EXECUTIVE SUMMARY AND FUTURE EVOLUTION

PARE

for

Third Final Yearly Report

of

PROJECT PARE

PERSPECTIVES FOR AERONAUTICAL RESEARCH IN EUROPE

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Executive Summary and Future Evolution

3.1 Introduction

The Executive Summary of the PARE (Perspectives for Aerospace Research in Europe) report is intended to highlight in a short document of 21 pages the main points of an extensive document[1] over 2000 pages long and indicate how it could be continued in the future. The task is not made any easier by the profound and brutal changes in the aeronautical scenario during the duration of the project:

- From the start in 1 October 2017 till the end of 2019, Aeronautics had one of the longest periods of sustained growth, defying the law of cycles, and only the two B737 Max accidents were reminders of earlier major crisis associated with the Comet and DC-10 accidents;
- The last year of the project 2020 saw the Covid-19 pandemic causing a worldwide crisis in many sectors, and for aeronautics the biggest decline in history, completely changing and reversing the previous sustained growth into a sharp and deep decline with uncertain recovery in extent and duration.

Most chapters 1-13 of the PARE report, written in the first two years of the project, reflect the continued boom period. Although the scenario is reversed by now, they are if anything more relevant as the standard against which to measure the present crisis and future recovery.

The chapters 14 to 20 reflect both the crisis of aviation and the environmental challenges of the future, and point to the future evolution that is the complementary part of the executive summary. The focus is therefore to use the well-known background of a strong aeronautical sector to try to understand the consequences of the present crisis and discern among the uncertainties of recovery.

3.2 The PARE Project in the Original Proposal

The PARE project in the original proposal was focused on the assessment of progress towards the achievement of the 23 ACARE Goals for Aeronautics in Europe stated in the Flightpath 2050 document[2] the methodology can be used to assess technological progress in any area[3] taking the past as the baseline, using the predictable future as horizon and extrapolating further as continuous progress or disruptive breakthroughs. The application of this methodology to the 5 sets of 23 ACARE Goals comprises the Chapters 2 to 6 of the PARE Yearly Report.

The 23 ACARE Goals are vertical aims supported on a 5 horizontal activities, each addressed in one Chapter 7 to 11 of the Part II of the PARE Yearly Report: (Chapter 7) Long-range Air Transport and the Wider Aircraft Market; (Chapter 8) Technologies Emerging within or outside the Aeronautical Sector with Major Potential Impact; (Chapter 9) Areas like Traffic Management, Certification, Safety and Security, and Open Markets where International Cooperation is paramount; (Chapters 10 and 11) Attraction of Young Talent and Gender Equality as both an Enlargement of the Workforce and Empowerment of Complementary Skills.

The Part II of the PARE report justifies 35 PARE Objectives, that together with the 23 ACARE Goals in Part I, form a set of 58 Recommendations for Aeronautical Research in Horizon Europe[3]. These Recommendations written for specialists have a corresponding text accessible to the general public in the form of a set of articles on key findings

[1] Ref1

[2] Ref2

[3] D6.3 Ref 3

and recommendations[4]. The Part III of the PARE Yearly Report was intended for specific case studies in Chapters 12 to 16 and in Part IV to future challenges in Chapters 17 to 19. These Chapters address the major changes in the Aeronautical Scenario that occurred in the second half of the project.

3.3 The Reference for Change due to the Pandemic and Environment

The PARE project in the original proposal left scope for specific "What if?" case studies, that were started at an early stage, on topics related to the growth of the Aeronautical sector, namely the prospects of the Chinese Aircraft Industry (Chapter 12) and of the Boeing Middle-of-the-Market Aircraft (Chapter 13). Soon after events that could not be foreseen brought inescapable additional case studies. The two Boeing 737 Max accidents created a crisis (Chapter 14) reminiscent of the De Havilland Comet and the McDonnell Douglas DC-10 accidents earlier in the Jet Age. Although the 737 ~Max crisis was a major upset it was dwarfed both in scale and effects by the Covid-19 pandemic, seen both as a major disruption of the airline traffic (Chapter 15) and a global crisis of the Aeronautical sector (Chapter 16). These case studies completed the Part III of the PARE Yearly Report.

Turning to the positive side, the major event in the second half of the PARE Project was the "New Green Deal" of the European Union aiming at the greening of aviation. The environmental issues were already a major topic of the PARE report from the outset, for example in Chapter 3. The "New Green Deal" of the EU brought an additional impetus to the challenges of the future in the Part IV of the PARE Yearly Report, addressing the decarbonisation of aviation (Chapter 17), sustainable fuels (Chapter 18) and efficient propulsion with low emissions (Chapter 19). The "Future Evolution" that is the main focus of the remainder of this "Executive Report" thus straddles the known past, the current crisis and the uncertain future concerning the consequences of the Covid-19 pandemic together with the promising overarching objective of greening of aviation.

3.4 Changing Structure of the Aircraft Market

The Jet Airliner Market was traditionally split into two sectors: (i) the Single-Aisle (SA) up to 200 seats with transcontinental ranges up to 3 000 nm; (ii) the Twin-Aisle (TA) Aircraft up to 600 seats with transoceanic ranges up to 10 000 nm. In fact, there was a Middle-of-the-Market (MM) before Boeing coined in the word, for 200-400 seats over 3 000 - 6 000 nm that could not be served by SA Aircraft, implying the use of TA Aircraft in their shorter range mode. The situation changed with the Airbus A321LR/XLR since for the first time a SA aircraft could cross oceans and become a moderate capacity 200-250 seat medium range 3 000 - 5 000 nm aircraft more economical and flexible that the oversize 300 seats plus TA designed for long ranges 8 000 – 10 000 nm and operated at shorter distances. Already before the Covid-19 pandemic the A321LR/XLR was the biggest seller, at the expense of both TA, due to better flexibility/efficiency and other SAs due to better range/capacity. The airliner market changed from 2 to 3 sectors: (i) the TA for long-range over 6 000 nm and 300 seats; (ii) the short SA for transcontinental range up to 3 000nm and up to 200 seats; (iii) the transoceanic SA for medium range 3 000 – 6 000 nm and capacity 200 – 300 seats. The Airbus A220 and A321XLR show SA in no longer one but two families of aircraft, since no single design can cover efficiently the full spectrum.

Thus, already before the Covid-19 pandemic the TA market was in decline, with reduced production rates for the B787 and A350, less orders for the B777X than expected and doubts about continued production of the A330neo. The Covid-19 pandemic and the uncoordinated confinement around the world hit hardest long-range air travel and depressed still more the TA market. The grounding of the 737Max before the Covid-19 pandemic weakened its position vis a vis the A320, but did not erode too much its loyal customer base. The Airbus-Bombardier deal brought

[4] Ref4

the A220 as a formidable competitor at the low end of the SA market, without a comparable Boeing competitor after the collapse of the Boeing-Embraer deal. The growing gap between the Airbus A320 and Boeing B737 families is due to the continuing success of the A321 selling strongly against the B737-9/10 with the Boeing MMA (Middle-of-the-Market Aircraft) cancelled and the FSA (Future Single Aisle) an uncertainty years away. The Covid-19 pandemic causes a shift to smaller, more efficient aircraft, favouring the A220/A320 pair over the B737 recently re-certificated with 385 grounded aircraft and 470 for sale at attractive prices that lured Easy Jet. The growing Airbus versus Boeing advantage has been masked by the steep downturn of the airliner market, with massive cancellations and delayed deliveries, and few new orders. Orders for airliners are a reflection of passenger traffic and its past, present and future variations.

3.5 Pre- and Post-Covid-19 Passenger Traffic

The evolution of air transport over more than a century has shown two consistent trends:

- The long-term growth of 3-7% in comparable to the growth of the economy and standard of living that dictate respectively the business and leisure travel;
- Air traffic amplifies the economic cycles with strong growth in economic expansion and prosperous living and stronger decline when there is less business to do and less resources for tourism.

The year 2019 before the Covid-19 pandemic was the most profitable ever for the airline industry. However only 20% of airlines had profits, and most of those profits were made by big airlines in North America, that for several years have chased high share prices and strong dividends, based on cost cutting, bank loans and low liquidity. Thus, the airline sector was already in a fragile position before the Covid-19 pandemic, with the majority of airlines not profitable and some profitable ones with modest reserves.

The Covid-19 pandemic may have started in China in early 2019 by local accounts, supported by evidence of a sharp decline in air traffic in the summer of 2019 suggesting a lockdown. The Chinese government alerted the World Health Organization (WHO) to the pandemic at the end of 2019, after the first sign of Covid-19 appeared in Europe in October in hospital cases in France and waste products in other countries. Covid-19 was recognized in Europe starting in Italy in early 2020, and continent-wide lockdown lead to a drop in traffic to 10-20% in just two weeks in March.

The sudden drop in passenger traffic due to confinement measures put airlines in a dire situation. A large part of the fleet was grounded, with only the part flying generating some revenue with low passenger load factors hardly covering flying costs. The airlines had to decide how to divide grounded aircraft into two groups: (i) "Parked", able to fly at shorter notice, but with more maintenance, (ii) "Stored", with less maintenance, but higher initial cost and longer time to return to flight. In all cases the revenue from reduced flying could not cover the costs of maintaining and oversized fleet. Partial and uncoordinated deconfinement implied a weak summer season, with airlines flying in 2020 only 50% of 2019 at a loss of 100 billion euros. The recovery of passenger traffic depends not only on deconfinement measures but also on confidence in health measures.

3.6 Health Measures and Passenger Confidence

The worst cases of Covid-19 have been hostels for the elderly, where long-term contact of vulnerable people have led to the spread of the virus and about half of the deaths in most countries. Even for a basically healthy population, long term presence in a limited space favours the spread of the virus as shown by the serious outbreaks affecting a significant fraction of the passengers and crew in cruise ships and warships. Even the much shorter trips in public transport may contribute to the spread of the virus as well as any large gathering in confined spaces. All this may discourage passengers from travelling several hours within the confines of an airport cabin. As a matter of fact the health measures in an aircraft cabin may be better than other means of transport may suggest.

Aircraft cabins use hospital grade air filters. The air in an aircraft is completely renewed every half hour, that is more often than almost any hospital or public building. In an aircraft cabin air comes in through vents in the roof and goes out through exists on the floor, so that the air flow is mostly vertical downwards; detailed CFD (Computational Fluid Dynamics) simulations of air conditioning flows in Airbus aircraft cabins have shown a very low probability of Covid-19 droplets flowing sideways from one seat to the next. Airliner cabins are cleaned between flights and more thoroughly daily, using UV (Ultraviolet) rays that kill all known viruses, as well as disinfectants in liquid and aerosol forms, and special fabrics: tests in a Boeing aircraft cabin have shown that all of these four groups of cleaning methods were able to kill a harmless live virus that is more resistant that Covid-19.

Cabin cleaning is only one part of health measures for Covid-19 safe air travel. Passengers should wear masks at all times, making discomfort another travel deterrent. There are exceptions, like British Airways, that does not require all passengers to wear masks. Temperature screening at cabin entry is a useful measure but cannot detect the virus in the incubation phase. All airport procedures, from entry to boarding, including identity, luggage and safety checks must comply with social distancing and masks should be worn at all times. All forms of contact should be avoided or minimized, so that biometric identification is preferable to paper passports. The safety and health procedures are based on guidelines that have not been standardized: some airlines require negative Covid-19 tests and provide rapid tests that may be less reliable. With the availability of vaccines they may be required. However, the disparity of confinement measures continues to be a major obstacle to air travel.

3.7 Cargo Expansion as Partial Compensation

Air travel has contributed to the worldwide spread of the Covid-19 pandemic as the fast means of long-distance transport, if adequate health measures are not taken or passenger screening is not effectively done. Aviation has redeemed itself as the main cargo transportation means to deliver medicines, respirators, vaccines and all sorts of medical equipment at short notice and large quantities. Aviation has also helped combat the Covid-19 pandemic by repatriating passengers stranded in faraway places in special flights with stringent health measures; aircraft and helicopters have been used to transfer patients out of saturated hospitals to medical facilities with spare capacity in other regions. Although the loss of regular airline traffic cannot be compensated by special and cargo flights, the latter have helped some airlines marginally survive.

Before the Covid-19 pandemic about half of air cargo was carried in the holds of passenger aircraft and the other half in dedicated freighters. The sharp decline in passenger traffic due to the Covid-19 pandemic thus almost halved the available cargo capacity, at a time when demand for cargo significantly increased due to the need for urgent delivery of substantial medical supplies to counter the same pandemic. Bringing back into service idle cargo aircraft, and more intensive use of freighters, was not enough to cope with increased demand. Passenger aircraft are used with parcels on seats restrained by nets as the quickest improvisation; removing the seats altogether makes better use of cabin capacity for cargo. The use of passenger cabins for cargo requires special procedures, since they do not have fire detection and extinguishers, as cargo holds do; thus, the cabin crew of passenger aircraft are replaced in cargo flights by sky marshals with fire extinguishers. The demand for air cargo is also sustained by e-commerce, than has been growing much faster that the general economy before Covid-19, and has increased with confinement. Thus, when the Covid-19 pandemic is overcome, the drop in related air cargo may be attenuated by the increase in e-commerce.

3.8 Leasing Companies: Cunning and Flexibility

Aircraft leasing represented less than 3% of the fleet 20 years ago and has grown to more than 30% at present. The fast growth of lessors has been driven by several factors. Aircraft lessors place large multi-year orders for airliners that are the buffer of aircraft manufacturers against oscillations in the airline market, providing a baseline of stable production to which are added scattered small orders; as the most welcome clients' aircraft lessors are also able to obtain the best prices and most favourable and flexible delivery conditions from aircraft manufacturers. Leasing aircraft allows airlines to size their fleets for steady average demand, and still meet peaks in demand without overcapacity. Aircraft leasing deals may be financially advantageous in the short or long term over direct purchase since they do not require large upfront investment. The growth in air traffic pre-Covid-19 and the grounding of the Boeing B737Max fleet after two accidents increased further the demand for aircraft leasing in 2019, prior to the Covid-19 crisis. In spite of the strong demand competition in the aircraft leasing market was deemed 'excessive' by the traditional western profit-led lessors, due to the emergence of state-financed Chinese lessors competing for market share at unbeatable prices.

The Covid-19 pandemic with large parts of airline fleets grounded, would appear to deplete demand for leases. In fact, the airlines in dire financial straights need to operate the most efficient aircraft with lower costs and less environmental constraints, implying the most modern, some of which are leases. Also, lessors were cunning enough to save existing contracts by allowing airlines deferred payments up to 9 months, bringing in a short-term no cost option and avoiding penalties for cancellations of contracts. The good news was that most airlines did honour their delayed payments and lessors gained a positive cash flow, since the number of new requests for delayed payments declined. Thus, leasing companies were able to survive the Covid-19 pandemic by being savvy and flexible. That flexibility extended to some leasing companies trading for airline shares or assets. Whereas some airlines went bankrupt, most airlines had a traffic decline of about 50% in 2020 relative to 2019 due to the Covid-19 pandemic, some lessors had no decline at all or even growth. The key was flexibility, being able to satisfy demand for cargo and special flights, providing aircraft, crew and maintenance tailored to specific situations including meeting the confinement rules and regulation in different parts of the world. Airlines operating large traffic flows in long-term standards conditions were sometimes unable to respond to short-term market opportunities with specific constraints, like repatriation and cargo flights, and had to enlist the help of lessors, more flexible in out-of-the-box operations.

3.9 Decline in Aircraft and Engine Market

The Covid-19 pandemic, with the grounding of up to 50% of airline fleets, has forced virtually every airline to renegotiate their contracts with aircraft lessors (Section 8) and aircraft and engine manufacturers (Section 9). Before the Covid-19 pandemic, the continuing long boom period led aircraft manufacturers to raise production rates to unprecedented levels, putting demands on suppliers like engine manufacturers that could hardly be met. Airbus had complete aircraft parked waiting for their engines, the so-called 'gliders', and struggled to deliver as much as its prosperous financial situation allowed. Boeing was in the opposite situation with the biggest losses in its century-old history due to the grounding of the B737Max, including 385 aircraft with airlines and 470 undelivered. Both Airbus and Boeing had large order backlogs, covering more than 5 years of production. The Covid-19 pandemic was an equalizing disaster for Airbus and Boeing, with order cancellations and deferrals and poor prospects of new orders for at least a couple of years.

The scenario on the engine side could not be better, since less aircraft mean less engines produced. All engine manufacturers were struggling with correcting problems with the new generation of in-service engines: the Pratt & Whitney (PW) geared fans, the GE/Snecma LEAP, the Rolls-Royce Trents and the General Electric GE90 in development: their inability to meet demand for production pre-Covid-19 changed abruptly post-Covid-19 to excess production capacity as for aircraft. In the case of engine manufacturers more than two-thirds of revenue comes from spares and maintenance over the lifetime of the engine. Some claim that engines are sometimes sold at a loss to be recovered with spares sales and maintenance services over the engine lifetime. With half of the fleet grounded and the other half flying less, engine hours dropped by more than 50%. In addition cash strapped airlines tend to postpone as long as possible major costly services, like engine overhauls. Thus a decline in production and revenue of 30% for aircraft manufacturers due to the Covid-19 pandemic, may become for engine manufacturers a 30% decline in production and 50% decline in revenue, due to an even larger decline in maintenance and repair. The aircraft and engine manufacturers are the upper tiers of a five-level supply chain through which cascade down the problems of declining production.

3.10 Supply Chain Survival and Rationalization

Before the Covid-19 pandemic the aeronautical supply chain was under intense pressure to produce more and cheaper. The increased production rates of aircraft and engines placed demands beyond the capacity of most lower tier suppliers. Some were wary of investing on increased production capacity in case the order boom would not last and the long upward cycle would come back to a decline. Other suppliers willing to take the risk to ride on the current boom had not enough funds for expansion and might not be able to obtain sufficient credit from banks or investors. Some suppliers did take the plunge indebting themselves to increase production capacity. The financial health of suppliers was not helped by a Boeing campaign to cut prices leaving profit margins below 10%, and competitive pressure lead Airbus to place not too different demands. Thus, the pre-Covid-19 supply chain was indebted to increase production volume with small profits, and highly vulnerable to a sharp decrease in production.

The reaction of suppliers to sharp decrease in production due to the Covid-19 pandemic varied according to their situation and exposure to the aircraft market. The suppliers with small exposure to the aeronautical market and remaining profitable business elsewhere could just leave. The suppliers with strong exposure to the aeronautical market and weak financial position could go bankrupt, scale down operations, be acquired or consolidated. Thus, the Covid-19 pandemic can cause a major re-structuring of the supply chain with horizontal consolidations and vertical integration. Concerning the latter, the suppliers of unique special equipment, essential for recovery after the pandemic, must be saved with funds and/or orders from upper tiers to keep them alive and fit. On the other hand, there may be no need for the suppliers of services, that the upper tiers can do themselves, now that they are no longer understaffed by excess work, and instead are struggling to occupy and shed an excessive workforce. The horizontal consolidations and vertical integration of the supply chain led to a restructuring focusing on the preservation of unique capabilities essential for recovery. That recovery will require the most efficient and environmentally friendly new aircraft, rather that bringing back into service older inefficient polluting models.

3.11 Used Market, Efficiency, and the Environment

The decline in passenger traffic due to the Covid-19 pandemic forced airlines to ground up to the half of their fleets. With reduced passenger demand the routes must be flown with the smallest most efficient aircraft, to preserve load factors and minimize costs, while meeting increasingly stringent environmental demands. It becomes imperative to use the most modern, efficient, and environmentally friendly aircraft, whether airline-owned or leased, to bolster the marginal operating economics. The older, less efficient, or more polluting aircraft are grounded and may never fly again. Aircraft values in the used market are likely to decline due to the increased supply of not so old aircraft. The value of such aircraft may depend mostly on engine spares. Some aircraft may return to flight in secondary roles like freighters and perhaps in more remote areas until stricter environmental standards inevitably apply worldwide.

The need for the newest aircraft for recovery from the Covid-19 crisis will ultimately be good news for aircraft markets and the supply chain. Airbus has reduced production rates by 30% for SA and more for TA, so that its backlog reduced by cancellations still lasts for the same 5-7 years. Boeing has reduced TA production by 50% or more like Airbus due to the reduced demand already apparent before Covid-19 plus the poor prospects of recovery in the long-haul sector. Boeing will take more than one year after the recent FAA undergrounding of the B737Max to bring 385 airline aircraft to service and sell 470 undelivered aircraft, keeping production at the lowest sustainable rate before ramping-up again. The few airlines with enough finance may be able to buy at unbeatable prices, like the Easy Jet order for undelivered Boeing B737Max. Aircraft orders may be few and far between until recovery from Covid-19 after 2023, but a rapid growth can be expected, and it can only be using the most modern aircraft. Thus after the Covid-19 pandemic the fewer smaller surviving airlines may have a strong and profitable expansion, and aircraft manufacturers and the supply chain will have to ramp-up again. This dream scenario, like the pre-Covid-19 growth, and unlike the present situation, will require surviving the current crisis.

3.12 Maintenance, Repair and Overhaul Sector

The pre-Covid-19 boom market meant that there was plenty of MRO (Maintenance, Repair and Overhaul) work, some done by airlines in-house, and a large part by OEM (Original Equipment Manufacturers) and specialist independent MRO organizations. The intensive activities of airlines increased MRO needs, and the OEMs busy with increasing production might leave a considerable share of work to prospering independent MRO organizations. Post-Covid-19 the reduced flying and deferred major overhauls reduce the total MRO work. The OEMs with over capacity due to reduced production may take more interest in MRO, with the advantage of supplying the original new spare parts. The independent MRO organizations will have to survive retaining existing long-term contracts and providing services at very competitive prices perhaps with cheap aftermarket parts from low value used aircraft. Thus the independent MRO organizations may face the sharpest downturn due to the Covid-19 pandemic, along with airlines, industry and other service suppliers, like air navigation and airports.

3.13 Air Navigation Service Suppliers

The transition from expansion to depression caused by the Covid-19 pandemic extends from reduced flying to less work for ANSPs (Air Navigation Service Providers). In the boom period before the Covid-19 pandemic ANSPs were struggling to provide enough capacity and minimize delays and diversions. Europe has one of the densest air traffic in the world, in particular in the central area around Germany, forcing diversions along longer roots with higher emissions and poorer economics. Some ANSPs were being blamed for not having trained enough ATCOs (Air Traffic Control Officers) to keep up with demand. The flight charges collected by Eurocontrol and distributed to ANSPs covered not only personnel costs, but also the maintenance and upgrading of equipment.

The Covid-19 pandemic brought an abrupt decline of air traffic to 10-20% of 2019 levels in March 2020 and less than 50% overall in the whole year. The ANSPs decided not to charge airlines for overflights, to avoid overburdening their marginal finances, and discourage further keeping part of the route network. The flight charges with reduced flying might not in any case cover ANSPs costs, that were fully covered by National Governments. The National Governments also agreed how to share the funding of Eurocontrol, since it was no longer collecting flight charges. The problem of ANSPs are not only financial, but also keeping the skills of ATCOs deprived of practice for several months. Like airline pilots, ATCOs are highly trained professionals, who must practice their skills in a real environment, and cannot depend only on simulators no matter how sophisticated. Thus special programs have been developed by airlines and ANSPs to keep the skills of respectively pilots and ATCOs and ensure a return to service with undiminished safety. The loss of revenue to cover significant fixed costs was a major effect of the Covid-19 pandemic directly on airlines, and by implications also on industry and service providers, including airports.

3.14 Airport Fees and Commercial Sales

Airports, like other aeronautical infrastructures, have significant personal, operational and maintenance costs, including building, runways, parking spaces, landing aids and passenger and luggage facilities. Airport revenues come mainly from two sources: (i) Airport charges, including landing fees, that have risen considerably in recent years, sometimes exceeding the cost of the flight ticket; (ii) Commercial sales from sometimes extensive shopping area that the passenger may be forced to cross to reach the boarding gate or exit the airport. The decline in air travel affected both sources of revenue, with less flights paying airport charges and fewer passengers indulging in less shopping. With less revenue to cover fixed and personnel costs airports become dependent on financing by local authorities. In countries with global confinement even major airports were closed, becoming parking lots for grounded aircraft lined along unusable runways. The Covid-19 pandemic caused a decline in all aeronautical activities with two exceptions: cargo (Section 7) and business travel (Section 15).

3.15 Corporate, Business and Chapter Travel

The business jets of large corporations are usually reserved for top executives, whose time is deemed too valuable to be wasted in airport queues, unsuitable flight schedules, unnecessary stopovers, and distant or inconvenient departure and arrival airports. Modern large business can fly direct from airports at or near headquarters to smaller airfields closer to destination than busy airport hubs. They provide work, meeting and rest conditions that cannot usually be matched by any first-class aircraft cabin. Although there is some trend for corporate jets to become available for lower executive ranks or larger groups in special cases, the latter use most often standard airline services.

The Covid-19 pandemic changed the situation in several ways. It brought a business decline, with less need for travel, and the incentive to replace face to face meetings by teleconferencing whenever possible. However a lower level of business travel is still needed, and the best answer may not be airline schedules reduced by poor demand, more frequent cancellations due to low load factors or Covid-19 constraints, further compounded by perception of health risks. As a consequence, the use of corporate jets has been extended to lower executive ranks and to more staff groups.

Whereas the largest corporations and wealthier rulers and individuals have their own private jets, many with not so vast resources or lower level of use, join fractional ownership schemes and/or use as necessary charters, fly-by-the-hour and other schemes. Thus the whole sector of business and individual non-scheduled airline travel has grown as an alternative to the perceived health risks of collective travel and to the degraded schedules and services of airline flights, Thus the only two sectors of aeronautical activity that may have escaped the sharp and deep depression brought the Covid-19 pandemic to airlines, industry and services, are the exceptions of air cargo and business travel. The latter are understandably not too keen to publicize their relative prosperity in a general context of depression, that has motivated government intervention.

3.16 Civil and Military Aviation Markets

Both in the aircraft and engine sector, as well as for the supply chain and equipment, the Covid-19 has affected most civil aviation dependent on airline orders and passenger traffic. On the military side most contracts are multi-year and from governments and thus much more stable. Thus the pre Covid-19 military contracts, plus ongoing conflicts around the world, are a source of revenue for dual role aeronautical companies, that are present both in the civil and military markets. Since the civil aviation market is about twice in overall value of military market this is only partial relief. The situation can vary widely depending on the exposure of a particular company, operator or service organization to the civil market or how strong their military backlog is. On the other hand, given the general economic decline, there are doubts whether defence budgets will be able in the future to sustain all the pre and pos-Covid-19 military contracts.

3.17 Insolvencies, Bail-Outs and Government Interventions

The depression in the aeronautical sector caused by the Covid-19 pandemic was deep enough to raise the issue of government interventions; as with other sectors the outcomes varied with country around the world. In the case of airlines, between the extremes of bankruptcy and full bail-out. One extreme was the case of airlines with a long record of poor financial performance, even flag carriers, like Thai Airlines, or several airlines in Latin America. With the host states having weak economies, and their difficulties aggravated by the Covid-19 pandemic, it would be difficult to decide to allocate substantial sums to a loss-making airline to avoid bankruptcy.

The opposite extreme is the case of Singapore Airliners and Cathay Pacific, both with long record of good service and financial performance. They would be worst hit airlines, having no domestic market, and being the most dependent on long-haul routes that face the worst effects of uncoordinated confinement across the globe. Both the Singapore and Hong Kong Governments facilitated through flights through their single large airport, but this could never compensate for the absence of domestic routes and sharp decline of international flights. Both Singapore and Hong Kong, as wealthy states with strong economies, would not be prevented by the Covid-19 pandemic from making the large investments needed to rescue their flag carriers, that always had performed well, and become victims of an exceptional decline not of their own making and entirely beyond their control. The government interventions in the ailing airline sector around the world ranged from controversial in the U.S. to painful in Europe.

3.18 Controversies with the CARES Act in America

The CARES (Coronavirus Aid, Relief and Economic Stability) bill of the United States Congress included the biggest bail-out of the aeronautical sector, by far in absolute value (190 B$) and also one of the highest in terms of percentage of revenue. The bill covered a six-month period up to 30 September 2020, set no long term objectives and made financial support dependent on a set of rules that turned out to become very controversial with claims of unequal treatment and diversionary counter-tactics. The first rule that airlines could not dismiss workers or reduce pay rates, was circumvented by some airlines cutting working hours and hence wages; this lead tom massive protests by workers and unions, including in the corridors of Congress. After the expiry of CARES, the failure to reach a new agreement with government, left airlines free to act on dismissals and wages.

A second CARES rule required airlines to keep domestic connections. This was quite hard on small local airlines forced to fly nearly empty aircraft along a full set of routes at a loss. It was much easier for large international airlines since they could: (i) eliminate international flights; (ii) reduce the frequency of domestic connections; (iii) replace direct flights by routing through hubs. As if this was not enough, some large airlines proposed 'codeshare' schemes, where they would no longer compete on the same route, and only one fly each route on behalf of all others. This division of flights was repeatedly rejected by the Department of Transportation.

A third CARES measure applied to airports basing allocations on low existing debts and high reserves. These criteria led controversial contrasts among airports in the same state: (i) a small airport could be funded for several years of operation whereas a large airport would cover costs of only a couple of months; (ii) two airports with similar traffic could have very different allocations; (iii) the largest airport in the State could receive less than others far smaller.

The support for the aeronautical industry was less controversial, although substantial, with the Boeing bill of 60 B$ raising some eyebrows in Congress. Although Boeing claimed that this covered the whole supply chain, most of that large sum would cover the massive losses due to the grounding of the B737Max for 18 months, recently lifted by the

FAA, before other airworthiness authorities worldwide. At the beginning of 2020 the Boeing Commercial Airplane Division was burning through 4B$ per month, and a 12 B$ loan was depleted in one quarter. The Boeing debt stood at about 30 B$, and it was stated that a 60 B$ bail-out would be needed, all this before the Covid-19 pandemic. Although the Covid-19 pandemic hit Boeing as hard as anyone else in the aeronautical sector, it motivated the CARES bill, that provided the 60 B$ cash injection needed by Boeing before, with less need for embarrassing justification. The airline rescue packages for flag carriers in Europe were made to measure and long-term, instead of the temporary six-month one-size-fits-all rules in the U.S.

3.19 Rescue of Flag Carriers in Europe

In Europe the low cost carriers (LCCs) were left on their own to face the consequences of the Covid-19 pandemic exercising their freedom to dismiss workers, cut wages and take other survival measures. The case of flag carriers did not attract specific government attention is some countries like Spain and Britain, where only generic relief measures were available; worse Iberia-British Airways complained of unfavourable confinement measures, and the latter even threatened to take government to court for imposing quarantine on most travellers. Lufthansa in spite of its strong service and financial record, had to accept a 9 B€ rescue bill with a bitter pill of conditions, including reduction of fleet size and loss of slots at key airports like Frankfurt and Munchen; in addition the German Government took equity in Lufthansa, and depending on future performance could become private again or be nationalised. Air-France-KLM had a rescue package shared 12 B€ and did not escape restrictions like shedding domestic routes in favour or high-speed trains.

The case of Alitalia and Olympic Airways was inevitable as both airlines have a long record of poor financial performance and multiple rescue packages respectively by the Italian and Greek Governments. Italy and Greece (like Spain and Portugal) are major tourist destinations, making imperative for any government the existence and survival of a flag carrier. The LCCs in particular, that already have a large share of the tourist market, with their typical aggressiveness, are the first to denounce in Brussels the state aid as an infringement of fair competition in the European single market. This time the dramatic situation created by the Covid-19 pandemic made it somewhat easier to gain approval in Brussels for negotiated government interventions. In the case of Alitalia the plans have ranged from a much smaller one-fifth size airline without global European stature to a full recovery to a national flag carrier status never quite achieved in the past. In France in particular and also in Germany, the government rescue package for the aeronautical sector were more comprehensive, including not only airlines but also industry.

3.20 Comprehensive Support for the Aeronautical Sector

Before the Covid-19 pandemic the two rivals in the Airbus-Boeing duopoly: (i) Boeing was 30 B$ in debt due to the grounding on the B737 Max, and was rescued by the 60 B$ CARES bill; (ii) Airbus had a healthy cash reserve mostly but not only due to strong sales of the A321LR/XLR, and needed no financial bail-out. The Airbus position towards the French Government was thus in favour of its airline clients and its supply chain, plus the full spectrum of Research, Development and Innovation (RD&I) activities. Thus France did not only bail-out AirFrance-KLM and like Germany made long-term plans for the survival and evolution of the aeronautical sector as a supplier of efficient and environmentally friendly aircraft in the future consistent with the New Green Deal of the European Union. The plan included not only the (i) rescue of the airline customer, but also (ii) sufficient contracts, including military long-term, to keep industry alive, (iii) support for smaller companies down the supply chain and (iv) reinforcement of academic, research and industrial capabilities key to the progress of aeronautics.

Although the most visible negative effects of the Covid-19 pandemic are a short-term economic decline and loss of jobs, there is another less visible long-term consequence: loss of skills. The pilots deprived of flying and air traffic controllers with no traffic to control may lose critical skills essential to maintain safety when air transport recovers from the crisis. The financial difficulties caused by the Covid-19 pandemic place industries and services in a survival mode, cutting all non-essential activities, and scrapping long-term plans. Their research and development activities that are key to progress in aeronautics and were supported continuously for decades have been cut abruptly by the Covid-19 induced cash shortage. In a depressed market with more cancelations that new orders there is no incentive to keep alive design teams, that took decades to form, and if disbanded will also be lost for decades. The New Green Deal in coordination with national governments achieves a symbiosis of two commendable objectives (i) it keeps alive the existing world class academic, research and industrial design capabilities that have historically been the basis of Europe's competitiveness in aeronautics; (ii) it directs these competences towards a more efficient and greener aviation, developing technologies like electrification and hydrogen propulsion that will be key to future generations of aircraft.

3.21 The Covid-19 Vaccine and Recovery from the Pandemic

The general expectation is that only a safe and effective Covid-19 vaccine will overcome the pandemic. A worldwide cooperation in an unprecedented scale has allowed the development of several vaccines in less than 1 year instead of the usual 4 years. Among the 30 or 40 vaccines in development using different principles, the Pfizer-Biontex and Moderna versions are most innovative and promising. They do not, like traditional vaccines, inject an inert version pathogen, to cause production of anti-bodies. They give a new use to a substance (RNA) known since the 90s, to trigger the DNA of cells to produce a protein that in turn causes the generation of Covid-19 anti-bodies. A new vaccine cannot give the knowledge of secondary effects available with regard to decades old vaccines. The current vaccine appears less intrusive than those of the past, and its wide application can stop the Covid-19 pandemic, even if some lesser secondary effects have to be addressed later. In principle a vaccine remains effective against the virus it is developed for, and has to be modified only in the case of major mutations.

The vaccination of most of the population of a country will take months, if it is assumed that the hospital services can do one-tenth of the population per month, in spite of being already overloaded with Covid-19 and other patients. In order to reach 60-70% of the population to stop the pandemic starting in January takes until July. If 30-40% of population vaccine is needed to diminish the scale and control the pandemic this could be reached in May. The first priority in the first month is the medical professionals that are most exposed and needed to keep full hospital capacity. Vaccination of the higher risk cases (elderly and respiratory diseases) could reduce the rate of infection in two months. A higher rate of vaccination could be achieved if pharmacies could be qualified and were provided with deep freezers needed to keep vaccines below -70 °C, as are available in hospitals. The success and rate of vaccination against Covid-19 may influence the recovery of the airlines, and hence of the whole aeronautical sector.

3.22 Survival, Recovery and Prosperity Calendar

The Covid-19 pandemic hit hardest the airlines in Europe in two weeks in March 2020 when the first wave of Covid-19 caused a general confinement brought traffic down by up to 80%. The modest recovery since then has left airlines in 2020 at 50% of the 2019 level. The critical strong summer season of 2020 was lost to the Covid-19 pandemic and government intervention was necessary to rescue flag carriers. The surviving airlines, most in a weak or marginal financial condition, now face a long weak winter season not helped by a second wave of Covid-19 before the end of 2020 and a possible third wave in the beginning of 2021. Governments are resorting to partial rather than global lockdowns and the availability of the vaccine may stem the third wave of Covid-19 in 2021. The critical issue for airlines struggling for survival through the low season is: how is the summer 2021 season going to be? It needs to be at least 50% of 2019, otherwise there is the risk of more bankruptcies or the need for a second intervention if governments are willing to do so. A 50% summer season depends on a successful fast vaccination campaign and immediate return of passenger confidence, neither of which is by any means assured.

Looking further into the future, past the end of the Covid-19 pandemic, whenever that eventually happens, the future looks far better that the present. A large part of the population tired of confinement will be eager for tourist travel beyond national confines; business and professional travel will grow with economic recovery, where teleconferencing is not adequate. Like in all past cases of strong resurgence of aviation, and perhaps even more out of this longer and deeper crises, the growth in demand for air travel is likely to be strong and sustained. On the other side, there will be less airlines after bankruptcies and consolidations, and they will be smaller due to downsizing. The excess of demand over supply will drive the lucky few airlines that have survived the pandemic into fast and profitable growth, in stark contrast with the current situation. The 'dream scenario' of airline travel growth will spread to industry and services, recover lost jobs and resume prosperous growth.

3.23 Post-Covid-19 Market and Employment Growth

Eurocontrol predicts that 2019 levels of traffic will be reached only in 2024 to 2029 depending on how effectively and fast the Covid-19 pandemic is contained. Regardless of date, the end of the pandemic will increase rapidly the demand for air travel and the shrunk airline sector will have to grow equally fast its offer. Airlines will have to re-hire, and will likely prefer those previously dismissed, even if they require retraining to recover their skills, as might be the case of pilots. Pre-Covid-19 there was an expectation of a major shortage of pilots due to two factors: (i) the strong growth of aviation in the 1990s brings a wave of retirements in the 2020s; (ii) the continued growth of aviation at a rate of 3-7% requires a steady stream of new pilots. Although the current 50% contraction makes a 3-7% yearly expansion look like a dream, the yearly growth after Covid-19 could be actually higher because of starting with a depression. Recently the BALPA (British Airline Pilots Association) warned newcomers against starting pilot courses, because there are thousands of unemployed pilots. At the same time one of the largest manufactures of flight simulators (CAE) predicted that tens of thousands of new pilots would be needed in the next two decades, and several thousand next year. In spite of the contrasting vested interests of BALPA and CAE, they may both be right, as the recovery from Covid-19 may be a dream after a nightmare.

A recovery from the Covid-19 pandemic to the traffic levels of 2019 does not mean that the aeronautical sector will look the same, because there will be plenty of change. The surviving airlines will be more lean and mean and may serve the same traffic without having to hire as much staff as before, however traffic growth will ensure that staffing levels reach new highs, and earlier job losses are recovered. Services will no longer be the same, for example air traffic management: (i) will still deal with aircraft at current altitudes but with an increasing number of drones; (ii) urban air mobility (UAM) will bring a new low level air traffic area; (iii) the increased launch rates of rockets and possible proliferation of hypersonic vehicles will make upper air space ATM in the stratosphere necessary. Not only the variety of aerospace vehicles will increase but also the demands of efficiency and environmental friendliness. Airlines in the future, both for economic and regulatory reasons, will be able to operate only the most efficient and environmentally friendly aircraft, which is the best possible news for industry since: (i) the post Covid-19 recovery of air traffic will require expansion by buying new aircraft; (ii) every new generation with better economics and lower emissions will have an assured market. The post Covid-19 recovery may be a change from nightmare to dream not only for airlines, industry and employment, but also the dawn of a new technological era, with electrification and hydrogen as the spearheads.

3.24 Fossil versus Clean Sources of Energy

The predominance up to the present of fossil fuels is based on high volumetric and weight energy density: one litre or one kilogram of kerosene, gasoline or diesel provides a substantial amount of energy. Also the cheapest energy supply is to take fuel from an oil well and refine. And although fossil fuels do have safety hazards a large investment has been made in infrastructure to handle them with acceptably low risks. Thus fossil fuels have been the default choice, until the consumption reached levels so high as to harm the environment, motivating other choices that were considered in the past but not pursued with much vigour.

The obvious way to finish with tailpipe emissions is to use electrical propulsion, although there are other environmental life-cycle considerations that have a considerable effect, and cannot be ignored in a superficial or incomplete assessment. The first issue is how the electricity is generated: fine if it is by hydroelectric, solar, wind or other environmentally friendly energy sources; less good if it involves burning fossil fuels, and replaces tailpipe emissions by emissions elsewhere. This could be addressed by increased or exclusive use of clean energy sources, but would require a large investment in order to be able to replace and phase-out all thermal power. The opposition to nuclear, that is environmentally clean except for radioactive waste with long life, limits another energy source. The ideal solution of controlled thermonuclear fusion as an inexhaustible source of clean power remains as a prospect for the future that keeps shifting away.

3.25 Thermal, Electric and Hybrid Propulsion

Thermal propulsion, based on burning fossil fuels, is a source of multiple harmful emissions: (i) carbon dioxide, as well as other greenhouse gases, that drive global warming; (ii) nitrogen oxides NOx whose presence in engine exhausts is hard to counter at the same time as carbon composites; (iii) soot and particles of various sizes that can cause health problems if not filtered to ensure sufficiently low concentrations; (iv) sulphur, lead and other residual compounds with undesirable environmental effects. Some narrow sighted policies of the past have not helped, such as focusing only on reducing carbon dioxide, favouring diesel over petrol, and then demonizing diesel due to high particle content, that was known from the beginning, though perhaps with less awareness of harmful medical aspects. In contrast gaseous fossil fuels, like Liquefied Petrol Gas (LPG) from refineries and Compressed Natural Gas (CNG) from oil wells, that are nearly particle free, have only partial incentives without exploiting their full potential.

Purely electric propulsion solves the problem of local tailpipe emissions, but besides the issue of electric energy generation, there are those of storage in batteries and recharging them. Recharging batteries is an infrastructure and standardization problem, but energy storage is the main issue: the power density of batteries is one order of magnitude lower than that of fossil fuels, and for similar range and performance a battery pack weights and occupies a volume an order of magnitude larger. With current technology this limits aircraft range to about 500 km when battery weight leaves no margin for payload. Future solid-state batteries may improve power-to-weight ratio but are still in laboratory stage and far from production. The currently available batteries with highest power-to-weight ratio like lithium-ion use rare earth metals, in limited supply in a few countries like China, with environmentally intrusive mining methods. The production of electric vehicles is also more polluting than that of fossil fuelled vehicles making the overall life-cycle environmental impact harder to assess.

Hybrid propulsion tries to harness the benefits and minimize the less desirable features of both thermal and electrical propulsion by combining them in a judicious ways such as : (i) in cars clean electric power in urban environments limiting the dead weight of batteries for travel elsewhere; (ii) in aircraft thermal engines optimized for cruise efficiency with extra electric power for take-off and landing and flight in terminal areas. Fuel cells using hydrogen have a better power-to-weight ratio than batteries, but still use rare metals, and have the same safety issues of runaway fires and explosions if charging limits are exceeded or in the presence of shocks. The case for electric and hybrid versus thermal propulsion can be fairly put as follows: the higher environmental impact of electric/hybrid vehicles in terms of mining raw materials, production of components and vehicles and their end-of-life scrapple or disposal compared with conventional vehicles, is compensated by lower emissions in operation over what distance? Whereas information on emissions in operation is mandatory in most countries much less is available on emissions at other stages of the life-cycle leading to widely varying estimates of where the cross-over lies.

3.26 Hydrogen. Production, Storage and Transport

Water is one of the most abundant elements on earth, and hydrolysis an almost endless source of hydrogen. However hydrolysis consumes more energy than is recovered burning hydrogen, and thus should use environmentally friendly energy sources like hydroelectric, wind or solar. A very significant expansion and large investment in clean energy sources would have to be made to produce hydrogen in quantities that would significantly reduce the dependence on fossil fuels. A large fraction of environmentally clean energy that cannot be used immediately or transferred to the grid is lost due to the inability to have long-term energy storage. For example there is more solar energy in summer when consumption is lower than in winter when consumption is higher. Using excess environmentally clean energy, that otherwise would be wasted, to produce hydrogen is in effect a long-term storage of energy, since hydrogen can be burned at a later date.

There is a misconception that storage and transport of hydrogen is more dangerous than for fossil fuels, when in fact both have comparable but different hazards and risks. The overused example against hydrogen is the fire of the Hindenburg airship on arrival in New York overlooking two facts: (i) there were many safe flights before; (ii) most of the passengers survived descending to the ground while the hydrogen burned upwards. The latter remark points to a far more relevant comparison that there are many more fires and explosions in liquid fuel (gasoline or diesel) cars than in gas fuelled (LNG or CNG) vehicles for two reasons: (i) compressed gases are stored in thick tanks far less likely to rupture than thin-walled petrol tanks; (ii) in case of a leak, gaseous fuels rise rapidly, and can be lighten up only for a second or two, whereas liquid fuels form a pool ready to catch fire or explode until cleared up. The planned use of hydrogen fuel in the Lockheed SR-71 Blackbird Spy Plane never materialized, but led to go tests attempting to cause the explosion of an hydrogen tank: in spite of multiple provocations only one succeeded in causing an explosion. In contrast there is a long and sad record of aircraft accidents that would have been survivable except for rupture fuel tanks, fuel leaks and pools and subsequent fires.

In conclusion hydrogen is neither more nor less dangerous than kerosene, and does carry comparable but different risks. There are decades of experience of handling safety fossil fuels like kerosene and aviation gasoline and a similar pool of experience must be developed to handle safety the different risks of a gaseous fuel like hydrogen First hydrogen has a very wide flammability range 5-75%, much larger than fossil fuels. Second hydrogen as the lightest element is one of the most volatile, and evaporation can be an issue in a long flight. Third liquefying hydrogen requires cooling and conversely evaporation releases heat: thus evaporating hydrogen must be vented quickly to the atmosphere, otherwise heat release and wide flammability limits can cause an explosion. Also burning liquid hydrogen is not as straightforward a gaseous hydrogen due to the evaporation phase in between. The biggest limitation of hydrogen is the need for large tanks, so that for long-ranges other sustainable fuels must be used.

3.27 Hydrogen versus Other Sustainable Fuels

Hydrogen is the lightest of all elements, and although its power density by weight is higher than that of fossil fuels, its power density per volume is one order of magnitude lower. For storage and transport hydrogen is compressed at 700 bar requiring thick and heavy tanks; this is acceptable for land vehicles that already use gaseous fossil fuels, like LPG or CNG. It is a non-starter for aircraft since: (i) the weight of hydrogen tanks is too high; (ii) the refuelling time is too long for quick turnarounds between flights. The solution for aircraft is Liquid Hydrogen (LH) that has higher density at lower pressures, but requires very low temperatures below 4 K. There is an extensive experience with LH as fuel and LOX (Liquid Oxygen) as oxidizer in the cryogenic propulsion of rockets and satellite launchers. The current trend is to retain LOX, that requires cryogenic temperatures below 30 K, thus less extreme than LH, and replace the latter by hydrocarbons, like methane or kerosene. Transferring the experience with LH from cryogenic rockets to aircraft is not entirely straightforward due to two major differences: (i) rockets fly for a few minutes and aircraft several hours, so issues like volatility are much more serious; (ii) the reliability of rockets is of the order of 10^{-2} far below $10^{-6} - 10^{-8}$

of civil aircraft, and this gap of several orders of magnitude requires far more stringent standards on design and equipment.

Hydrogen is presented as the ultimate clean fuel, since its burning produces only water vapour, and no carbon or nitrogen oxides, particles and other harmful substances like fossil fuels. This is true for land vehicles and ships, but at the cruise altitudes of airliners in the stratosphere water vapour is a greenhouse gas. In any case burning hydrogen in the stratosphere is preferable to burning fossil fuels, but it may not be totally harmless due to the production of contrails. Contrails or condensation trails are formed by small ice crystals due to the freezing of water droplets in certain atmospheric conditions. The effect of contrails on global warming is not large but is not well known and more research is needed about burning hydrogen in the stratosphere. The greenhouse effect of contrails can be avoided in two ways. First contrails can be avoided by changing altitude to atmospheric conditions where ice crystals no longer form; this may complicate Air Traffic Management (ATM) and reduce airspace capacity. Another possibility would be to trap water vapour if possible into water tanks, and then to dump the water overboard when reaching an altitude where contrails no longer form. Both solutions are not devoid of practical problems.

The low volume density of hydrogen raises the issue of tank volume and housing: (i) for a regional aircraft with range up to 1000 km hydrogen tanks could be housed in an extended aft fuselage behind the cabin aft pressure bulkhead; (ii) for a medium range aircraft up to 3000-5000 km a configuration with large internal volume like a flying wing might be needed to accommodate cylindrical hydrogen tanks in a complex structure; (iii) for ranges beyond 5000 km and up to 16000 km hydrogen is simply not a viable option, since the high drag of large hydrogen tanks defeats any attempt to increase range by requiring even larger tanks in a losing battle. The only alternative for long-rang flights is sustainable fuels that can be produced combining hydrogen with carbon dioxide extracted from the atmosphere, compensating the emissions when burning the fuel, for net zero environmental effect. The ideal sustainable fuel should also be a drop-in fuel that can be used in current engines and use the existing refuelling infrastructure. It cannot be as cheap as kerosene, as there is a price to pay for a cleaner environment. Other alternative fuels are possible, ranging from derived waste products to algae blooms, but excluding competition with food crops. The main challenge with alternative sustainable fuels is producing sufficiently large quantities, since 80% of all aeronautical fuel consumption is due to long-range flights. The choice of which technology is most suitable, thermal, electric or hybrid, battery, fuel cell or turbine, hydrogen or synthetic fuel, depends on the range of the aerial vehicle or type of transport: local, regional, medium or long range.

3.28 Electric Power for Local Transport

The low power to weight ratio of batteries limits aircraft range to about 500 km and endurance as well. This enough for training flights and Urban Air Mobility (UAM). The preferred form of UAM is e-VTOL (Electric Vertical Take-off and Landing) for which more than a hundred projects exist worldwide with various configurations. Although e-VTOL vehicles are sometimes presented as a novelty, they use similar technologies to helicopters, with much less range, speed and endurance, due to the weight of batteries. The main advantage of e-VTOL is the absence of local emissions and low operating costs if electricity is cheap. Turn-around times depend on recharging batteries or exchanging battery packs. The safety and certification issues are similar for e-VTOLs or for helicopters that have operated for decades in urban environments. The take-off and landing phases absorb most of the energy of e-VTOLs on short flights, and thus an aborted landing, with re-climb and re-descent may require significant reserves.

The claims that e-VTOLs could replace cars and UAM eliminate congestion in roads are too optimistic. The number of car movements in a large urban area in one day compares with the total number of flights worldwide in a year; clearly UAM is a niche market well below 1% of road traffic in cities. The claim that e-VTOLs can land in a pad anywhere is limited by community noise, even if it is less than for helicopters. In an emergency an e-VTOL may require a rolling landing; thus a vertiport is best thought of as two landing pads connected by short runways. The claim that since e-VTOLs move in three dimensions there is more capacity than for land vehicles moving in two dimensions also requires qualification. Air Traffic Management (ATM) is much more complex than road traffic. Also e-VTOLs may have to share low level airspace with drones, that also claim an expanding market. The low level airspace has been used for a long time for emergency medical flights and police and surveillance services, that have low frequency but must have priority over other users. In conclusion e-VTOL and UAM have a bright future that will gradually unfold as ATM, certification, safety, infrastructure and other issues are resolved.

3.29 Hybrid Thermoelectric Propulsion for Regional Traffic

In the case of regional transport aircrafts up to 100 seats and with ranges up to 1000 km, electrification cannot be the sole solution, but holds good promise compared purely thermal propulsion, in a suitable hybrid combination. Aircraft spend most of their time in cruise, when they need much less power than when flying in terminal areas, for climb after take-off and orbiting waiting to descend to land. Thus designing the engines for cruise gives a significant efficiency gain, if additional power can be found for terminal flight phases. Taking into account the limited duration of the latter, battery power may be feasible and fuel cells preferable due to superior power-to-weight ratio. Multiple challenges remain, besides the safety issues of over/undercharging, runaway fires or explosion, that also apply on the ground, and require reliable control systems. As always in aircraft weight is a problem, not only for large battery packs, but also for fuel cells, in the latter case due to the "plant", that is the ancillary equipment needed for safe operation. For aeronautical applications both the maximum power and power density of fuel cells must be improved over what is available. The power requirements on the electrical part of hybrid propulsion increase giving allowance for aborted landing and turn-arounds or for diversion to another airport.

The use of electric power for propulsion involves the three stages of generation, transport and final drive, with the intermediate transport phase being the most critical at high power levels. Electricity may be provided by batteries or fuel cells for lower powers or by gas turbines driving electric generators up to very high powers, so generation is not the main issue. Nor the driving of propellers by electric motors, whose efficiencies above 90% far exceed the 40-60% achievable with Internal Combustion Engines (ICEs). The critical issue is that an aircraft in flight needs megawatts of power, and transferring that energy in electric forum implies thousands of Volts and Ampère. High voltages can cause electromagnetic interference, and arcing and sparks occur more easily in the thin air of higher cruising altitudes. Electric currents of the order of thousands of Ampère cause strong dissipation, that is not only an energy loss, but also a source of heat difficult to dissipate in flight. Transport of electric currents without electric resistance in supraconducting cables needs temperatures close to absolute zero and may not work at high powers far from the ground state of matter. Very strong magnetic fields are generated in laboratories on the ground using integrated electric generators – effectors that avoid the transport of large electric currents over some distance. Until high-powered integrated electric generator-motors can be developed, hybrid thermo electric propulsion may be limited to regional aircraft, with no alternative to thermal propulsion for medium or long-range airliners.

3.30 Hydrogen Energy for Medium Range

Beyond 100 seats and 1000 km thermal engines are needed, and burning hydrogen rather than fossil fuels is a far cleaner alternative. The main limitation is the low volumetric power density of hydrogen requiring large fuel tanks in the case of Liquid Hydrogen (LH) and worse for gaseous hydrogen. Hydrogen tanks aft of the cabin rear bulkhead in an extended fuselage can be sufficient for a regional aircraft up to 100 seats with a range up to 1000 km, with turbine cruise engines burning hydrogen also used in fuel cells for extra power in terminal flight. For ranges in excess of 4000-6000 km the volume and drag of hydrogen tanks becomes prohibitive in terms of aircraft design. For ranges between 1000 and 6000 km, and up to 200 seats, turbine power with hydrogen fuel is feasible if substantial tank volume can be found. The most voluminous aircraft configuration with low drag is the flying wing, since the long wing chord allows a thick airfoil and enables a large volume and high lift to drag ratio. This leaves the problem of fitting a passenger cabin and large hydrogen fuel capacity in a flying wing.

A conventional aircraft has an optimal structural configuration with a pressurized cylindrical fuselage and liquid fuel in the wings. In the case of a flying wing the passenger cabin should still be a cylinder for pressurization and the tanks for LH also cylinders (excluding spheres that waste more volume). A flying wing with internal pressurized cylinders for the passenger cabin and LH tanks would need a complex support structure, besides some configuration issues. For example if the passenger cabin was a long cylinder along the centreline with cylindrical LH tanks at the sides, at least two problems would arise: (i) it would be difficult to meet the certification requirement of passenger evacuation in no more than 90 seconds from half the exits at one end of the fuselage; (ii) passengers might not feel too comfortable in a windowless cabin flanked by LH tanks. Placing the passenger cabin outboard instead of at the centreline would reduce cabin height and cause larger roll accelerations in banked flight in turns. The only reasonable alternative might be a wide and short forward passenger cabin with as many windows and emergency exits as possible, but less straightforward to pressurize than a cylindrical cabin. The cylindrical LH tanks behind the cabin could cause some weight distribution problems as the fuel is consumed during the flight and the tanks become empty. Since hydrogen is relatively light, even in LH forum, this might be a tractable stability and control problem.

3.31 Sustainable Fuels for Long-range Flight

For long range flights beyond 6000 km and 250 seat none of the preceding alternatives is feasible: (i) batteries would be far too heavy for the aircraft to leave the ground; (ii) fuel cells cannot come remotely close to the power needed; (iii) electric power in the tens of megawatts cannot be safely transported in an aircraft; (iv) hydrogen tanks with sufficient capacity would cause too much drag. As an example, in the case (iv) trying to increase range with more hydrogen fuel, would require larger LH tanks, increase drag and the extra power needed would consume the additional hydrogen, with no improvement in range. For high capacities above 250 seats and long ranges of more than 6000 km there is no viable short-term option, and perhaps not even in the mid-term, to sustainable aviation fuels. Ideally these should have: (i) a comparable volumetric and mass energy density to kerosene to give similar flight performance and range with the same fuel tanks; (ii) meet similar flammability, volatility and other standards to allow the use of the same operational procedures and refuelling infrastructure; (iii) have similar combustion properties to allow the use of the same engines or with a minimal modification. If the ideal "drop in" synthetic fuels cannot be found then modification have to be made to current practices.

Coming back to environmental impact, and considering only local emissions: (i) electric power is in principle emissions free or could cut emissions by up to 80-90%; (ii) hybrid power could cut emissions by up to 30-60%, and more if the hydrogen is used; (iii) hydrogen could be almost emissions free as electric propulsion; (iv) alternative synthetic fuels would not be "emissions free" but could be "carbon neutral". For example if the synthetic fuel is obtained combining hydrogen with carbon dioxide taken from the atmosphere, its burning cannot put more carbon dioxide into the atmosphere than was taken away, and it is carbon neutral. If the synthetic fuel comes from plants or algae that have grown consuming carbon dioxide from the atmosphere, then it will not be emissions free but can be carbon neutral. However synthetic fuels should not compete with food crops or reduce arable land, as might be the case of ethanol from sugar cane. There are many potential sources of synthetic sustainable aviation fuels, from urban, organic, rural and forest waste to algae blooms. The main issues are environmental benefit, production capacity and cost premium over fossil fuels. The multiple possibilities in terms of emerging technologies and available fuels could affect the evolution of the Airbus-Boeing duopoly from the current to future generations of aircraft.

3.32 Current Status of the Airbus-Boeing Duopoly

Airbus has risen over four decades from an upstart to an equal player with a roughly 50:50 share in the duopoly with Boeing. Boeing still has the lead in TA, while the balance tilts towards Airbus in SA, with the mid-market A321XL/XLR tipping the scales to 60:40 in Airbus favour. The production of TAs is being cut further after Covid-19. The B787 and

A350 will certainly survive as the main competitors, whereas the A330neo might not contrary to Airbus claims, and the B777X is unlikely to become the profitable success Boeing claims.

Although TA have much higher value per aircraft than SA, the latter will increase in overall market value by sheer numbers, with the Covid-19 and post-Covid-19 trend to smaller aircraft for acceptable load factors with less traffic. Boeing is in a poor position in all three sub-sectors of SA. In spite of the B737MAX accidents, Boeing retains a loyal customer base, and this "central" SA sector is where it competes better with the accident free A320neo. In the lower end of the SA sector, the Airbus-Bombardier deal bring a modern and efficient C-series re-badged A220, with no Boeing counterpart; the smaller Embraer E-series might not compete too well with the larger A220, and the collapse of a late reactive Boeing-Embraer deal left Boeing with no competitor at all, rather that smaller B737 models that do no better than the A319. The biggest gap in at the upper end of the SA market, where the stretched Boeing B737-9110 can hardly compete with the intercontinental and long-range capabilities of the A321LR/XLR. The latter was the only big seller before Covid-19, stealing sales from TA for medium range routes 3000-6000 nm up to 250 passengers, and accounting for most of the growing gap in favour of the A320 family versus the B737 family.

3.33 The Boeing MMA and FSA Prospects

Boeing is left in a catching-up mode in the SA market. Not only because it has to bring back into service 385 B737MAX grounded by airlines and in addition deliver 470 new aircraft that were parked as soon as they left production lines. Worse Boeing has no real competition for the A321LR/XLR unless it develops an all new aircraft, because the B737/New Generation/MAX in its third generation lacks further development potential still available in the second-generation A320/neo. Boeing did not wish to develop the third generation B737Max and hoped airlines would wait for an all-new replacement later in the decade: the success of the A320neo, as the Airbus reaction to the Bombardier C-series, left Boeing no choice other than to bring a third generation B373Max in order to keep their biggest costumers. Boeing contemplated for several years in all-new MMA (Middle of the Market Aircraft) described as a TA with 300 seats and 6000 nm range and superior economics. The last claim looked dubious even with the assumption of lower production costs through increased automation, and after several years of postponed launches, the MMA was cancelled in favour of a more realistic FSA (Future Single Aisle).

The prospects for the Boeing FSA are limited by a major set of obstacles. First the SA market is now so broad, from the A220 at the small end to the A321XLR at the large end, that it can no longer be covered by a single aircraft. Boeing could choose perhaps the FSA to compete at the mid/high end with the A320/A321: this could leave the low end SA market to the A220, and Airbus could develop a long-range A220 to undermine the FSA on thin routes with unbeatable economics. Second the FSA will take at least 5 years to come to service, and its development must start as soon as possible, to stem the increasing SA sales leadership of the A321; however current technology is not yet a generation ahead of that in the B737Max/A321XLR at least as regards engines, and it would take major advances in other areas like aerodynamic configuration or structural / material advances for the FSA to offer significant efficiency / emissions benefits over the current generation; if Boeing succeeded in such a design, with the benefit of hindsight Airbus could counter with a new no less efficient aircraft. Third Boeing would need 10-15 B$ over five years to develop an all new FSA; Airbus could at much lower cost bring into service sooner further A220 and A321XLR developments to undermine the FSA market, and then deliver a further blow using the revenue to develop an all new aircraft with insight to make it superior to the FSA. Boeing is in a catch-up mode in the SA market, only disguised temporarily by the Covid-19 pandemic. After recovery the 60:40 split may shift further in favour of Airbus; with Boeing struggling to catch-up in the SA market and Airbus having most cards to play to retain and reinforce leadership. Boeing may not be able to compete on its own in the long term, in which case an intervention by the American government in the second largest defense contractor is possible, and the Covid-19/B737Max bailout of 60 B$ may not be the last. The Airbus vs. Boeing position could be further strengthened in the future if Airbus leads the greening of aviation with electrified propulsion and the use of hydrogen and synthetic fuels.

3.34 The Transition from Fossil to Hydrogen Propulsion

The new European Green Deal strongly supports a new environmentally friendly hydrogen economy, including the aviation sector, that is one of the most challenging applications, both in technology and infrastructure. There is a sizeable list of major hurdles to be overcome, starting with six (i) to (vi) on the technology. First (i) for acceptable tank volume and refuelling time hydrogen must be used in liquid form, requiring temperature below 4 K at all stages prior to combustion; although liquid hydrogen (LH) has been used as cryogenic fuel for rockets for more than half a century, a rocket flight of a few minutes puts less cooling and insulation problems than an aircraft flight of several hours. Second (ii) aviation as the safest means of transport requires an overall safety level 10^{-6} to 10^{-8} several orders of magnitude greater than the 10^{-2} of rockets, demanding higher grades of equipment and systems; third (iii) hydrogen is the lightest element and very volatile, and losses must be considered in long flights at high altitudes with low atmospheric pressure; fourth (iv) evaporation of hydrogen releases heat, that could ignite a fire or explosion, unless quick venting is assured; fifth (v) combustion of liquid hydrogen is not as straightforward as of gaseous hydrogen due to the intermediate evaporation process; sixth (vi) and last but not least certification and operations will differ significantly from current aircraft fuel and propulsion systems requiring new standards and safety procedures.

As if six technological challenges were not enough there are at least another eight (vii) to (xiv) potential non-technological barriers. First with (vii) the need for major hydrogen refuelling infrastructure at airports, with implications at several levels. At political level (viii) some oil producing regions of the world might not welcome hydrogen at their airports, if economic prevail over environmental issues. Second (viii) if Europe gains a lead in hydrogen propulsion for aircraft, some of its competitors might choose to limit operations simply by not providing hydrogen fuelling facilities at airports. Third (ix) a combination of political and economic obstacles limiting the availability of hydrogen to airports and other areas of the world could prevent break-even of an hydrogen aircraft program, as happened with Concorde which was easily discriminated against as the first civil supersonic transport. Forth (x) the potential political and economic obstacles (vii) to (ix) to hydrogen supply at airports could be easily disguised by at least four (xi) to (xiv) local issues that could occur. First (xi) the investment in expensive hydrogen refuelling infrastructure may not be justified, because it does not apply to long range aircraft, and is limited to less than 20% of total fuel needs. Second (xiii) the option of local production of hydrogen would add further cost and require space and planning permissions. Third (xiii) the alternative of bringing in hydrogen in a gasoduct would require large tanks, again raising space and safety issues. Fourth (xiv) and final near airport communities might object to major hydrogen facilities, although by that time roadside hydrogen fuelling stations should already be well established. The status of the Airbus-Boeing duopoly and emerging technologies for clean aviation will drive the configuration of the next generations of airliners.

3.35 The Next and Following Generation of Aircraft

The Covid-19 pandemic has caused a sharp decline in air transport and the aircraft market, in which all are losers to a smaller or greater extent, and no one can claim any success other than surviving. When emerging from the Covid-19 crisis, the pre-Covid-19 shift in the Airbus-Boeing towards Airbus should become more evident. Also with Boeing in a catch-up mode and Airbus with the upper hand in the SA market gaining importance relative to the TA market the Airbus advantage could increase beyond the capabilities of Boeing on its own. Airbus and the European Aeronautical Research, Development and Innovation (RDI) sector is surviving through the Covid-19 pandemic putting new resources on technology for clean aviation, namely (a) electrification, (b) hydrogen and (c) other sustainable fuels. On the other hand there is plenty of development potential left in traditional technologies like aerodynamics propulsion, materials, structures, production, avionics, control, computing, sensors and telecommunications. And there is much promise in emerging technologies, like additive manufacturing, artificial intelligence, big data and operational aspects, like air traffic management, weather hazards, cybersecurity and resistance to malicious acts remain as relevant as ever in requiring advances to meet evolving needs. Thus aeronautics RDI needs to cover all these aspects to ensure that the next generations of aircraft remain competitive, by combining the most effective among the mature technologies.

Of the three clean aviation technologies (c) sustainable fuels is the most promising in the near term because: (i) it has the largest impact, since 80% of aviation fuel consumption is long-range flights, for which electrification or hydrogen is not an alternative; (ii) alternative sustainable fuels in "drop-in" cases, or with modest modification of existing procedures and infrastructure are easiest to implement in operations. Considerable challenges remain in producing the required large quantities at reasonable cost. The technologies for (b) electric and hybrid propulsion have near and mid-term promise for local and regional transport up to 1000 km and 100 seats and can make a contribution to local environment to complement (c) synthetic fuels for local and global environments. The technologies for hydrogen propulsion in the 100-250 seat 1000-6000 km range are the most challenging and longer term. They are worth developing vigorously for medium range aircraft of the next generation, even if they become fully mature in the generation after, and have only partial use in the next generation. The traditional technologies should not be neglected in any case, as they are the background and safety next for the next generation. The next generation of aircraft will use developments of current technologies together with new technologies that may become sufficiently mature by then.

3.36 Conclusion

The main concern in aviation at present is the emergence from its biggest ever crisis in the form of the Covi-19 pandemic. The success of the vaccination campaign will determine when airline traffic will recover with the removal of confinement measures and return of passenger health confidence. Harmonized confinement rules and health safety procedures on a regional and worldwide context would be highly beneficial for an earlier return to normal flight operations. The remaining major question is if traffic will return to 2019 pre-Covid-19 levels and if so when, considering both professional and leisure travel. Concerning short-term professional travel for small meetings, like travel outward one-day, meeting the next day, and return the third day, teleconferencing is a more efficient alternative. Conversely for a week long large congress or fair with hundreds or thousands of people, travel time is less of an issue and teleconferencing does not provide comparable opportunities for direct informal interaction. Concerning leisure travel, the recommendations to stay home or take holidays in country may have changed the habits of some, but many other will eager to compensate for unwanted confinement. The attractions of travel to see the real thing and meet the real people will not be replaced by the virtual world, that in many case stimulates interest in the actual experience. Thus air transport is expected to regain 2019 levels in 2024-2029 according to Eurocontrol depending on the success of anti-Covid-19 measures, and should resume historic growth after surpassing 2019 levels. The recovery of air transport will entail that of associated services and also of the aircraft industry. The difficult conditions of aviation in the Covid-19 pandemic, and the uncertainties surrounding the time and scale of recovery, should not prevent a farther reaching look into the future.

Aviation is perhaps at the biggest crossroads in its century old existence. The Covid-19 pandemic is the biggest crisis in the history of aviation entirely due to causes outside the aeronautical sector. The recovery from the Covid-19 pandemic will take place in a different world with much greater environmental concerns. In order keep the ever increasing efficiency while reversing the environmental impact new technologies will revolutionize aviation broadening its scope with urban air mobility and increased use of stratospheric upper space by rocket launches and hypersonic vehicles. Thus aviation will emerge from the Covid-19 pandemic into an era of technological possibilities that will mark the difference between the XXth and XXIst centuries. The traditional technologies will continue to evolve and combined with emerging and new maturing technologies will enable a wider variety of vehicles and missions, with more design and operational options based on advances in RDI.