7221c77563c93/Technology-roadmap-2050.pdf.

IATA, 2020. Standard into-plane fueling service levels and safety. In: International Air Transport Association. In: https://www.iata.org/contentassets/828efe1a6a2a487aacaa8fe7642f0c72/iftp-standard-fueling-procedures_service-levels-and-safety-v1.00.pdf.

ICAO, 2013. Phase of Flight. International Civil Aviation Organization. http://www.intlaviationstandards.org/Documents/PhaseofFlightDefinitions.pdf.

ICAO, 2018. Sustainable Aviation Fuels Guide. International Civil Aviation Organization. https://www.icao.int/environmental-protection/Documents/Sustainable%20Aviation%20Fuels%20Guide_100519.pdf.

ICAO, 2019. CO2 emissions from commercial aviation. In: 2018. International Civil Aviation Organization. Assembly – 40th Session. Working paper. https://www.icao.int/Meetings/a40/Documents/WP/wp_560_en.pdf.

ICAO, 2022. Report on the Feasibility of a Long-Term Aspirational Goal (LTAG) for International Civil Aviation CO2 Emission Reductions. Appendix M3 – Technology Sub Group Report, pp. 76–81. March 2022. https://www.icao.int/environmental-protection/LTAG/Documents/ICAO_LTAG_Report_AppendixM3.pdf.

Janić, M., 2009. Airport Analysis, Planning and Design: Demand, Capacity and Congestion. Nova Science Publishers.

Kivits, R., Charles, M.B., Ryan, N., 2010. A post-carbon aviation future: airports and the transition to a cleaner aviation sector. Futures 42 (3), 199–211. https://doi.org/10.1016/j.futures.2009.11.005.

Kramer, S., Andac, G., Heyne, J., Ellsworth, J., Herzig, P., Lewis, K.C., 2022. Perspectives on fully synthesized sustainable aviation fuels: direction and opportunities. Front. Energy Res. 9, 1–7. https://doi.org/10.3389/fenrg.2021.782823ABRA.

Mangold, J., Silberhorn, D., Moebs, N., Dzikus, N., Hoelzen, J., Zill, T., Strohmayer, A., 2022. Refueling of LH2 aircraft—assessment of turnaround procedures and aircraft design implication. Energies 15 (7), 2475. https://doi.org/10.3390/en15072475, 2022.

McKinsey, 2020. Hydrogen-powered aviation. A fact-based study of hydrogen technology, economics, and climate impact by 2050. Clean Sky 2 JU and Fuel Cells and Hydrogen 2 JU. https://www.fch.europa.eu/sites/default/files/FCH%20Docs/20200507_Hydrogen%20Powered%20Aviation%20report_FINAL%20web%20%28ID%208706035%29.pdf.

Midkiff, A.H., Hansman, J.R., Reynolds, T.G., 2004. Air carrier flight operations. In: International Center for Air Transportation. Massachusetts Institute of Technology. https://dspace.mit.edu/bitstream/handle/1721.1/35725/FlightOpsICATfinal2.pdf.

Modarress, B., Ansari, A., 2020. Environmental degradation and the implementation of the circular economy in commercial aviation. Sustain. J. Rec. 13 (4), 178–184. https://doi.org/10.1089/sus.2020.0006.

National Academies of Sciences, 2015. Engineering, and medicine. In: Overview of Airport Fueling Operations. The National Academies Press, Washington, DC. https://doi.org/10.17226/22141, 25–29.

National Academies of Sciences, 2016. Engineering, and medicine. In: Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. The National Academies Press, Washington, DC. https://doi.org/10.17226/23490.

Overton, J., 2022. The growth in greenhouse gas emissions from commercial aviation. Environ. Energy Study Inst. 1–10. Issue brief. https://www.eesi.org/files/IssueBrief_Climate_Impacts_Aviation_2019rev2022.pdf.

Postma-Kurlanc, A., Leadbetter, H., Pickard, C., 2022. Hydrogen Infrastructure and Operations. Airports, Airlines and Airspace. FlyZero. Aerosp. Technol. Inst. Report N. FZO-CST-POS-0035. March 2022. 1-78. https://www.ati.org.uk/wp-content/uploads/2022/03/FZO-CST-POS-0035-Airports-Airlines-Airspace-Operations-and-Hydrogen-Infrastructure.pdf.

Rondinelli, S., Gardi, A., Kapoor, R., Sabatini, R., 2017. Benefits and challenges of liquid hydrogen fuels in commercial aviation. Int. J. Sustain. Aviat. 3 (3), 200–216. https://doi.org/10.1504/ijsa.2017.086845.

Ryan, F., Coughlan, M., Cronin, P., 2009. Interviewing in qualitative research: the one-to-one interview. Int. J. Ther. Rehabil. 16 (6), 309–314. https://doi.org/10.12968/ijtr.2009.16.6.42433.

Ryley, T., Baumeister, S., Coulter, L., 2020. Climate change influences on aviation: a literature review. Transport Pol. 92 (2020), 55–64. https://doi.org/10.1016/j.tranpol.2020.04.010.

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, 160–166. https://doi.org/10.1038/s41560-018-0294-x.

Schmidt, M., Paul, A., Cole, M., Ploetner, K.O., 2014. Implications of aircraft concepts using alternative energy on ground operation. In: 18h Air Transport Research Society (ATRS) World Conference. Bordeaux. Document-ID: 245, pp. 1–12.

Staack, I., Sobron, A., Krus, P., 2021. The potential of full-electric aircraft for civil transportation: from the Breguet range equation to operational aspects. CEAS Aeronaut. J. 12, 803–819. https://doi.org/10.1007/s13272-021-00530-w.

Tabares, D.A., Mora-Camino, F., 2017. Aircraft ground handling: analysis for automation. In: 17th AIAA Aviation Technology, Integration, and Operations Conference. Jun 2017, pp. 1–16. https://doi.org/10.2514/6.2017-3425. Denver.

Van der Sman, E., Peerlings, B., Kos, J., Lieshout, R., Boonekamp, T., 2021. Destination 2050 – a Route to Net Zero European Aviation Netherlands Aerospace Centre and SEO Amsterdam Economics. Report N. NLR-CR-2020-510. February 2021. 1-106. https://www.destination2050.eu/wp-content/uploads/2021/02/Destination2050_Report.pdf.

Vergara, G.M., 2019. Explaining airline competition differences between the EU and the U.S. Max Weber Symposium. Eur. Univ. Inst. 1–18. https://commons.lib.jmu.edu/cgi/viewcontent.cgi?article=1029&context=ese.

Wright Electric, 2022. The Wright Spirit. https://www.weflywright.com/.

WSDOT, 2020. Washington Electric Aircraft Feasibility Study. Washington State Department of Transportation. November 2020. 124-135. https://wsdot.wa.gov/sites/default/files/2021-11/WSDOT-Electric-Aircraft-Feasibility-Study.pdf.