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Review

Prospects for Green Aircraft Critical Technologies and Operational Aspects

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Abstract

The aim of this paper is to give an overview of emerging technologies for the greening of aviation, how they can be applied to different classes of aircraft, and the challenges to be overcome in achieving efficiency and environmental objectives. The following steps are part of the journey towards the greening of aviation: (i) developing and maturing new technologies, including electrification and sustainable fuels; (ii) where possible, using new technologies in the current fleet to maximize short-term benefits—i.e., EU Fit for 55; (iii) when it is not possible to retrofit new technologies to current aircraft, incorporating them into new next-generation aircraft designs from 2035; and (iv) replacing existing fleets with new, cleaner aircraft to meet the ICAO Net Zero 2050 goal. These technologies of prime importance will have to be supplemented by operational, regulatory, and economic enablers to support wide deployment. There will not be one solution that meets the requirements of all aircraft classes or mission profiles, but rather a combination of electrification, hydrogen propulsion, and sustainable aviation fuels will be required. Achievement of aviation's environmental goals will hence not solely be a function of technological progress but also certification pathways, investment in infrastructure, and integrated policy strategies.

Keywords: green aviation; sustainable aircraft technologies; hydrogen fuel; hybrid–electric propulsion; e-VTOL; SAFs; regional aircraft; medium and long-range transport

1. Introduction

The history of aviation has evolved through four phases: (i) the pioneering period before the first World War (WWI), when the aim was simple, stable flight, that is, staying aloft safely between predictable take-off and landing sequences; (ii) the period starting with WWI through the second World War (WWII), up to and including the Cold War, when the aim was performance, i.e., going faster, higher and farther; (iii) the peace dividends of the post-war economic boom, which included the growth of the civil aviation market beyond the military sector, providing the world's population with large-scale safe, reliable and affordable air transport across the far reaches of the world; (iv) the new challenge for aviation, which is to contribute its fair share to the preservation of the environment. This last phase (iv) is the subject of monographs in book form [1] and extensive reviews in aeronautical journals referencing green [2] and sustainable [3] aviation, and emphasizing the need for new ideas [4] to face urgent environmental challenges) [5]. The greening of aviation, requires the development and adoption of new disruptive technologies [6] such

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as hydrogen-fueled aircraft [7,8] and electric [9] and hybrid thermoelectric [10] propulsion. The European Union (EU) has been a worldwide champion and leader of environmental protection, as demonstrated by its leadership in establishing aviation targets and implementation measures, including technological roadmaps [11], establishment of environmental goals [12] and operational measures and regulations [13]. In this context, the European Commission (EC) has steadily supported research and innovation in green aviation, including, among many others, two projects [14]: (i) PARE (Perspectives for Aviation Research in Europe), relating to general aeronautical technology, in 2018–2021 [15], and (ii) EFACA (Environmentally Friendly Aviation for All Classes of Aircraft), specifically detailing environmentally friendly design, in 2023–2026 [16].

The present paper focuses on the relation between, on one hand, (a) emerging technologies for the greening of aviation, and, on the other hand, (b) their implications for aircraft design and associated operational issues. Thus, the objective is not solely a review of the state of the art of green aviation technologies, as already covered in the literature, as we also incorporate extensive references concerning strategies [17] and policies [18], specific technologies, like electrification [19], and application to specific classes of aircraft, like electric vertical take-off and landing e-VTOL [20]. Neither is the objective mainly to report on the numerous projects—many from start-ups and developments and testing of green aircraft designs—whose status and specification are documented in reference works [21]. The critical aspect perhaps less well-covered in the literature is the link between (a) and (b), specifically the NASA technological readiness level (TRL [22]) and EASA certification readiness level (CRL [23]) of green aviation technologies, addressing a sequence of critical implementation steps. The aim is to answer the following questions: (i) What is the level of maturity of each technology with respect to achieving its environmental benefits? (ii) How can these technologies be applied to a new generation of aircraft that are at least as efficient as their predecessors while being more friendly to the environment? (iii) What are the challenges in applying green technologies to aircraft design, and what are the implications for widespread practical use? Thus, the aim is not just a review of cleaner technologies and their applications but an overview identifying which technologies apply to which classes of aircraft and what benefits and limitations may be associated with operational use.

The views expressed are those of the authors and not necessarily quotations from the existing literature; they may be more or less optimistic regarding the effectiveness and readiness of green aviation technology. The aim is neither that of a research paper proposing new ideas nor a review of the current literature, but rather an overview of the wider subject, possibly covering gaps in the existing literature, and may be original in that sense. The aim of a wider overview means that the scope is broader than usual reviews on electrification and hydrogen and synthetic fuels for aircraft, addressing topics less covered in the literature, like on-board hydrogen production, superconducting electric systems, and solar-powered aircraft. Thus, the technologies considered concern not only emerging technologies but also their development potential on timescales of application to the next generation of aircraft and beyond. These aims do not require to consider every type of aircraft but rather an important class from each of the following four groups: (i) battery power, (ii) hydrogen fuel cells, (iii) hydrogen-fueled gas turbines, and (iv) synthetic aviation fuels. Concerning each of these technologies, the topics addressed are as follows: (i) How can the technology be applied to that class of aircraft? (ii) What environmental benefits can be expected? (iii) What are the operational challenges and limitations associated with the aircraft design? (iv) What impact is the technology likely to have on the greening of aviation, specifically, to what extent, and on what timescale? These four questions are the motivation for emerging green aviation technologies, but extend well beyond the

technologies themselves by focusing on the path to practical application and widespread use, which are the ultimate measures of environmental impact and benefit.

The emerging technologies providing a path towards the greening of aviation are considered for four aircraft classes: (Section 2) battery power for small short-range aircraft such as electric vertical take-off and landing (e-VTOL) for urban air mobility (UAM); (Section 3) fuel cells combined with turbines providing Hybrid Turboelectric Power (HTEP) for regional aircraft; (Section 4) hydrogen-fueled gas turbines for narrow-body short- and medium-range (SMR) jetliners; and (Section 5) sustainable aviation fuels (SAFs) for long-range widebody jetliners. In addition, four "exotic technologies" are considered: (Section 6) large flying wings with sufficient internal volume for LH tanks; (Section 7) hydrogen on-board production, avoiding the challenges of LH fuel systems and supply; (Section 8) tens of MW superconducting electrics for large jet liners using gas turbines to drive electric generators for distributed propulsion; and (Section 9) solar-powered aircraft with potentially unlimited endurance but small payloads and low speed, which can cause vulnerability to storms. The conclusion (Section 10) summarizes the main objectives and challenges in the context of the implementation of new environmental technologies in diverse classes of aircraft.

2. Battery Power for e-VTOL

The use of batteries [24] in aviation has expanded from auxiliary power sources in "more electric aircraft" [25] to main sources of propulsion [26] enabled by lithium-ion batteries that: (i) offer the benefit of [27] higher power-to-weight ratio than previous generations of lead-acid and alkaline batteries; (ii) have safety risks [28] associated with susceptibility to shock, thermal runaway and explosion. Battery technology has gone through three generations (Section 2.1), with the more recent lithium-ion technology enabling the propulsion of small short-range aircraft (Section 2.2), including e-VTOLs. The issues relevant to e-VTOL operations include: (Section 2.3) vulnerability to adverse weather; (Section 2.4) use of helicopter pads for take-off and landing; (Section 2.5) design of dedicated vertiports; (Section 2.6) expectations of operating costs; (Section 2.7) provision of niche transport rather than easing urban congestion; (Section 2.8) payload-range extension using hydrogen fuel cells; (Section 2.9) program costs, and timescales to achieve certification and reach operational use (Section 2.10).

2.1. Four-Generations of Battery Technologies

The replacement of lead-acid [29] by alkaline batteries like nickel cadmium [30] was far from problem-free, although such issues belong to a distant and forgotten past; the replacement of alkaline by lithium-ion [31,32] batteries was also not entirely problem-free; witness the battery fires [33] on the Boeing 787, which were solved by better separation, cooling and venting. The risks of overcharged and undercharged lithium-ion batteries catching fire, causing a thermal runway across a whole battery pack [34–37], have been mastered, as witnessed by their relatively safe regular use in millions of cars. Batteries were used for a long time in aviation as electricity supplies and back-ups and engine starting, electrical actuation, and to power electronics. The lithium-ion batteries have for the first time the power-to-weight ratio to enable their use in propulsion of cars and small short-range aircraft. A fourth generation of solid-state batteries [38,39] could increase power-to-weight ratio and improve payload range, but would still face development challenges like durability.

There are a variety of battery chemistries at the research stage promising higher power-to-weight ratios and safer operation than current lithium-ion batteries, but still facing challenges on the path to wide use. The promising emerging battery technologies

include the choice of electrolytes [40,41], metal–air [42], aluminum-ion [43] and flow [44,45] chemistries and configurations. One of the issues is the formation of dendrites growing from one electrode, and causing a short-circuit if reaching the other electrode, thus limiting the number of charge cycles and battery life, which affects replacement costs. The battery packs generally require structural support, but this is simplified in the case of structurally light and multifunctional [46,47] batteries. Battery propulsion [48] is feasible for small aircraft up to 10 seats over ranges of a few hundred km. Considerable attention [49] has been given to Urban Air Mobility (UAM) and Innovative Air Mobility (IAM) using [50] e-VTOL (electrical Vertical Take-Off and Landing), for which the requirements for vertical flight limit range to about 100 km with up to four passengers.

2.2. e-VTOLs for Urban Air Mobility

The most visible progress [51] has been in e-VTOL, including innovations that promise urban air mobility (UAM) while remaining local-emissions-free by using electric power [52] supplied by batteries [53]. In fact, e-VTOLs are not emission-free over their entire life cycle, due to the mining of rare earths for batteries; the production of electric equipment like motors, inverters and controllers; and their end-of-life disposal, with only partial recycling possible so far. e-VTOLs are not an entirely new mode of transportation, but rather an alternative to helicopters, with no local emissions and possibly less community noise annoyance, but also less speed and payload range, and other limitations. The key differentiator is that the power-to-weight ratio of a battery is far lower than a fossil-fueled gas turbine. Being low-speed aircraft, e-VTOLs can have a variety of configurations, often with multiple propellers, with horizontal axis for propulsion, vertical axis for lift, and tilting for transition.

2.3. Flight in Adverse Weather

The disk loading, defined as total weight divided by total propeller or rotor area, is higher for e-VTOLs relative to conventional helicopters, implying that the former, unlike the latter, are not able to autorotate to a safe landing in case of engine failure. This may be mitigated by e-VTOLs having multiple engines and interconnected propellers; flying in an urban environment may not leave many locations for autorotation landing, anyway. e-VTOLs, compared with helicopters [54], have less hovering capability and less ability to counter the strong winds and windshears that may occur in the wakes of tall buildings. Besides being more vulnerable to urban weather than helicopters, e-VTOLs may not be able to avoid storms by overflying them. Thus, e-VTOL operations should ensure at departure acceptable weather for the whole flight, up to and including safe landing [55], based on the weather predictions over their relatively short durations of flight.

2.4. Use of Helicopter Pads

Besides the flight and weather safety [56,57], e-VTOL operations depend on suitably located take-off and landing sites. It is to be expected that e-VTOL operations start along existing helicopter routes, for example, linking airports to city centers. Using helicopter landing and take-off sites for e-VTOLs may require investment in new fast-charging electric infrastructure and battery storage facilities. The higher disk loading of e-VTOLs, compared with helicopters, creates a stronger downwash flow, which causes an outwash near the ground and may require a larger safety area around the lift-off point at take-off and touchdown point at landing. For this reason, not all existing smaller helipads may be usable by e-VTOLs. Also, the helipads at tall buildings of large corporations may not be available for public use for security reasons. Larger helicopter landing spots at airports or near hospitals or government buildings should be able to accommodate e-VTOLs with some extra precautions for downwash/outwash.

2.5. Dedicated Vertiports

The design of dedicated vertiports for e-VTOLs [58] could minimize downwash/outwash effects [59] by using perforated landing pads and ducting away the excess airflow below. The use of roofs of car parking structures or other existing buildings for e-VTOL operations may not be an easy alternative to dedicated vertiports, because in each case there must be a significant investment in infrastructure, such as electric charging and battery storage, passenger air cargo terminals and other related facilities. Also, vertiports, like airports, may depend on commerce and shopping at passenger terminals, in order to balance finances and charge affordable landing/take-off fees. This leaves the questions of land permission and the substantial investment to build the vertiport in the first place. Local authorities may authorize, but not invest in, vertiports for e-VTOL transport for the wealthy, so a business case must be made to build a vertiport and recover the investment.

2.6. Travel Costs

It is often argued that e-VTOLs will be cheap transport, assuming low cost of electricity; that may not always be the case. However, the cost of battery replacement could easily exceed the cost of electricity. To be economically viable, e-VTOLs should make several flights per day, which is feasible due to their short-range flights, even at low speeds; also, fast charging may be used to reduce turnaround times at vertiports. Thus used, an e-VTOL will accumulate many cycles using fast charging, which reduces battery life. The battery charging options affect the lifetime of batteries and the economics of transport vehicles they power [60,61]. An e-VTOL flying six times per day every day of the year accumulates 2k cycles per year. If an e-VTOL can fly with 80% battery charge, as in the case of a car driving with a battery lasting 10k cycles, the economics of battery replacement every 5 years should be sustainable. If an e-VTOL requires 90% power for flight, with a battery life of 1k cycles, battery replacement costs every half year may become unsustainable, as shown by some project cancellations.

2.7. Niche Transportation

The claim that e-VTOLs will replace taxis and ease urban congestion is unlikely to be realized soon, due to at least five reasons. First, taxis are door-to-door transport, and an e-VTOL would require a taxi to the vertiport at departure, and a taxi from the vertiport at arrival, except for locations close to the vertiportsSecond, flying an e-VTOL will require a certificated pilot for vertical flight, according to current EASA/FAA rules, one whose salary is not that of a taxi driver. Third, the permission for unmanned e-VTOLs carrying fare-paying passengers over populated urban areas is likely to come later than autonomous cars in city streets. Fourth, the battery replacement costs and the maintenance demands of e-VTOLs could well exceed those of taxis. Fifth, the number of car movements in a large city is millions per day and it is hard to imagine a network of vertiports and air traffic management capable of safely supporting comparable e-VTOL traffic levels, which would be needed to ease congestion.

2.8. Payload-Range Extension

The early uses of e-VTOL are likely to be as a replacement, and possible expansion, of short-range helicopter flights, benefiting from the absence of local emissions, and possibly making less noise. Tasks would include the transport of wealthy individuals and valuable medical supplies, and responding to medical emergencies [62]. e-VTOLs would be free from the flight safety constraints over cities [63] if operated in remote areas, for agricultural or surveillance duties, for which drones could be an alternative [64]. e-VTOLs might suit law enforcement authorities [65] whose requirements involve short flight times or limited endurance. The use of e-VTOLs for logistic transport of military supplies was tested [66] by the

armed forces of the United States for use in the Pacific theater. The e-VTOLs' payload range is too short for the vast distances between Pacific Islands, a determination which led to the development of alternative hybrid propulsion systems. Using hydrogen fuel cells (Section 3) instead of only battery power can significantly extend the payload range of e-VTOLs [67].

2.9. Program Cost and Timescale

The current more than 100 e-VTOL projects worldwide may lead to half a dozen certified and operating vehicles to be used for urban air mobility [68] and as local vertical flight transport alternatives to helicopters [69], as well as create one of the elements of the emerging low-altitude economy [70], below the flight levels of current airliners. The early optimistic estimate of development times of 2–3 years and costs of hundreds of millions, has given way to the realization that taking an e-VTOL through certification to operations may cost 1–2 billion over 5–10 years, through six stages: (i) the low speed of e-VTOLs allows a variety of configurations, which can be tested first at small scale, including the most critical phase of transition between vertical and horizontal flight; (ii) the small-scale demonstrators are followed by full-scale prototypes with payload ranges comparable to the operational vehicle; (iii) the full-scale prototypes are replaced by compliant e-VTOLs meeting all certification requirements; (iv) the compliant e-VTOLs are used for test flying and demonstrations leading to certification of flight and production facilities; (v) the certified e-VTOLs are produced for initial operational use, and may not be profitable at the beginning due to limited scale; and (vi) the larger-scale use of e-VTOLs should then lead to operations with suitable returns on investment.

2.10. Operational Use

Some of the e-VTOL projects are not short of "orders", loosely describing anything from expressions of interest to the (more rare) paid deposits. The "valley of death" is the long and costly development and certification process. The pioneers of e-VTOL in Europe (Figure 1) have collapsed without government support or rescue [71,72], or survive marginally on budgets that need reinforcement to reach certification. In the United States the tests by the Defense Department of three e-VTOLs, while not leading so far to production orders, have supported [73] development of the three types (Figures 2–4), likely leading to certification. In China (Figure 5), the "low altitude economy" [74], including projects other than e-VTOLs, has enjoyed strong support not only from the central government but also from the provinces, benefiting also from the large battery ecosystem for cars. The better-financed e-VTOLs further along the development process may benefit from the support of large car companies [75] seeking further applications of their electric vehicle technologies.



Figure 1. The Volo-City e-VTOL [76] was one of the European projects without support comparable to the U.S. competitors, and went bankrupt before certification, after an investment of over 1 billion euros, before being sold to a Chinese company for less than 40 million euros (Creative Commons, Wikimedia).



Figure 2. The three e-VTOL developments most likely to reach certification in the West are the Archers Midnight (Figure 2), Joby S4 (Figure 3) and Beta Alia (Figure 4). Archer Midnight e-VTOL [77] production aircraft mockup at unveiling event (Creative Commons, Wikimedia).



Figure 3. All 3 U.S. e-VTOLs benefited from tests as "last mile" transports for the Department of Defense. The payload range required for inter-island logistics in the Pacific Ocean is well beyond battery power and can be met only by changing to hydrogen fuel cells. Joby Aviation S4 [78] experimental eVTOL aircraft at Edwards Air Force Base (Creative Commons, Wikimedia).



Figure 4. The 3 U.S. e-VTOL competitors follow different strategies: (i) aiming directly for e-VTOL or using conventional STOL (Short Take-Off and Landing) versions for earlier certification, operational use and return on investment; (ii) relying on multiple suppliers with previous certification experience or opting for vertical integration with most subsystems designed and produced in-house for greater efficiency. BETA ALIA electric aircraft [79] on the flightline at Joint Base Andrews, Md., USA, 18 October 2023 (Creative Commons, Wikimedia).



Figure 5. The Ehang 184 [80] is the first e-VTOL to be certified, although the Chinese certification may not meet the demanding standards of the EASA (European Aeronautical Safety Agency) and FAA (Federal Administration Aviation) in the West. The Chinese "low altitude economy", supported by central and provincial governments, and benefiting from experience with electric cars, is advancing rapidly, with a larger number of designs than those seen in the West, some larger, in particular, the cargo designs. Although presented as civilian programs, they may give China an inter-island logistics capability in the Pacific both greater and larger than the publicized plans of the U.S. military (Creative Commons, Wikimedia).

2.11. Battery Power for Conventional Aircraft

The power-to-weight ratio associated with the lithium-ion batteries that enable propulsion of an e-VTOL with up to four passengers over ranges of 100 km, without the demands of vertical flight, for a conventional aircraft, would enable ranges up to 400 km with 10 passengers. At the smallest scale, the first all-electric aircraft certified by EASA is a training aircraft, and its low cost per flight hour is more important than constraints associated with limited range or endurance. At the higher end, the first hybrid versions of the most widely used regional turboprops, namely, the ATR 72 and Dash 8, are likely to use hybridized turboprop engines, with 10% of their total power provided by large battery packs. A much higher level of hybridization, that is, electric power as a percentage of total power, is possible in hybrid-turboelectric propulsion (HTEP), using hydrogen fuel cells as the main electrical power source. The use of HFC allows hybridization above 30% in HTEP, and up to 100% hybridization for the all-electric aircraft powered entirely by HFC. The HFC has a slow response time for flight emergencies or fast power surges, and batteries are used to cover the power gap. This is in addition to the use of batteries in more electric aircraft (MEA) to support electric and electronic systems, with electric power also used for air conditioning and actuators.

3. Hybrid Turboelectric Propulsion

The higher power-to-weight ratio of hydrogen fuel cells relative to batteries enables hybrid turboelectric propulsion (Section 3.1) for regional propeller airliners (Section 3.2), in combination with gas turbines and battery back-ups (Section 3.3). The design of aircraft with HFC (Section 3.4) is more challenging than for land vehicles (Section 3.5), due to flight conditions including the operation at altitude (Section 3.6). The viability of HTEP regional airliners is not only a matter of maturing the technology (Section 3.7), but also the availability of hydrogen support infrastructure at airports (Section 3.8).

3.1. Turboelectric Propulsion

A helicopter, depending on size, can accommodate up to 40 passengers, reach a speed of more than 300 km/h and have a range in excess of 800 km. A convertible can travel faster and further. In contrast, most current e-VTOLs are limited to four passengers, speeds

below 150 km/h and ranges of less than 200 km, due to the low power-to-weight ratio of their batteries. The same e-VTOL may carry the same payload over more than 1000 km by replacing the battery-electric propulsion (BEP) with hydrogen fuel cells (HFC) with much better power-to-weight ratios. The HFC are currently limited to powers up to 1–2 MW, and thus are suitable for twin-engine regional aircraft with ranges up to 1000 km with 100 passengers, replacing turboprops with hybrid turbo-electrical propulsion.

3.2. Regional Airliners

A typical current regional airliner (Figure 6) uses turboprops, combining a jet engine with a propeller that is more efficient at low speeds; however, the turboprop is sized for maximum power at take-off but operates most of the time at partial power during cruise flight, with reduced efficiency. In HTEP (Figure 7): (i) the gas turbine (GT) is optimized for maximum efficiency in cruise; (ii) the extra power needed for take-off, climb and other flight phases is provided by an electric motor (EM), supplied with electric current from an HFC; and (iii) the GT and EM drive the propeller, either in series or in parallel. Since the HFC has no carbon emissions and operates at low altitudes, it contributes to better local air quality (LAQ) near airports. HTEP may reduce total flight emissions by 10% to 60% compared to turboprop, depending on the degree of hybridization, which is the percentage of total power supplied as electricity by the HFC.



Figure 6. ATR 72-600 [81] regional turboprop airliner in flight. This is the latest version of the ATR regional airliner family developed jointly by Airbus and Leonardo and remains the market leader for propeller aircraft, which have superior fuel efficiency compared with jetliners, operating at lower altitudes and shorter ranges from smaller airfields (Creative Commons, Wikimedia).

3.3. Battery Back-Up

HTEP does not dispense with batteries, because the HFC has slow response, on the order of several seconds, to sudden power demands. Thus, in case of failure of the GT, or need for a fast power surge in an emergency, backup batteries are needed to close the power gap until the HFC delivers full power. A regional aircraft, regardless of type of propulsion, must have reserves for failed landing and turning around, and for diversion to another airport due to this reason or due to adverse weather near the destination airport. For turboprop aircraft the reserves mean extra fuel, whereas for HTEP they may require upgraded design.

3.4. HFC in Aircraft

The empty weight of a regional aircraft is higher with HTEP than with turboprops, due to the extra weight of the HFC, electric equipment and hydrogen tanks, which also increase volume and hence surface area and drag. Hydrogen is much lighter than fossil fuel equal to the same energy, and the reduced fuel weight implies that the total take-off weight may

be comparable for a TP or HTEP with the same range and full passenger capacity. In the case of a TP, a reduction in the number of passengers may allow a larger fuel load and longer range, helped by the aircraft becoming lighter as fuel is consumed. For HTEP, the amount of hydrogen is limited by tank volume, its consumption has a small effect on weight, and the weight penalty of the HFC and electrical equipment remains, and thus range does not increase much with reduced passenger numbers. The same applies to e-VTOLs, which always carry the same battery weight, whereas helicopters become lighter as fuel is consumed.

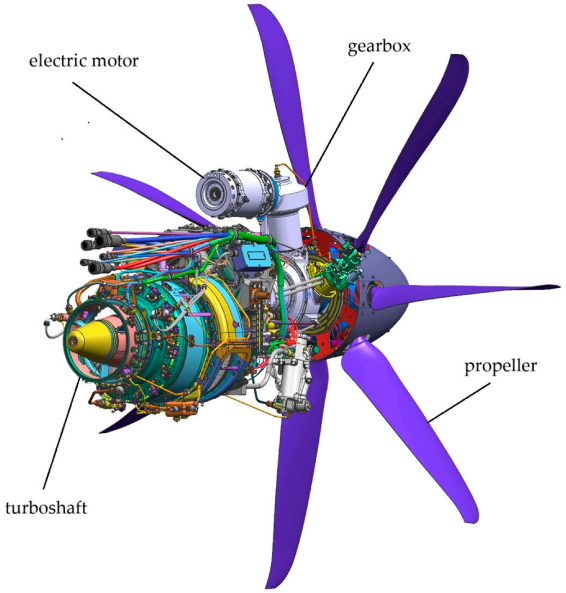


Figure 7. The WP1 of the EFACA Project includes the ground bench testing by Ivchenko-Progress of a hybrid propulsion system consisting of a gas turbine and electric motor driving a 7-blade propeller through a combiner gearbox. The electric motor has a much higher rotation speed than the gas turbine, making the design of a combining gearbox more challenging, possibly a world first.

3.5. Land-Based Experience

Most of the experience with HFC comes from cars, trucks, trains and ships, as well as fixed installations at approximately ground level. For an aircraft application HFC faces two issues: (i) flight loads and vibrations; and (ii) effects of altitude. The HFC itself can be only a fraction of the weight and volume of a fuel cell stack, including oxygen and hydrogen supply and cooling and control systems. The dissipation of the heat limits the efficiency of an HTC to 40–60%, which is still better than the 40% of an internal combustion engine (ICE) and far below the more than 90% for an electric motor (EM).

3.6. Altitude Effects

Heat dissipation requires heat exchangers, which became larger in the less-dense air at altitude, causing more drag. The heat dissipation is improved for solid oxide fuel cells (SOFC), which operate at much higher temperatures (600–800 °C) than the 80–200 °C of current permeable membrane fuel cells (PEMFC). The use of solid-state fuel cells [82] in hybrid-turboelectric or all-electric commercial aircraft [83] depends on advances in technology [84] concerning chemistry [85], membranes [86] and stability of components [87], and is subject to varying power demands [88]. As for batteries, solid-state fuel cells (i) have issues such as thermal management [89] and control [90] and (ii) depend on details of electrochemical processes, including materials [91,92], components [93] and design [94]. However, SOFC are slower to start and gain power than PEMFC and require more battery assistance to cover power gaps. The high operating temperatures of SOFC relative to PEMFC introduce additional safety risks. The SOFC technology lags behind PEMFC in

maturity, and whereas PEMFC are widely used, SOFC are still in development. SOFCs have the advantage that, unlike PEMFC, they can use fuels other than hydrogen and can enable on-board hydrogen production (Section 6). The critical elements in HFCs are the electrode materials, the chemical composition of the electrolyte and the physico-chemical properties of the membrane [95,96], and operation depends on water flows and heat dissipation [97,98]. Replacing liquid cooling by phase change plus heat pump (PCHP) cooling promises [99] reduction of heat losses, higher efficiency and improved operation at altitude.

3.7. Technology Maturation

The regional turboprop market is more or less static, with growth concentrated in larger jet-powered airliners, which although less efficient, fly faster in the smoother air at higher altitudes, with gas turbine vibrations and noise less intrusive than propellers, yielding greater passenger comfort. The application of HTEP to regional propeller aircraft could consist of (a) conversion of existing turboprops or (b) replacement by totally new, cleaner aircraft that could expand the market.

3.8. Support Infrastructure

In all cases, the availability of hydrogen refueling ground infrastructure at airports is essential to support hydrogen-fueled aircraft using either HFC (Section 3) or direct hydrogen combustion gas turbines (Section 4), to resupply on-board hydrogen tanks and fuel systems [100,101]. Universal Hydrogen based in Toulouse developed both (1) an on-board hydrogen conversion kit for regional aircraft and (2) the associated hydrogen-fueled ground infrastructure, but went bankrupt before practical use. Plans for flight testing a twin turboprop airliner with one engine replaced by HTEP are being pursued in Europe and America. There are several HTEP regional aircraft projects with 30 to 80 seats at various stages of development, still short of certification, but with prospective order books.

The WP2 of the EFACA Project includes the laboratory demonstration of a novel PCHP cooling system that improves the performance of the PEM fuel cells (Figure 8).

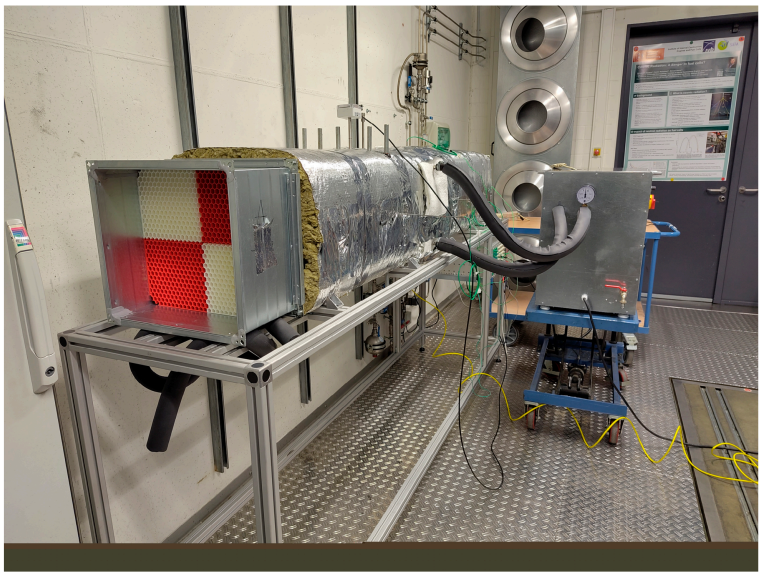


Figure 8. The WP2 of the EFACA Project includes the design of testing at Braunschweig Technical University (TU Braunschweig) of a hydrogen fuel cell (HFC) with a novel phase change heat pump (PCHP) cooling system that reduces heat losses, increases efficiency and improves performance at altitude. The conventional liquid cooling (LC) of the hydrogen fuel cells (HFC) currently used to dissipate the heat of operation requires heat exchangers that become larger and cause more drag when at altitude, given their design. The replacement of liquid by PCHP cooling addresses these issues.

4. Hydrogen-Fueled Narrow-Body Jetliners

The use of LH in aircraft (Section 4.1) poses new challenges relative to the experience with rockets (Section 4.2). The safety risks are different for fossil fuels and hydrogen (Section 4.3), with factors including: (Section 4.4) flammability range; (Section 4.5) corrosion and leaks; (Section 4.6) thermal insulation; and (Section 4.7) combustion stability. LH as fuel raises several operational and design issues: (Section 4.8) contrail formation and means of avoidance, including (Section 4.9) the WET engine; (Section 4.10) accommodating the large volume of LH tanks is a major aircraft design consideration (Section 4.11); and (Section 4.11) LH support infrastructure would be required at airports (Section 4.12).

4.1. LH for Aircraft

The low power-to-weight ratio of batteries limits their use to small, slow, short-range aircraft such as the e-VTOLs for UAM (Section 2). The higher power-to-weight ratio of HFC enables the HTEP of regional airliners of up to 100 seats and 1000 km in range, limited by the maximum achievable power of 1–2 MW. This is insufficient for jet-powered single-/twin-aisle medium/long-range aircraft requiring 10–40 MW of power. Hydrogen can still be used for single-aisle medium-range (SMR)jetliners, for direct combustion in gas turbines, with the size of the tanks limiting their use to aircraft with 200 passengers and a 3000 km range. Hydrogen is the lightest of elements, and although its energy density per unit weight is four times larger than that of fossil fuel, its energy density per unit volume is much lower, even (a) compressed at 300–600 atm or (b) in liquid form, at cryogenic temperatures below 20 K. Ships and land vehicles use compressed hydrogen at high pressure, usually up to 600 bar. This leads to heavy tanks that are not suitable for aviation; in addition, the long filling times would lead to excessive turn-around times between flights, negatively affecting economics. Thus, for aviation the best choice is liquid hydrogen (LH). Hydrogen energy systems [102] have a greater application potential in aviation [103] due to the liquid hydrogen [104], which avoids the problems of high-pressure gaseous hydrogen at 350–700 bar, requiring heavy tanks, along with long refueling times that are incompatible with an economically efficient fast turnaround at airports between flights. Hydrogen contributes to the sustainability of aviation [105] because its use is carbon-free [106] in propulsion systems [107], including both hydrogen fuel cells and gas turbines [108]. For hydrogen-fueled aircraft [109] using turbine power [110], hydrogen has particular challenges for engine design [111]. Hydrogen is much lighter than air, and thus has a higher speed of sound, implying a faster advance of combustion front and sharper rise of instabilities, leading to opposite extremes of flame extinction or flashback overheating of fuel injectors, requiring specific design of spray nozzles and combustors.

4.2. Experience with Rockets

Considering the use of LH in rockets, there have been decades of experience (since the 1960s) with its use as a cryogenic propellant in the rocket engines of satellite launchers and early inter-continental ballistic missiles (ICBMs), including the following aspects: (i) liquid hydrogen is used as a fuel below 20 K; (ii) liquid oxygen is used as an oxidizer below 60 K in the proportion of 1:8 by weight; and (iii) in each case, propellant tanks have to be filled shortly before the flight to avoid excessive evaporation. This constraint is met in the structure of a countdown for a satellite launcher. This limitation on the launch readiness of the ICBM and other ballistic missiles led to the replacement of LH/LOX by solid propellants that can be stored permanently on-board for launch at short notice. The current trend in satellite launchers at present is to retain the use of LOX (still cryogenic but at temperatures not as low as LH) and replace LH with hydrocarbons (kerosene, methane). This is the reverse of aviation, since satellite launches are far less numerous than aircraft

flights, and in spite of the former's greater environmental impact. The experience with LH in rockets is only partly relevant to aviation: (i) a rocket flight lasts minutes, versus hours for an aircraft flight; and (ii) the safety level is 10^{-2}–10^{-3} for rockets, versus 10^{-6}–10^{-9} for aircraft. Hence, aviation is much more safety-critical with respect to LH than is the case for rockets.

4.3. Safety Risks

All fuels pose safety risks, which are different for fossil fuels and hydrogen. The safety risks of fossil fuels are well-known from their widespread use over decades, whereas hydrogen poses new challenges concerning color, smell, flammability, corrosion and evaporation. The safety issues of hydrogen include storage and transportation [112] for land vehicles [113] as well as aircraft [114]. Hydrogen, unlike fossil fuels, has no color or smell, and since it is the simplest molecule, it is not straightforward to change these properties. Hydrogen can be lethal to humans in closed spaces, and its detection requires sensors at suitable locations where higher concentrations may be expected; this is a lesser problem in open spaces since, as the lightest of gases, hydrogen quickly rises in the atmosphere.

4.4. Flammability Range

Hydrogen burns in air with a much wider flammability range (10–90%) than demonstrated by fossil fuels. Since it is much lighter, with a molecular weight of 2 for hydrogen and 29 for air, the speed of sound is 4–5 times faster, leading to faster flame propagation, and more rapid growth of instabilities that can lead to explosions. These problems are more of an issue in closed, rather than open, spaces. In the much-publicized Hindenburg accident, the airship was completely burned by rising hydrogen, and the passengers escaped below. Venting means that hydrogen quickly rises in the atmosphere and will not burn or explode unless there is an immediate spark or ignition source. In contrast, liquid fossil fuel leaked on the ground will remain a fire and/or explosion risk until it is fully absorbed.

4.5. Corrosion and Leaks

As the smallest of molecules, hydrogen leaks through junctions much more easily than larger hydrocarbons; thus, bolted junctions between tubes may be leak-proof for fossil fuels, but not for hydrogen, requiring soldered or leak-proof joins. Hydrogen is also corrosive, requiring protective coating for iron pipes, or the use of other metals, like aluminum. The use of LH at temperatures below -250 °C may also cause brittleness of materials. The liquefaction of hydrogen is an endothermic process requiring significant amounts of energy. Conversely, if LH leaks, it is likely to evaporate, as the temperature exceeds 30 K, thus releasing heat in an exothermic reaction, which, together with high flammability, may lead to fire or explosion. For safety, hydrogen leaks, which are hardly totally avoidable, should be readily vented out of closed spaces into the atmosphere.

4.6. Thermal Insulation

Using LH implies not only the energy consumption of liquefaction but also the thermal insulation required to keep the temperature below 20 K. This is particularly critical for LH storage and transportation. The large-scale use of hydrogen [114] involves transportation [115] and safety [116] issues. The use of liquid organic hydrogen carriers (LOHC) involves [117] chemical processes [118] that would be more difficult to implement in aeronautics, as compared to the direct use of liquid hydrogen [119], which must contain LH for longer periods with minimal leaks, while allowing for its venting. LH tanks are dewar vessels, with a vacuum between the inner, corrosion-free or protected wall and outer, thermally insulated wall. Liquid hydrogen tanks require lower cryogenic temperatures than other liquified gases [120], and their use in aircraft [121] requires structural computations [122],

including those of thermal effects. The support structure required to link LH tanks to the aircraft could be avoided by using conformal LH tanks fitting the external shape of the aircraft and maximizing the use of available volume. Conformal LH tanks have been demonstrated in laboratory conditions; their use in aircraft would face certification challenges to prove that they are leak-proof when used as load-bearing structures. Although LH is about one-third the density of fossil fuel, it requires heavier tanks, depending on the gravity factor, which compares the weight of the empty and full LH tank. Composite LH tanks have a more favorable gravity factor than metallic tanks but pose greater challenges of durability and manufacture.

Conformal LH tanks fitting the shape of an aircraft structure are an emerging technology maximizing the use of available volume for fuel and simplifying the support structure. LH sloshing in tanks may be limited by internal partitions, not only to avoid center-of-gravity shifts affecting flight stability, but also to limit transitions between ortho- and parahydrogen [123,124] due to the change of electron spin alignment, which can lead to heat release. The entire fuel system of an LH-fueled aircraft must be kept at cryogenic temperatures below 20 K, including storage tank, fuel lines, pumps and all other equipment up to the vaporizer that precedes the combustion chamber. The cryogenic technologies [125] for a complete hydrogen fuel system include not only the tank and fuel lines, but also the vaporizer [126] and pumps [127]. There has been considerable experience with cryogenic pumps [128] in mobile machinery [129], including turbopumps of rocket engines in satellite launchers, which have very high speeds [130]. The cryogenic pumps [131] for aerospace applications [132] must operate efficiently without cavitation [133] in aircraft for flight times of hours, much longer than the minutes of rocket launchers of satellites.

4.7. Combustion Stability

The combustion of hydrogen may require a burner design different from that for fossil fuels, due to the higher flame speed and faster growth of instabilities (Figure 9). Thus, a combustion chamber for hydrogen may have a different geometry and injector design from that for fossil fuels; designing a dual combustor able to use either fossil fuel or hydrogen is not an easy task. The main environmental advantage of hydrogen over fossil fuel is that its combustion does not produce carbon oxides, along with their global warming effects. Although hydrogen combustion is carbon-free, it is not emission-free as regards other components such as nitrogen oxides; the combustion temperature of hydrogen is higher than those of fossil fuels, leading to higher emissions of nitrogen oxides unless special measures are taken. Depending on the production method, hydrogen may result in the emission of less sulfur and particles than fossil fuel.

4.8. Contrails Formation

The combustion of hydrogen produces mainly large amounts of water vapor, which is not a problem for ships and land vehicles operating at low altitudes. However, water vapor, in the form of contrails, is a greenhouse gas at aircraft flight altitudes; there is a lack of consensus as to how important it is relative to carbon oxides, as regards the global warming effect, from dominant to small. Contrails are ice crystals that form around exhaust particles at specific atmospheric conditions. The formation of contrails can be avoided by altitude change, with a small effect on fuel consumption and carbon emissions for a single aircraft. However, in a congested airspace, changing the flight level of one aircraft may affect several others, requiring air traffic management (ATM) changes. Furthermore, contrails last a short time of hours or days, whereas carbon oxides stay in the atmosphere for many years. The trade-off in eliminating short-term contrails and increasing long-term carbon oxide concentrations even by a small amount may not be obvious.

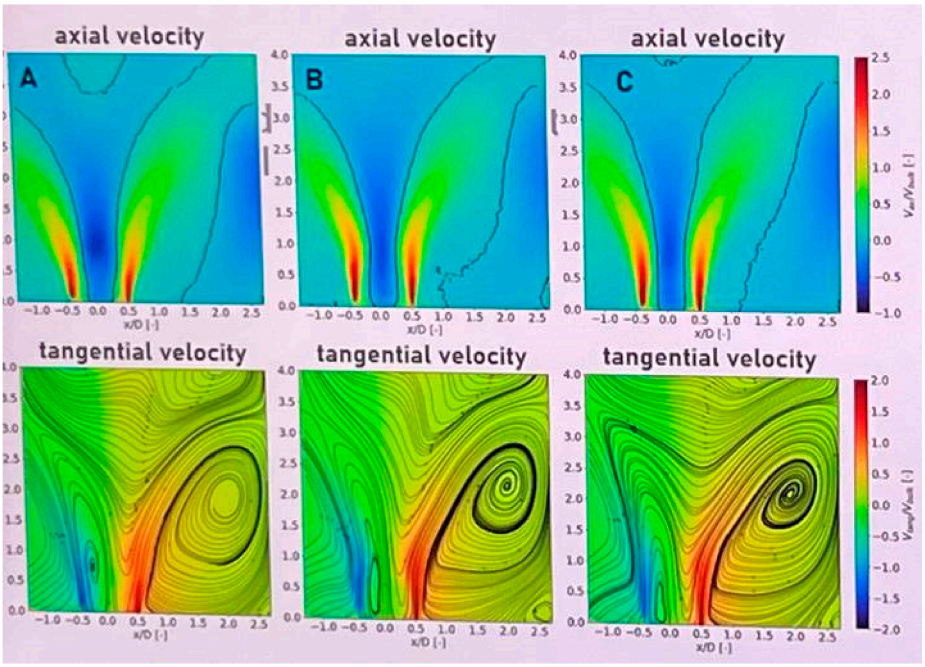


Figure 9. The WP3 of the EFACA Project includes laboratory testing of a liquid hydrogen fuel system, achieving stable combustion with a novel dual swirl injector design, with particle image velocimetry showing the flow pattern, in the reference isothermal case. The higher speed of sound in hydrogen compared with air leads to faster flame propagation and quicker growth of instabilities, which may have the opposite effects of overheating, flashback of the burner or flame extinction. The special dual swirl coaxial hydrogen burner demonstrated stable combustion, without flashback or extinction, over a relatively wide range of operating conditions.

4.9. WET Engine

Contrails can be minimized in engine design and operation [134], and by using "purified" fuel, fuel with less particles around which the ice crystals of contrails can form. There is also the opposite alternative of injecting ice crystals into the exhaust so that the contrails have a smaller number of larger particles and decay faster, before cirrus clouds can form. A much more technically complex solution is the WET (water exhaust treatment) engine: (i) the water vapor in the exhaust is captured and condensed in an heat exchanger with some loss of thrust; (ii) the resulting water can be injected into the combustion chamber to provide more oxygen and increase power, as in the water-injected piston engines of the past; and (iii) the use of water injection in the compressor may reduce temperature and allow for a higher compression ratio and increased efficiency. Thus, the WET engine could gain power and efficiency relative to the conventional gas turbine, with complexity, weight, volume and cost penalties in the trade-off.

4.10. LH Tank Volume

The main impact on airliner design when using LH fuel is not only the need for a cryogenic fuel system, but also the large volume of LH tanks. For the same energy as fossil fuel, LH has 3–4 times less weight and occupies 3–4 times the volume. The large volume required for LH requires more space, in locations that would need to be safe, relative to the passengers and crew. Under-fuselage LH tanks would be a safety risk near the cabin in a belly landing and take up valuable luggage and cargo space. Over-fuselage LH tanks would still be close to the passenger cabin, with difficulties involved with access, and the large frontal area would increase drag and reduce payload range. LH tanks should be spherical, or short-cylindrical with hemispherical ends, for pressurization, and would be difficult to accommodate within an aircraft wing (like fossil-fuel tanks), except for the

large flying wing associated with aircraft carrying more than 200 passengers. LH tanks in the fuselage, separating the crew cockpit from the passenger cabin, would lengthen the cabin just as much as would placing LH tanks in the rear fuselage, behind the rear cabin bulkhead, which is a safer option.

4.11. Aircraft Design

The LH tanks in the rear fuselage behind the rear cabin bulkhead may be the safest location, with the least weight penalty. The LH fuel tanks in the rear fuselage may not affect the pitch trim too much as the LH is consumed during the flight, because LH is light, although a larger horizontal tailplane may be needed. The extra weight of the LH tanks and cryogenic fuel system would increase empty weight relative to a fossil-fuel airliner, and the lower weight of LH could lead to similar total take-off weight for the same numbers of passengers and payload. The LH tanks in the rear fuselage increase fuselage length, wet area and drag, and may require taller landing gear for rotation at take-off, lead to smaller angle-of-attack and higher lift-off speed, and need longer runways for take-off and landing. A shorter aircraft would result from a flying-wing configuration, possibly requiring a larger number of LH tanks in the wings, and a more complex and heavier supporting structure. As shown by the Airbus ZERO-e, both designs are feasible: (i) a propeller-driven regional airliner with HTEP and LH tanks in the rear fuselage; and (ii) a flying-wing medium-range jet liner with LH tanks in the wing. Both aircraft designs pose significant technological challenges, which Airbus considered for the next generation of aircraft, prompted by the importance given to the greening of aviation, and broader environmental issues in the EU. Boeing sees LH as a candidate fuel for a follow-on, rather than the next generation of airliners, given the decreasing incentives or actual disincentives by the present American administration, which is more favorable to fossil fuels than the EU. Airbus slowed its hydrogen-fueled zero-e aircraft design efforts, postponing them to a future generation, mainly for the non-technical but crippling issue of the availability of hydrogen fueling infrastructure, to avoid a "hydrogen Concorde". Concorde was a remarkable technological achievement more than half a century ago, still unsurpassed today, whose brilliant technological success was undermined economically by restrictions that penalized its unique capabilities relative to less advanced contemporary designs.

4.12. LH Supply at Airports

The hydrogen refueling infrastructure is not yet widespread for cars and trucks, and the case for airports [135] is even more complex, balancing safety features and the need for fast turnaround times between flights [136], to avoid degrading airline operating economies. The supply of LH in large quantities to an airport could be made by: (i) many LH trucks, possibly causing congestion of roads that already may have heavy traffic; (ii) a hydrogen pipeline associated with costs, land permissions and other issues; or (iii) local LH production requiring space and investment in facilities. In all cases, hydrogen storage and refueling [136] of aircraft would require more space and investment and need to comply with safety issues and obtain various building permissions, a process which might be affected by the reactions of local residents. More than 60% of the relevant fuel consumption is by long-range aircraft that do not use LH, and the LH part of the remaining fleet would have to justify the return on the large investment in LH facilities. An LH-fueled airliner, even the most successful one in overcoming all the considerable technological challenges, would require, for economic viability, that LH-refueling facilities be available at all hubs and nearly all major and regional airports. The large investment required and risk on return on investment make this an uncertain prospect even in the EU, which is the most environmentally conscious region in the world. The current US administration favors fossil

fuels or SAFs at most, undermining the prospects of US airports building expensive LH-fueling infrastructure for Airbus aircraft, while Boeing has no aircraft that would require such systems. Would oil-producing countries be keen on large investments in airports for LH infrastructure to replace fossil fuels and SAFs? A viable worldwide airport LH-refueling infrastructure must be available in time for the LH-fueled aircraft to be economically viable, bearing in mind the considerable technological challenges in its development. The existing airport fueling infrastructure can be used with synthetic aviation fuels (SAF) with properties similar to those of fossil fuels.

5. SAFs for Widebody Jetliners

For large, long-range jetliners (Figure 10) the large volume of LH tanks is not feasible, leaving as the only near-term possibility (Section 5.1) the use of synthetic aviation fuels (SAFs), which are drop-in fuels (Section 5.2), to the extent that they can be used with current aircraft and ground fuel systems (Section 5.3), possibly with small modifications, like combustors and seals. The use of SAFs is determined by the availability of feedstocks and refineries (Section 5.4) and the effect on transportation costs (Section 5.5). The contribution to the greening of aviation (Section 5.6) is greater for technologies applicable to classes of aircraft with larger contribution to world emissions (Section 5.7).



Figure 10. The Boeing B777 (shown) [137] and the Airbus A350 are long-range twin-aisle jetliners for which the only near-term option to reduce environmental impact is replacing fossil fuels with synthetic fuels. SAFs are a carbon-free solution for long-range aviation that account for over 60% of all carbon dioxide emissions associated with aviation, which are currently about 3% of world emissions. SAF production is currently less than 1% of total aviation fuel consumption and will have to increase sharply to meet environmental goals, overcoming challenges in feedstock, refineries and costs (Creative Commons, Wikimedia).

5.1. Synthetic Fuels

The four main paths for the greening of aviation are: (i) the use of battery power for electric propulsion that is limited (Section 2) to small, slow aircraft over short ranges due to the low power-to-weight ratio (PWR) of the batteries; (ii) the PWR improves sufficiently for hydrogen or solid oxide fuel cells (FC) to enable (Section 3) hybrid turbo-electric propulsion of regional airliners of up to 100 seats and with a 1000 km range; (iii) improvement of the FCs, which are limited in power by the current technology to about 1–2 MW, which is not sufficient for jet airliners, but which may use liquid hydrogen-fueled gas turbines for airliners up to 200 seats and 3000 km range; and (iv) improvements in the low energy density per unit volume of LH, which presently requires large tanks that are incompatible with large airliners, because the higher drag leads to a losing spiral of more thrust and fuel, so SAFs must be used. Battery power (i) is locally emissions free, whereas hydrogen fuel (ii) is carbon-free and SAFs (iii) are carbon neutral, that is, when burned, release to the

atmosphere an amount of carbon oxides comparable to that absorbed from the atmosphere in the fuel production process.

5.2. Fuel Blending

The main advantage of SAFs is that they "drop in" fuels [138] that use the existing airport infrastructure for fossil fuels and can replace the latter on existing aircraft, with no significant changes to the engine or fuel system. The ideal of "drop in" creates some requirements, since fuel in an aircraft serves not only to power the engines, but can also act as lubricant and have other functions, like serving as a heat sink. Thus, it is necessary to show that long-term use of SAF does not degrade elements of the fuel system, like seals, and does not cause contamination or other issues when used as a replacement for fossil fuel. In fact, the use of SAFs may entail some adaptation of the combustors of jet engines and changes elsewhere in the fuel system that are much smaller than a far-reaching switch to LH. SAFs are currently blended with fossil fuel up to a 50% mix. Both Airbus and Boeing plan to have all their aircraft certified for 100% SAF use by 2030.

5.3. Drop-In Properties

SAF must satisfy a set of criteria, including flammability, volatility, viscosity, and others, like fossil fuels, and are subject to the qualification process [139] of the SAE (Society of Automotive Engineers of the United States). Thus, the adoption and widespread use of a new SAF production path is a long and costly process, with the number of alternative SAF products less than 10 at present and increasing gradually. SAFs are distinguished by the feedstock, which provides raw material, and the chemical process of refining into the final fuel. The use of sustainable fuels in aviation [140] depends on a complete life cycle [141], including feedstocks [142], production methods [143] and distribution network [144]. The reference is the pioneering Fischer–Tropsch process, developed in Germany during WW II, which converted the abundant coal to synthetic fuel to overcome the lack of access to oil wells of fossil fuel. The simplest path to SAF is biofuel [145], which should not compete with food crops. This requirement is enforced in the European Union, but not always elsewhere. For example, more than half of the corn production in the US is used to produce ethanol to mix with petrol for cars, providing an important source of income for farmers. Ethanol from sugar cane is widely used in Brazil, including in cars, with higher blend than the 5% and 10% of, respectively, E5 and E10 in Europe. The use of organic waste, be it cooking oil or urban or forest waste, to produce SAF is a win–win situation, since it disposes of waste, transforming it into a useful fuel, although the refining process involves high energy consumption. However, all the waste currently available could supply only a fraction of the current aviation fuel consumption [146] [139], with added competition from other fuel users.

5.4. Feed Stocks and Refineries

The SAF replacements for kerosene [147] with lowest environmental impact in feedstocks and production [148] are power-to-x [149], and in-particular power-to-liquid [150], e-fuels that convert electrical power to chemical power. One of the cleanest paths used to produce SAFs is e-fuels: (i) clean energy, from wind turbines or solar panels, is used for the hydrolysis of water, producing green hydrogen, in contrast to the grey/blue hydrogen from, respectively, fossil fuels and natural gas, which are polluting; and (ii) the green hydrogen is combined with carbon dioxide captured from the atmosphere to produce SAF, in a totally clean process. However, each of these stages has serious implications. First, the hydrolysis of water requires a large amount of energy, and even if a large fraction of all electrical energy currently available were used it would not produce enough SAF to meet the relevant needs. Thus e-fuel production to meet most needs would need a vastly

expanded electricity production network. Also, carbon capture from the atmosphere is not a straightforward chemical process and its use on an industrial scale remains to be demonstrated. The cost of e-fuels is directly dependent on the cost of electricity, and the consumption of water contributes to the depletion of another valuable resource. The same issue of water consumption is relevant to algae blooms, which have the highest density of oil per unit area, although the efficiency of conversion to fuel is low. On the other hand, hydrogen production requires pure water for hydrolysis. In contrast algae bloom projects could use the salt water of the oceans.

5.5. Availability and Cost

Besides the limitations in producing the large quantities of fuel needed, SAFs have a high cost, currently three to five times that of fossil fuel. There is nothing cheaper or simpler than drilling a hole in the ground to collect oil for a refinery, or capturing natural gas, since nature carried out the production work over millions of years. By contrast, SAFs are a man-made, contemporaneous production, and thus require feedstocks that may be limited and refineries that represent a significant investment. SAFs currently account for less than 1% of fuel consumption, and the SAF mandates to increase that proportion steadily to significant levels by 2050 face major hurdles: (a) producers say they can meet the needs but need guarantees of consumption and demand in the long-term to justify the significant investments in refineries; (b) airlines are buying all the SAF available and new refineries may have production sold for several years before they open, yet airlines claim there is a possibly shortage of supply; and (c) the underlying issue is the high cost of SAF, with SAF mandates reaching over a trillion of euros in Europe alone.

5.6. Greening of Aviation

Europe is the world leader in environmental protection, including decarbonization, matched perhaps by Japan, which is acutely aware of its dependence on imported oil. However, Europe represents only 6% of global emissions, and even if this is reduced to zero, the effect on global climate would be small. The other world economies comparable in scale to Europe, namely, the United States and China, have far larger contributions to worldwide emissions and do less to reduce them. The current US administration, which is skeptical on climate change, is acting in the reverse direction, increasing oil production by the use of environmentally damaging technology.

In the specific context of aviation, fuel is about 30% of the direct operating cost. High SAF percentages, at 3–5 times fossil-fuel cost, could increase ticket prices beyond the 10–20% "environmental surcharge" that passengers might accept. Higher values in one part of the world would put airlines in that region at disadvantage relative to their international competitors and could harm the mobility that is essential to the world economy.

5.7. Classes of Aircraft

So far, four classes of aircraft and four emerging technologies that are being implemented, or could be available for the next generation of aircraft, have been considered: (i) battery power for small, slow short-range urban/local transport (Section 2); (ii) hydrogen fuel cells for turbo-electric propulsion of regional aircraft (Section 3); (iii) liquid hydrogen-fueled medium range jetliners (Section 4) with compressed hydrogen, a possibility for small business jets with longer turnaround times between flights; and (iv) SAFs, which are needed for large, long-range airliners like twin-aisle jumbo jets, and could be used by all other aircraft, although they may have lower priority. The next four sections consider more speculative technologies for the greening of aviation, which could be mature by the advent of the next generation, or later generations, of aircraft: (v) a large blended wing–body (BWB) or flying-wing (FW) airliner with sufficient internal volume of LH for

long-range flight (Section 6); (vi) hydrogen production on-board the aircraft immediately prior to combustion, avoiding the problems of LH supply at airports and storage in the aircraft (Section 7); (vii) turbo-electric propulsion for large, long range airliners requiring tens of megawatts of power (Section 8); and (viii) at the opposite end, that of low power, a solar-powered aircraft flying at stratospheric altitude acting as a pseudo-satellite (Section 9). These more speculative technologies have sound scientific bases, but face greater challenges of technological maturation into practical use in aviation.

6. The Blended Wing–Body or Flying Wing

The flying-wing, or blended wing–body, configuration combines high aerodynamic efficiency (Section 6.1) with large internal volume for LH tanks (Section 6.2). These twin benefits may be reduced by other considerations: (Section 6.3) engine location over the rear part of the wing shields engine noise but reduces cruise speed; (Section 6.4) the pitch-down effect of engine thrust must be countered at take-off and landing and also (Section 6.5) trimmed in cruise; and (Section 6.6) boundary layer ingestion is inevitable and may be exploited by flush or buried engines. Additionally, compared with cargo aircraft and in-flight refueling tankers (Section 6.7) passenger airliners have specific emergency evacuation requirements (Section 6.8).

6.1. Aerodynamic Efficiency

The large volume of liquid hydrogen needed for the long range intercontinental flight of a large airliner with high passenger capacity suggests a blended wing–body (BWB) or flying-wing (FW) configuration with the added benefit of higher aerodynamic efficiency than a conventional tube-and-wing aircraft. The BWB design [151] has found application in military aircraft, and been considered for subsonic airliners [152]. The critical technologies involved [153] include aerodynamics [154] and control [155], which can be simulated [156] and flight-tested [157]. The FW configuration also applies to UAVs [158,159] that do not face the higher certification challenges of manned and passenger-carrying aircraft. A 20% gain in aerodynamic efficiency, rather than the overoptimistic claims of up to 60%, is already significant in higher lift-to-drag ratio and associated lower thrust, fuel consumption and emissions. However, from the purely aerodynamic gain, other penalties may be subtracted, including those related to (i) housing the LH fuel in the wing (Section 6.2); (ii) engine location and cruise speed (Section 6.3); (iii) pitch trim at cruise (Section 6.4); (iv) take-off and landing performance (Section 6.5); (v) certification rules on cabin evacuation (Section 6.5); and (vi) passenger comfort in roll maneuvers. The issues other than the last two apply to a cargo or tanker BWB/FW, but the case of an airliner also needs to be considered.

6.2. Housing LH Fuel in the Wing

For reasons of pressurization, LH is best housed in spherical tanks, or short cylindrical tanks with hemispherical ends. The need for dewar-like double walls, with a vacuum in-between, and thermal insulation outside, to keep internal temperatures below 20 K, leads to heavy tanks, even if metal is replaced by a composite construction. A typical gravity factor of about 0.6 means that the tank weight is 60% of the LH fuel it contains. To the weight of the tanks must be added the weight of the supporting structure, which is simpler in the rear of a cylindrical fuselage of a tube-and-wing aircraft, than inside the wing of a blended wing–body. Storing LH inside a flying wing may require a larger number of tanks and a more complex and heavier supporting structure, which would negate some of the aerodynamic benefits. The problem of housing LH in a flying wing is more severe for a small, blended wing–body, and thus this approach is a more viable option for a long-range aircraft with large capacity. The optimal solution would be conformal composite cryogenic

LH tanks, which is a demanding technology on laboratory scale, but also challenging to scale-up to a large BWB-FW.

6.3. Engine Location and Cruise Speed

In a tube and wing aircraft (TAW), the engines may be located (i) in nacelles under the wing, in undisturbed airflow; or (ii) at the sides of the aft fuselage, spaced enough to avoid ingestion of the boundary layer and associated distortion of engine inlet flow. These locations do not provide shielding of noise radiated to the ground, unlike the overwing engines used only in the VFW Fokker 614 regional jet, whose cruise speed was reduced to Mach 0.6 because of the accelerated flow above the wing. In the case of a BWB the preferred engine location [160] is above the rear section, providing noise-shielding to the ground. The airflow is accelerated over the wing, and overwing engine nacelles face compressibility effects and cause shock waves at lower free-stream cruise velocities. Thus, the cruise Mach number of a BWB with engine nacelles over the rear of the wing could be lower than a conventional TAW, increasing flight times and decreasing productivity and economic yield. One solution would be flush, or buried, engines that would have to tolerate the inlet flow distortion associated with boundary layer ingestion. The boundary layer at the rear of a FW is quite thick, and thus boundary layer ingestion could be an issue even for engines in nacelles, and more so for flush, or buried, engines.

6.4. Pitch Down on Take-Off and Landing

The engines above the rear of a flying wing cause a strong pitch-down moment that must be compensated by a pitch-up from the control surfaces. A BWB tends to require a relatively large angle-of-attack for low-speed flight [161], in particular, during the climb after take-off and during the approach to landing. This may require a long undercarriage to be folded into the voluminous wing. The aircraft should not be too long, in order to avoid tail scrapes. The relatively short BWB implies a shorter moment arm for the elevators that provide pitch control. Together with a large pitching moment in order to have a high angle of attack against pitch-down from the engines, this requires large elevator area and/or deflection, leading to high drag. The high drag can be favorable for steep approaches, but for take-off, the aircraft will require a high thrust for the relatively short duration of flight.

6.5. Pitch Trim and Yaw Control

The engine pitch-down with aft overwing engines in FW is present at all stages of flight and requires sufficient pitch-up from control surfaces to trim the aircraft. This is most important during the longest stage of flight, at cruise, when the control pitch-up to trim engine pitch-down would need upward elevator deflection, increasing drag, decreasing lift and detracting from the high lift-to-drag ratio of the untrimmed FW, together with its fuel consumption and emission benefits. A flying wing has the whole leading edge and trailing edge free for flight control, and high-lift surfaces [162], allowing for a variety of pitch trim strategies [163] to minimize trim drag [164]. Concerning yaw control, having a single or twin vertical tail, due to the short moment arm, would require a large area, and cause high drag, again detracting from aerodynamic efficiency. The vertical control surfaces could be placed at the wing tips, with the known aerodynamic benefits of winglets; however, the yaw moment arm would be small unless the wing is highly swept, and yaw control would cause wing torsional loads and potentially trigger aeroelastic effects and flutter.

6.6. The Tailless BWB with Buried Engines

The historic stability problems exhibited by FW since the pioneering flights of the 1930s have been mastered by progress in modern flight control. This is shown on a large scale by bombers like the Northrop/Grumman B-1 Spirit and B-21 Raider and on a smaller

scale by a variety of drones like the Dassault Neuron. The FW has a trailing edge entirely free to enable control surfaces that could be labelled, inward to outward, as inner and outer elevators, inner, mid and outer flaps and inner and outer ailerons. The designations of elevators, flaps, elevons and ailerons, as well as spoilers and leading-edge slats, may be superseded in a FW by all surfaces along the trailing and leading edges being made movable, up or down, with or without gaps, leaving a wide freedom in choosing among numerous combinations of deflections of multiple surfaces to provide control in all axes and aerodynamic braking, without the need for separate vertical, horizontal or canted control surfaces, which add drag and decrease stealth [165,166]. These aircraft also deal with engine pitch-down and boundary layer ingestion issues by having intakes near the leading edge, with a thin boundary layer, and buried engines, with the "penalty" of longer engine inlet and exhaust ducts, which may reduce noise and improve stealth.

6.7. Cargo, Tanker and Passenger Aircraft

The BWB configuration is favorable for cargo aircraft, combining aerodynamic efficiency with large internal volume, even if LH tanks and a buried propulsion system consume some of the volume. The benefit is even greater for a tanker aircraft, since the improved aerodynamic efficiency and lower fuel consumption mean that a larger fraction of the total fuel load is available for transfer to other aircraft at longer ranges. For passenger aircraft, the large internal volume allows a spacious cabin, but other aspects of passenger comfort and safety must be addressed. In a conventional TAW aircraft, passengers are seated 4 to 12 abreast, not too far from windows, lessening the impression of a "claustrophobic tube". In a BWB jetliner, with seating more than 15 abreast, windows are remote for most passengers, and an outside view can be provided by video, as already happens today. During a roll maneuver, like a turn, passengers in a BWB seating much farther from the aircraft axis will experience larger displacements, which may raise issues. The main remaining issue is cabin evacuation in an emergency.

6.8. Cabin Evacuation in an Emergency

Certification requires cabin evacuation in no more than 90 s, in darkness, using only one side of the cabin, with no prior knowledge of which side will be used. This must be demonstrated by a normal airline flight crew and a cabin filled with a group of passengers representative of the age diversity in the society, with inspectors hidden to observe the results. In a TAW with a narrow fuselage, all that the passengers must do is go to the nearest safety exit, in a quick and orderly way, which is not always the case. In a BWB with a wide fuselage, if all passengers go for the nearest exit in sight, there will be a pile-up at some exits, and underuse of other exits, increasing complete evacuation time, besides the risk of a chaotic, rather than orderly, exit. For the safe evacuation of a BWB cabin in minimum time: (i) the cabin crew must be trained to direct passengers to the most suitable exit, not necessarily the closest, so as to ensure the even, maximum use of each exit; and (ii) the passengers must follow the instructions of the cabin crew, trusting them above any superficial self-impressions, and proceeding swiftly in an orderly way to the assigned exit. The benefits of crew training and passenger discipline were well demonstrated, for example, in a TAW aircraft, by a fire at Tokyo airport, in which the whole aircraft burned down, and everyone on board escaped unhurt.

7. Hydrogen Production on Board the Aircraft

The use of LH raises a different focus relative to the safety issues [167,168] that also apply to fossil fuels, including (Section 7.1) ignition and (Section 7.2) explosion, in particular, in a crash (Section 7.3). The on-board hydrogen production prior to combustion

by reforming kerosene (Section 7.4) would have several benefits: (i) no need for LH ground infrastructure; (ii) no need for large-volume LH tanks; and (iii) no risks of hydrogen storage. Unfortunately, current methods of reforming kerosene or other fuels to extract hydrogen require high temperatures and produce carbon oxides that are difficult to capture. The use of other dense hydrogen sources, like ammonia (Section 7.5), is unsafe at airports. The most desirable process of hydrogen production on board, by molecular separation of hydrocarbons into hydrogen and carbon, without production of carbon oxides damaging to the environment, appears to be beyond currently available physico-chemical technologies (Section 7.6). The ideal fuel (Section 7.6) should have 20 desirable properties.

7.1. Fuel Risks

Concerns about the explosion potential of hydrogen storage systems are not new, but are generally exaggerated. In a U.S. military R&D program during the 1980s with hydrogen fuel in the Lockheed SR-71 Blackbird (Figure 11), there were over 70 test attempts to explode hydrogen-filled tanks—even with gunfire—without success, in most cases. Venting of hydrogen is quite effective since it is the lightest gas, and rises rapidly in the atmosphere, with little time for ignition: (i) in the much-publicized Hindenburg accident, the airship burned upward, and the passengers escaped below; (ii) the Hindenburg used hydrogen instead of helium (inert) because only the United States had enough helium at the time and refused to supply it to Germany; and (iii) liquid fossil fuel from a burst tank or splashed on the ground may be more likely to catch fire or explode, over a longer time.



Figure 11. Lockheed SR-71 Blackbird [169] strategic reconnaissance aircraft in flight. The design enabling it to fly at Mach 3.2 at 24 km altitude required a special propulsion design and fuel specification. The alternative of using hydrogen was considered and found safer than expected in ground tests, although it did not proceed to flight experiments (Creative Commons, Wikimedia).

7.2. Ignition and Explosion

A high risk of explosion exists for air mixtures in confined spaces, but: (i) a hydrogen leak valve has been developed with a chemical reaction that converts hydrogen back to water; and (ii) it is also claimed that this allows the keeping of hydrogen tanks in confined spaces, even aboard aircraft if the reliability level 10^{-9} is achievable. Concerning the risk of explosion in an aircraft crash, it already exists with fossil fuels and may not be higher for SAFs or hydrogen.

7.3. Crash Effects

Aircraft designs should keep LH tanks far from passenger spaces, e.g., behind the aft fuselage bulkhead, rather than in under-fuselage holds. Designs have been proposed with LH in a twin fuselage or in a streamlined tank at the mid-span of the wings, but these have lower aerodynamic efficiencies. In an emergency, fuel is dispensed overboard, and

hydrogen could be vented, similarly, prior to landing; vaporization of LH involves heat release, which must be considered. In the case of take-off with full fuel levels (fossil, SAF or LH) early failure does not give time for fuel venting; an explosion in a populated area could lead to negative publicity or a ban on flights. A safe alternative could be hydrogen production on board, followed immediately by combustion, with the added benefit of not needing large cryogenic LH tanks and special airport LH-fueling infrastructure.

7.4. Fuel Reforming

Concerning onboard hydrogen production: (i) a liquid fuel, with the energy density of fossil fuel, would use current tank capacity and fuel systems; (ii) reforming of the fuel, which could be kerosene, would be employed to produce hydrogen; (iii) there is the option of the direct use of kerosene, or reforming into hydrogen, and burning either in the same combustor, if compatible; (iv) reforming produces carbon oxides (or soot) that are polluting, and are difficult to capture on board; and (v) ammonia could be a hazardous by-product. Items (iv) and (v) exclude the option of fuel reforming.

7.5. Exclusion of Ammonia

Ammonia has been suggested as fuel, since (i) in liquid form it has about the same energy density as fossil fuel when supplying hydrogen. However (ii), ammonia is toxic, corrosive, and explosive and has a higher safety risk than LH; (iii) hundreds of thousands of tons of ammonia are carried around the world in specially designed ships that do not use city harbors but rather remote harbors; and (iv) ammonia use at airports is hardly conceivable.

7.6. Molecular Decomposition of Hydrocarbon

The clean method of hydrogen production is hydrolysis of water, separating hydrogen and oxygen, without producing any other compounds, in a process that could be called "molecular decomposition" into atoms. Another possible designation is "molecular fission" of molecules into atoms, by analogy with "atomic fission" of a heavy atom like uranium or plutonium into lighter atoms. The process of "molecular decomposition" or "molecular fission" of a hydrocarbon molecule would split it into hydrogen and carbon atoms, without producing other compounds, like carbon oxides, that are harmful to the environment. Unfortunately, molecular decomposition or fission of hydrocarbons into pure hydrogen and carbon does not appear to be feasible with current physico-chemical technology. If sometime in the future the molecular decomposition or fission of hydrocarbons become technologically possible, the practical benefits would be considerable: (i) no need for complex and costly hydrogen transport, storage and refueling at airports; (ii) the volume of fuel tanks on board the aircraft would be the same as those for fossil fuel, instead of three times larger for LH, driving airliner design and limiting passenger capacity and range; and (iii) hydrogen production just prior to combustion would eliminate the risks and complexities of cryogenic storage tanks, fuel pumps, vaporizers and other elements of the complete fuel system. As long as the weight and size of a safe hydrocarbon decomposition/fission system would be moderate, the benefits would be well worth the extra effort.

7.7. The Ideal Fuel

The eco-friendly fuel that aviation (and other means of transport) needs should have a long list of 20 desirable properties: (i) no CO_2, NO_X, sulfur or particle emissions; (ii) water vapor should be captured to avoid contrails, and water fed to the engine to increase power or efficiency; (iii) an energy density per unit volume not less than those of fossil fuels allows the use of the same tanks, providing undiminished range without aircraft redesign; (iv) an energy density per unit weight higher than those of fossil fuels leads to reduced

weight of fuel (1/3 for LH) for better payload range; (v) "drop-in" fuel—no changes to the engine, onboard or ground fuel systems; (vi) not toxic; (vii) not corrosive, or protective coatings available; (viii) not explosive; (ix) not too volatile; (x) not subject to ignition, except for combustion in well-defined limited conditions; (xi) leak detected by smell and color; (xii) good lubricant; (xiii) not damaging ducts, joins or seals with long-term use; (xiv) available in sufficient quantity; (xv) sufficient feedstocks; (xvi) energy consumption in production is acceptable; (xvii) investment in refineries is attractive; (xviii) production is not polluting; (xix) easy distribution and storage; and (xx) acceptable cost. Can this "holy grail" or mythical fuel ever be found? Some say it is already here: the "fuel flow" of electrons of electric currents.

8. Tens of MW Electrics for Widebodies

A large airliner requires tens of megawatts of power for flight (Section 8.1) that could be produced by a gas turbine driving an electric generator to supply electricity to efficient electric motors driving propellers (Section 8.1). The transport of such large amounts of electrical energy would imply high voltages and large currents (Section 8.2), perhaps beyond the limits of current superconductivity technologies. The alternative would be distributed propulsion with integrated modules (Section 8.3) comprising the gas turbine–electric generator–motor–propeller.

8.1. Power for Flight

The power needed for the propulsion of a long-range widebody (up to 400 passengers for 16,000 km range) is tens of megawatts, and would far exceed the power levels of up to 2 MW of the current more electric aircraft [170] [162], but would still be compatible with generation by gas turbine, driving the alternator and distributed propulsion system with propellers driven by electric motors. (Propulsion efficiency: (i) thermal turbines, Carnot cycle: $\leq$40%; (ii) hydrogen fuel cells: $\leq$60%; (iii) electric motors: $\geq$90%.) The main issue is how to carry around an aircraft with high electric power, say, 40 MW = 8000 V $\times$ 5000 A.

8.2. Superconductivity in Aircraft

High voltage—8 kV—involves: (i) electromagnetic interference with onboard equipment; (ii) risk of electric discharges, greater at altitude; and (iii) the possibility of insufficient electric insulation. The large current—8000 A—involves: (i) high energy loss by dissipation by the Joule effect; (ii) considerable heat generation; and (iii) the question of how to dispose of heat, in particular, at high altitude. One possible solution to the last factor is superconducting cables. Superconductivity means zero electric resistance and energy transport without losses at 0 K = $-$273 °C, and: (i) superconductivity applies to matter in the ground state at absolute zero temperature; (ii) superconductivity may be possible at "higher" or "room" temperatures—higher than zero; (iii) is there the possibility of superconducting cables with cryogenic cooling by LH at 20 K?; (iv) would this apply at high power levels of tens of MW?; and (v) perhaps reduced electrical resistance at moderate powers and cryogenic temperatures would still be of benefit.

8.3. Distributed Propulsion

Experience with extreme voltages and magnetic fields already exists: (i) simulations of lightning and electromagnetic pulses; (ii) very large currents with high voltages involved; and (iii) an electric supply close to effector, with short or no cabling. Is an electrically powered long-range widebody airliner possible? (i) Integrated propulsion units might combine gas turbine + alternator + electric motor + propeller with minimal cabling; (ii) distributed propulsion system with many integrated units with moderate power could be employed

(no need for superconductivity); and (iii) is there the possibility of multiple miniaturized integrated propulsion units with moderate total cost?

9. Solar-Powered High-Altitude Aircraft

The opposite end to the tens of MW of power required to fly a large long-range twin-aisle jumbo airliner is the tens of kW available to an unmanned lightweight solar-powered aircraft flying higher above the clouds and possibly having a comparable wingspan. The solar-powered aircraft could be an alternative to satellites (Section 9.1), with almost unlimited endurance (Section 9.2), if its lightweight structure (Section 9.3) can withstand stratospheric winds (Section 9.4), and the weather conditions during climb and descent (Section 9.5), as shown in around-the-world flight (Section 9.6).

9.1. High-Altitude Pseudo-Satellite

A solar-powered aircraft [171] flying in the stratosphere at a high altitude of 20 km, acting as pseudo satellite [172], would be much closer to the ground than the minimum altitude of 200 km of a real satellite (RS) orbiting the earth. Also, the High-Altitude Pseudo Satellite (HAPS) could remain flying permanently over the same geographical area, whereas a Low Orbit Real Satellite (LORS) would pass overhead 16 times per day, remaining visible for tens of minutes at a time. A Geostationary satellite (GEOS) would remain fixed over a given geographical location at a much greater distance of 36,000 km, or six times the radius of the earth. A low earth orbit satellite constellation with intersatellite data links would remain visible all the time, at a distance of no less than 200 km, which is at least 10 times the altitude of the HAPS. Thus, the HAPS could do earth observation with higher resolution and provide telecommunication and internet links with less power, within its limited payload capabilities, but more like a large, stratospheric balloon.

9.2. Endurance of Days, Months or Years

A high-altitude solar-powered aircraft, always flying above clouds, could collect solar energy during the day, using a fraction of the power immediately to fly, and storing the rest in batteries to fly through the night. In this way, endurance could be days, months or years, limited only by the reliability of the equipment and ability to survive the environment. In contrast, a low altitude satellite could decay, could require thrust for stabilization or pointing, and have its lifetime limited by available fuel, unless it could be refueled, which would require another satellite mission. The HAPS would not depend on any limited-on board fuel supply, would not drift unpredictably with the wind around the world like a stratospheric balloon, and could potentially remain over a chosen geographical location for an almost indefinite time.

9.3. Flight Velocity and Stratospheric Winds

The energy of solar radiation per unit area is quite low, and the wing would need a large area covered with solar panels to collect enough energy for flight. Thus, the wingspan of a HAPS could be comparable to that of a large airliner, yet the energy would be only enough to fly at about 100 km/h in the rarefied air at 20 km altitude in the stratosphere, compared with about 1000 km/h for a jet liner at 11 km altitude at the tropopause. Stratospheric winds vary widely, but may reach close to 200 km/h. A HAPS flying against the wind would experience high relative velocity, putting larger aerodynamic loads on its light and not so strong structure. A HAPS flying along a faster downwind would be flying backwards relative to the wind, which could cause serious stability and control problems. To provide permanent coverage over a given geographical area, the HAPS would have to fly a closed loop, with both upwind and downwind legs.

9.4. Weight and Structural Strength

The limited power available to fly a HAPS, and its low speed, correspond to a modest lift that can compensate for a comparable weight. Some of that weight must be allocated to heavy batteries with sufficient capacity to sustain flying through the night. The remaining available weight that is not allocated to the HAPS structure is the available payload. Thus, even with the lightest possible structure, the payload of a HAPS may be tens of kilograms, compared to hundreds for a medium-sized satellite, and thousands for a large satellite. Thus, a HAPS is closer to earth-based users than a satellite would be, and needs less power for communications and links, but is more limited in the available on-board power and weight of equipment it can carry. Likewise, a HAPS is closer to the earth for high resolution observation, but its limited payload may restrict the size and weight of sensors, to the extent limited by possible solutions in miniaturization.

9.5. Vulnerability to Weather and Turbulence

The limited allowance for the structural weight, and the large wing area needed for solar panels, together with the large span for glider-like aerodynamic efficiency, with low drag, equal thrust, and limited lift equal to weight, imply a light and flexible structure. HAPS are quite vulnerable to storms and turbulence, which can cause complex coupled wing bending and torsional vibrations that are difficult to control. Several HAPS have suffered accidents in unfavorable weather. HAPS trials are preferably conducted in sunny deserts at times of low turbulence. This to some extent is due to the aim of using HAPS to provide communication and internet to remote locations deprived of ground infrastructure.

The main problem in HAPS operation is its climbing to the operational altitude of 20 km, and to a lesser extent, the return to earth. Due to the low levels of power available, the climb to operational altitude can take hours or days and it may not tolerate extended periods without sunlight due to cloud cover. The biggest risk, which is harder to predict, is turbulence or storms at low altitudes, with their high atmospheric density compared to stratospheric design point, causing high loads or strong vibrations on a lightweight, flexible structure.

9.6. Long Duration and 'Round-the-World Flights

In spite of all challenges, HAPS have demonstrated flight endurances of several days, which are impossible for any other heavier-than-air aircraft on its own. More remarkably, the Solar Impulse was the first solar-powered aircraft to fly around the world. It took 2 years with multiple hops, spaced by the wait for favorable weather, with the longest leg the trans-Pacific, from Asia to Hawaii. The most remarkable achievement of Solar Impulse was the ability to carry two pilots, far above the few tens of kilograms of payload of most HAPS. A comparison can be made with the Global Flyer of Burt Rutan, which also carried two pilots around the world in 2 days of continuous flight instead of 2 years of hopping from one location to another. This contrast shows the maturity of powered flight consuming fuel in an engine, after a century of development, and also the potential of solar power in its first steps, as become available due to advances in solar panels, batteries and structures.

10. Conclusions

The Sections 2–9 have provided an assessment of (i) the main emerging green aviation technologies, like batteries, hydrogen fuel cells, synthetic fuels and electrification, and the classes of aircraft for which they are effective; (ii) the fact that there is no universal one-size-fits-all solution, and thus each technology is considered for a class of aircraft in which it is most promising; (iii) the reality that the benefits of emerging green technologies come

at the expense of penalties like increased complexity, weight and volume, and possibly new safety issues; (iv) the fact that these negatives may be underestimated by proponents of new technologies, but are in fact the challenges to be overcome for their successful application; (v) the conclusion that for these reasons, the focus has been not only on the often-advertised benefits of emerging green aviation technologies, but also on how to overcome the challenges of their implementation; and (vi) the fact that overcoming these challenges will determine the timescale and scope of application of green aviation technologies and their contribution to meeting environmental targets.

The main practical conclusions are summarized next. (A) Sustainable aviation fuels (i) are carbon neutral, but not emissions-free, and SAFs are the best short-term prospect to decarbonize aviation; (ii) apply to all classes of aircraft; (iii) are the only near-term option for long-range fights, involving more than 60% of total world fuel consumption; and (iv) present the question that large quantities are needed: Feedstocks? Energy consumption? Investment in refineries? Fuel and ticket costs? (B) Carbon-free hydrogen-fueled turbines: (i) are viable for "narrowbody" airliner replacements; (ii) are viable for aircraft of up to 150–200 passengers, 1000–2000 NM range, less than of 30% of world fuel consumption of aviation; (iii) involve other emissions to be considered: NO_x particles, sulphur, aerosols; (iv) involve the effect of contrails—ATM flight adjustments, fuel treatment with fewer particles, the capture of water vapor and injection into engines; (v) require LH, which requires cryogenic fuel systems aboard aircraft, supplies at airports, and production locally or elsewhere with transport; (vi) involve certification and operations post-2035, for the next or subsequent generations of airliners; (vii) involve a level of maturity and timescale very much dependent on technological progress and funding support; and (viii) are possible for a next-generation airliner? Boeing—No, generation after maybe, and Airbus—postponed project zero-e due to lack of airport infrastructure. (C) Hybrid turboelectric propulsion (i) involves no emissions from hydrogen fuel cells (HFC) + reduced emissions for turbines in hybrid propulsion systems; (ii) corresponds to a small proportion of world fuel usage: less than 10%; (iii) is relevant for local air quality (LAQ) near regional airports, in particular if emissions-free flight below 900 m altitude is achieved; (iv) is feasible in the near term converting existing regional airliners with hybrid turbine—HFC or HFC power units of 0.5–2 MW; and (v) involves greater efficiency for medium-term, all new, designs incorporating all benefits of hybrid propulsion. (D) Battery-powered aircraft: (i) involve no local emissions from small battery-powered aircraft; (ii) involve a small fraction of current fuel consumption but could be increasingly significant in the future; (iii) involve a large potential market for private flying, urban transportation, urgent medical supplies, law enforcement, agriculture, and remote site "inspection"; (iv) are relevant to a large number of "start-up" projects and innovative configurations of which only a few will survive through development time and cost to reach certification; and (v) present multiple "open" operational issues: safety, urban weather, vertiports, ATM, economics, and adverse weather, which may delay, but not prevent, a gradually growing market. The path to Net Zero by 2050 [1–4,13] will call for collective action on policy, industry, and research. Changing technology is not enough; public acceptability, regulatory coherence, and economic viability will be key to determining success in the greening of aviation.

The paper covers not only (i) technologies for greening of aviation and (ii) designs of environmentally friendly aircraft, but also (iii) the gap between the two, which is the main focus: what are the benefits and limitations of each technology, to which classes of aircraft it can be applied, and what are the operational benefits and limitations? Whereas plentiful references can be found in the literature about (i) new green technologies and (ii) new aircraft designs, the gap between the two is less well-covered because: (i) the scientific community developing new technologies is aware of and motivated by the originality of

discovery but is less aware of the compromises and practical implementation aspects in overall aircraft design and operations, such accelerations and vibrations from flight and propulsion, and pressure and temperature changes with altitude; and (ii) the companies and start-ups proposing new aircraft designs are more likely to emphasize the advances they represent over the current fleet than to detail other competitive technologies and associated limitations. In focusing on the gap between (i) and (ii), some of the statements are not supported by direct references and are rather design, experimental testing and operational lessons and assessments based on diffuse or indirect literature and the authors' assessment of the potential and limitations of each technology. Consequently, most references fall in the class of (i) technology or (ii) design, with the gap being covered more by judgement of how (i) and (ii) can be combined. Thus, the references list below support most but not all the statements in the paper, which is not just a literature review, and goes beyond an assessment of the state-of-the-art of technologies for the greening of aviation extending to their expected evolution and likely benefits and limitations.

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Abbreviations and Acronyms

ATM	Air Traffic Management
BWB	Blended Wing–Body
CRL	Certification Readiness Level
EASA	European Union Aviation Safety Agency
EC	European Commission
EU	European Union
e-VTOL	electric Vertical Take-Off and Landing
FAA	Federal Aviation Administration
GEOS	Geostationary Satellite
GHG	Green House Gas
HAPS	High-Altitude Pseudo Satellite
HFC	Hydrogen Fuel Cells
HTEP	Hybrid Turboelectric Power
ICAO	International Civil Aviation Organization
ICBM	Intercontinental Ballistic Missile
LAQ	Local Air Quality

LH	Liquid Hydrogen
LORS	Low Orbit Real Satellite
MW	Megawatt
PEM	Proton Exchange Membrane
RS	Real Satellite
SAFs	Sustainable Aviation Fuels
SOFC	Solid Oxide Fuel Cell
TAW	Tube and Wing
TRL	Technology Readiness Level
UAM	Urban Air Mobility
WP	Work Package
WW	World War

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