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Impact of tank gravimetric efficiency on propulsion system integration for a first-generation hydrogen civil airliner

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Abstract

Civil aircraft that fly long ranges consume a large fraction of civil aviation fuel, injecting an important amount of aviation carbon into the atmosphere. Decarbonising solutions must consider this sector. A philosophical-analytical feasibility of an airliner family to assist in the elimination of carbon dioxide emissions from civil aviation is proposed. It comprises four models based on the integration of the body of a large two-deck airliner with the engines, wings and flight surfaces of a long-range twin widebody jet. The objective of the investigation presented here is to evaluate the impact of liquid hydrogen tank technology in terms of gravimetric efficiency. A range of hydrogen storage gravimetric efficiencies was evaluated; from a pessimistic value of 0.30 to a futuristic value of 0.85. This parameter has a profound influence on the overall fuel system weight and an impact on the integrated performance. The resulting impact is relatively small for the short-range aircraft; it increases with range and is important for the longer-range aircraft. For shorter-range aircraft variants, the tanks needed to store the hydrogen are relatively small, so the impact of tank weight is not significant. Longer range aircraft are weight constrained and the influence of tank weight is important. In the case of the longest range, the deliverable distance increases from slightly over 4,000 nautical miles, with a gravimetric efficiency of 0.3, to nearly 7,000 with a gravimetric efficiency of 0.85.

Nomenclature

Δ	change
BPR	bypass ratio
FCV	fuel calorific value (lower) (MJ/kg)
HVLER	Aircraft variant – Hydrogen Very Large Aircraft Extended Range
HVLLR	Aircraft variant – Hydrogen Very Large Aircraft Long Range
HVLMR	Aircraft variant – Hydrogen Very Large Aircraft Medium Range
HVLSR	Aircraft variant – Hydrogen Very Large Aircraft Short Range
ISA	International Standard Atmosphere
MLI	multi-layer insulation
NOx	nitrogen oxides
SFC	specific fuel consumption (kg/s/MN)
SLS	sea level static
TET	turbine entry temperature (K)
η_{grav}	Tank Gravimetric Efficiency = Fuel Weight/(Fuel + Tank Weight)

This paper is a version of a presentation due to be given at the 2022 ISABE Conference

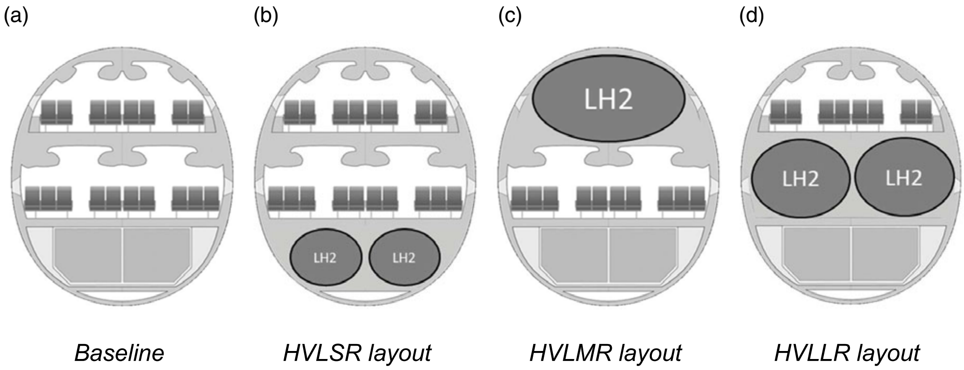

Figure 1. *A Baseline, b HVLSR layout, c HVLMR layout, d HVLLR layout. Image from Ssolbergj and Tillier – Creative commons licenced modified by authors.*

1.0 The Aircraft Family

Extreme decarbonisation is promised for 2050, but emerging is a strong consensus that this may be too late. The use of hydrogen as a civil aviation fuel is an alternative to decarbonise aviation [2, 3, 20]. Switching jet engine fuel to hydrogen promises to decarbonise civil aviation if hydrogen production is carbon-free. Furthermore, hydrogen offers the challenge and potential to deliver much lower NOx than hydrocarbon fuels [3]. Hydrogen also removes other harmful emissions such as unburnt hydrocarbons, aromatic compounds, sulphur oxides, soot and smoke. These plus careful flight management are expected to lead to contrail reduction [11, 21]. Hydrogen for civil aviation is currently becoming increasingly popular, but it requires large changes in aircraft, infrastructure, management, safety and regulation. Such a change will be expensive. However, the authors firmly believe that, socially and economically, it is a far superior alternative to the vast economic damage that will result from reducing air traffic. Hydrogen is a technology solution to provide combined sustainability in environmental, economic and social terms. With the appropriate investments an introduction in approximately 15 years is conceivable.

A major challenge with the use of hydrogen is the low density of the fuel, even in its liquid form. For the present study, liquid hydrogen is stored at 21.5K and 1.25 bar, so insulation will require a great deal of attention. The authors based their tank design philosophy on expanded analytical studies informed by previous Cranfield work [5, 7, 20]. Tanks need to be insulated to prevent heat leakages into the liquid hydrogen with no need for an active cooling system. Low-pressure storage does not demand thick walls. Fuel withdrawals through engine feeding lines reduce tank pressure and temperature, while heat leakages increase them. Pressure and temperature are regulated through two mechanisms. To prevent excessive increase in pressure and temperature, due to heat leakages, a bleed valve lets hydrogen escape to a venting space in a safe way, restoring pressure and temperature inside the tank. To avoid undesirable low pressure inside the tanks, warmer or preheated hydrogen can be fed back into the tanks from feeding lines.

Figure 1 shows the cross-section of the fuselage of the aircraft used for the study; it also illustrates the cabin arrangements and tank locations of three of the four members of the family. The aircraft has two decks to carry passengers; the lower deck larger than the upper one. The aircraft also has large underdeck storage for storage and/or cargo. In Huete et al. [8] the authors proposed three variants of a hydrogen-fuelled airliner derived from this concept: HVLMR, HVLLR and HVLER for medium-, long- and extended-range capability, respectively. The idea of long and extended range applies to hydrogen in this case and implies much shorter flights than the capabilities of a modern conventional airliner. The first, HVLMR, considers the use of the upper deck to house fuel tanks; HVLLR is conceived with the fuel tank in the lower deck; and HVLER is a combination. The baseline weight of the tanks considered here is 1.22 times the weight of the hydrogen contained. These results were communicated in Huete

Table 1. *Comparison of HVLSR, HVLMR, HVLLR and HVLER with the 'design donor' aircraft. Baseline η_{grav} is 0.45 – Note magnitude of tank weight*

	AIRBUS A350–1000,	AIRBUS A380–800	HVLSR	HVLMR	HVLLR	HVLER
Mass (tonnes)						
Ramp	317	577	288	274	304	310
Max. take-off	316	575	287	273	303	309
Max. landing	236	394	275	251	275	276
Max. payload	68	83	80	50	45	36
Operational empty	155	276	194	200	299	238
H2 Tank (gravimetric eff. 0.45)			20	33	51	59
Engines	2	4	2	2	2	2
Cruise thrust/engine (kN)	87	81	84	81	88	90
Static thrust/engine (kN)	432	374	421	406	441	448
Range (nm)	8,700	8,000	1,800	3,300	4,800	5,600
Pax (2 class)	315	555	720	388	332	232

et al. [8] for a baseline gravimetric efficiency (ratio of weight of hydrogen to weight of hydrogen plus tank) of around 0.45. The tank arrangement of HVLER, although not shown in Fig. 1, can be implied from the arrangements of the other members of the family.

For the present study a fourth member of the family is added: HVLSR. This aircraft is conceived as a 'slot relief' solution for very busy airports on the same continent. It offers a useful transcontinental range and a large capacity. In this design the storage or cargo space is used for liquid hydrogen, leaving the use of the two decks for passenger accommodation.

The estimated vehicle capability, for an introduction accelerator philosophy, is good and practical. It does not match the payload or the high ranges of current aircraft using conventional fuels, but it fares well as an introductory accelerator technology to decarbonise aviation. Table 1 shows details of the proposed aircraft and a comparison with the existing 'technology donor aircraft' [8]. Figure 2 shows a schematic arrangement of the four members of the family; Fig. 3 shows the payload-range diagrams of the members of the family calculated from methods derived from [4, 13, 15, 17, 19]; and Fig. 4 shows the design range of the aircraft against the backdrop of civil aviation characteristics [18]. Figure 4 also shows, for the first innovation wave, the contributions of hybrid, electric and fuel cell propulsion juxtaposed with hydrogen propulsion in gas turbines. With a modest tank gravimetric efficiency of 0.45, the range offered by the aircraft family HVLSR, HVLMR, HVLLR and HVLER covers more than 97% of existing aircraft departures and accounts for 90% of total fuel consumption. Furthermore, the authors advocate that the remaining 2% of flights could be carried out adding a stop. In this context, the range of 5,500 nautical miles is considered important because it allows the aircraft to reach the other side the planet with a single stop (see Table 2).

2.0 Impact of Tank Gravimetric Efficiency

During this early investigation it became apparent that the tank gravimetric efficiency is a parameter that will significantly influence the performance characteristics of the integrated aircraft and powerplant. The objective of the work described here is to evaluate the impact of gravimetric efficiency on the integrated performance of the vehicles. Using the methods established in Ref. [9] a detailed parametric analysis was carried out.

In that study the gravimetric efficiency was evaluated for a range of considerations and design philosophies. Figure 5 shows some results of gravimetric efficiency for a particular tank design as a function of insulation philosophies. Given that the subject of the study is the first innovation wave, material properties are assumed to be conventional. Three cases were evaluated: A multi-layer insulation (MLI) arrangement and foam insulation with two different types of insulation.

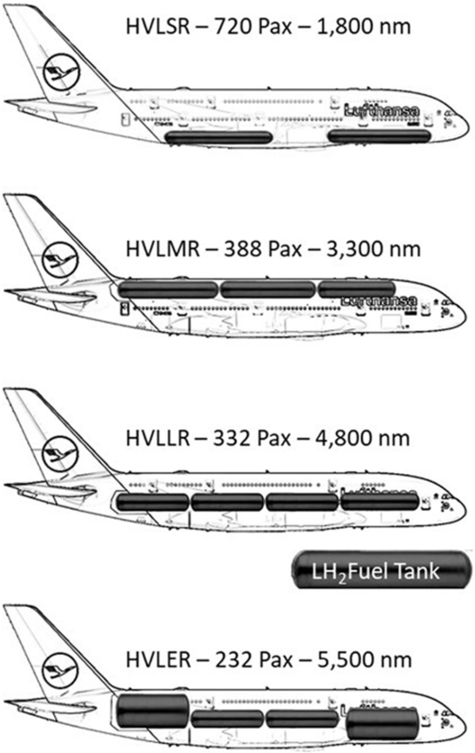

Figure 2. *Four airliner family concepts.*
Images courtesy (Lufthansa 2020 [11]) and modified by the authors.

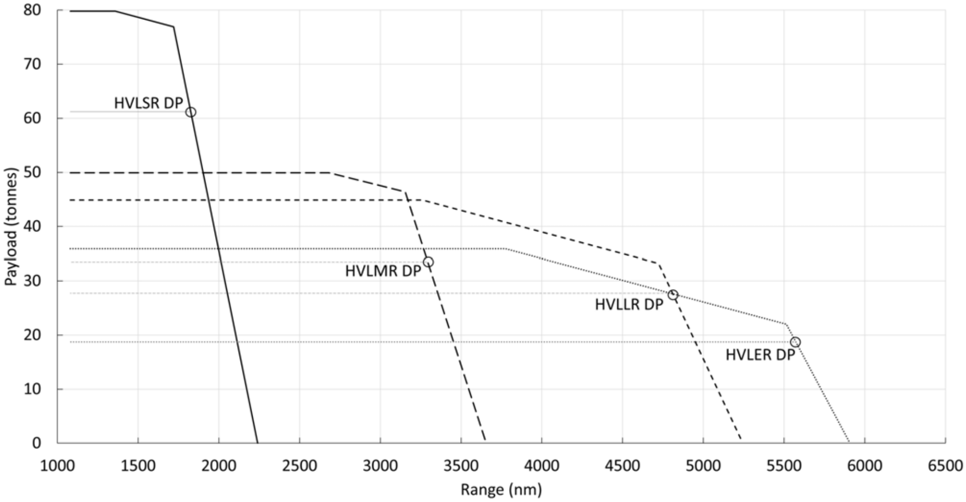

Figure 3. *Payload range diagrams for the aircraft family, for a gravimetric efficiency of 0.45 with the design points of Fig. 2 indicated.*

In Fig. 5, MLI indicates an arrangement with two containers, one inside the other and separated by a vacuum. Stiffened panels make the structure lighter. For this arrangement the primary insulator is the vacuum layer, and the weight of the tank increases as the maximum operating pressure increases. This is because the internal walls of the tank need to be made stronger and heavier to withstand the

Table 2. *Distances between some airports, a measure of the usefulness of the aircraft family (Source Wikipedia)*

Table of distances	nm	km
London – Athens	1,293	2,395
Dublin – Moscow	1,514	2,804
Singapore – Shanghai	2,048	3,792
Boston – Los Angeles	2,241	4,150
Ottawa – Madrid	3,085	5,713
Johannesburg – Rio de J	3,850	7,130
New York – Honolulu	4,330	8,020
Sydney – Honolulu	4,401	8,150
Ottawa – Lagos	4,671	8,651
Ottawa – Buenos Aires	4,882	9,042
Dakar – Mumbai	5,148	9,535
Mumbai – Sydney	5,508	10,200
Montevideo – Nairobi	5,510	10,205
Ottawa – Tokyo	5,583	10,340
London – Singapore	5,879	10,888
London – Buenos Aires	6,009	11,128
Montevieo – Cairo	6,282	11,634
Ottawa – Mumbai	6,582	12,190
Ottawa – Calcutta	6,641	12,300
Athens – Santiago	6,775	12,547

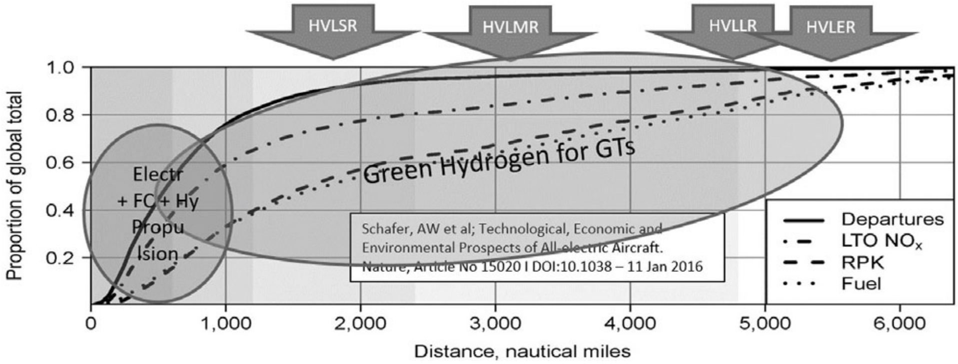

Figure 4. *HVLSR, HVLMR, HVLLR and HVLER capabilities with a baseline gravimetric efficiency of 0.45. Reference (18) annotated by the authors.*

higher pressures. Thus, higher maximum operating pressure results in a lower gravimetric efficiency. The usefulness of a high-pressure capability is to contain the hydrogen boiloff without the need to vent during periods when the fuel demand for the engines is low or null. Venting the boiloff enables a lighter tank but it introduces other issues. This suggests a design dichotomy of lighter tanks with more complex boiloff management or heavier tanks with simpler boiloff management; this design dichotomy deserves detailed attention.

In the case of foam insulated tanks, there are two trends to consider. The first is the impact of insulation. Contrary to the case of vacuum insulated tanks, in which the minimum vacuum thickness provides enough insulation and takes hundreds of hours for the pressure to build up to reach the maximum value, foam insulated tanks have a limited time to maximum pressure or dormancy time. Thus, for a given

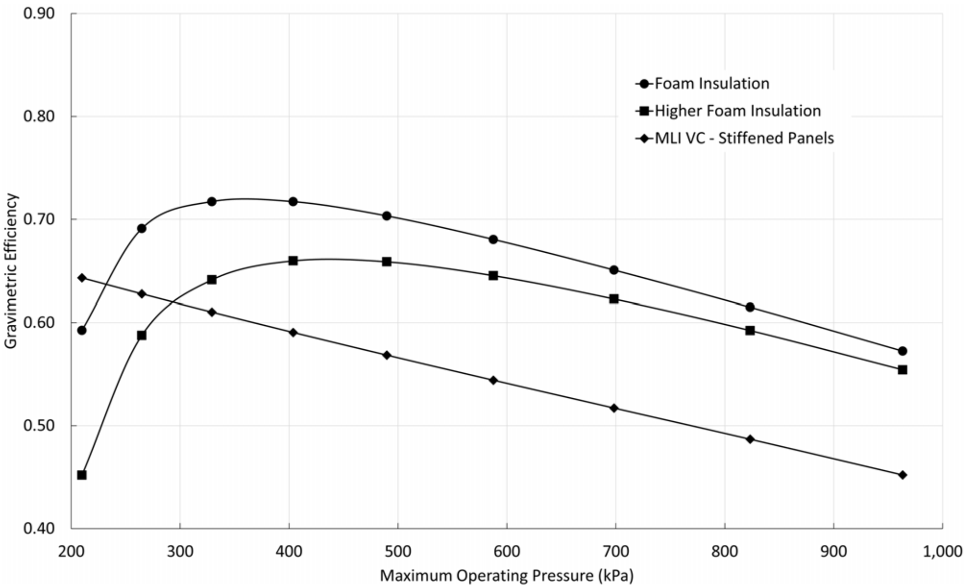

Figure 5. *Gravimetric efficiency of tank options evaluated for a 100m^3 tank. The tank is cylindrical with hemispherical ends, a diameter of 4m and a length of 9.3m.*

dormancy time, the lower the maximum operating pressure, the thicker the insulation required to avoid heat influx and pressure increase. The second is the effect of internal wall of the tank, like vacuum insulated tanks. The sum of the weight of the insulation plus the wall shows a minimum value at some point, which coincides with the highest value of gravimetric efficiency. Figure 5 shows that with relatively conservative technology, gravimetric efficiencies of 0.65–0.70 can be achieved.

In Fig. 5 the trend indicated for 'Foam Insulation' corresponds to a tank that takes 12hrs for the pressure to build up from 160kPa (representative of tank pressure at landing) to maximum operating Pressure in near-to-empty condition. This condition is the fastest pressure rise condition and it could happen on an overnight stop. The trend indicating 'higher foam insulation' corresponds to a 24-hr dormancy time under the same circumstances. Tank wall weight is linearly dependent on maximum operating pressure and does not depend on dormancy time. Insulation thickness is dependent on both maximum operating pressure and dormancy time, and for a longer dormancy time, it moves the design to a lower value of gravimetric efficiency.

The above results were used to determine the range of gravimetric efficiencies to be used in the parametric evaluation. The lowest value and pessimistic boundary of the evaluation was chosen as 0.3. This is in line with McKinsey (2020) [1]. The results of the investigation outlined for Fig. 5 coupled with an optimistic scenario for light material developments, were used to suggest a higher and optimistic gravimetric efficiency boundary of 0.85. These gravimetric efficiency results were then used in the integration evaluation method explained in Ref. [8]. Essentially, an internally developed program evaluates the performance of the aircraft based on weight correlations by Ref. [20] and aerodynamic correlations by Ref. [16]. Engines were assessed using Turbomatch [14]. The program has been validated for large modern existing aircraft – A330/350/380 and B787/777 through several checks: aircraft drag and thrust, payload-range diagrams, and take-off and landing field length are contrasted with those published from the manufacturer. For the hydrogen aircraft, fuselage lay-out is modified to accommodate hydrogen tanks and a reduced passenger capacity is evaluated without exceeding the maximum structural load limit. In an iterative process, optimum wings and engines are down selected to match standard cruise conditions, take-off length and approach speed. Only the impact of tank gravimetric efficiency in tank

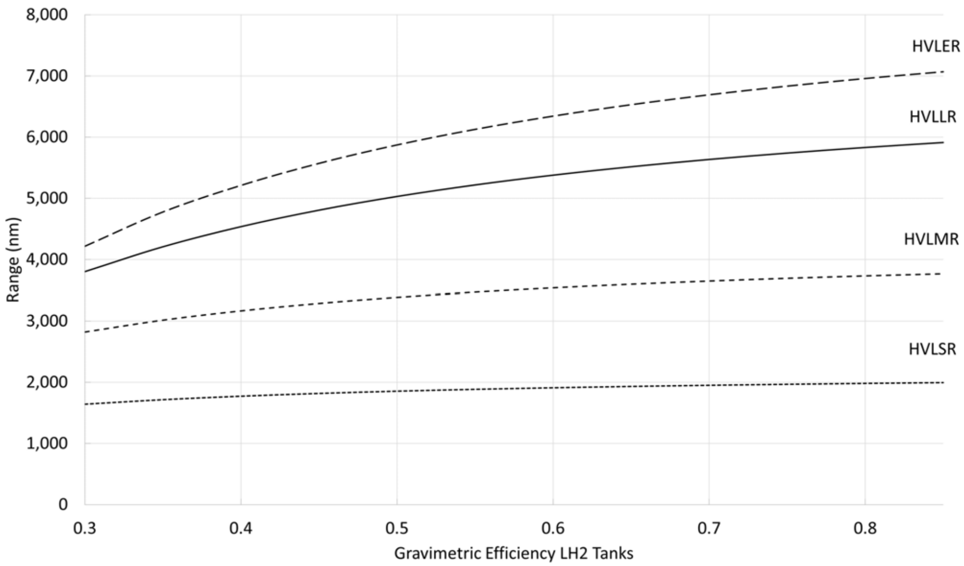

Figure 6. *Impact of liquid hydrogen tank gravimetric efficiency on aircraft range.*

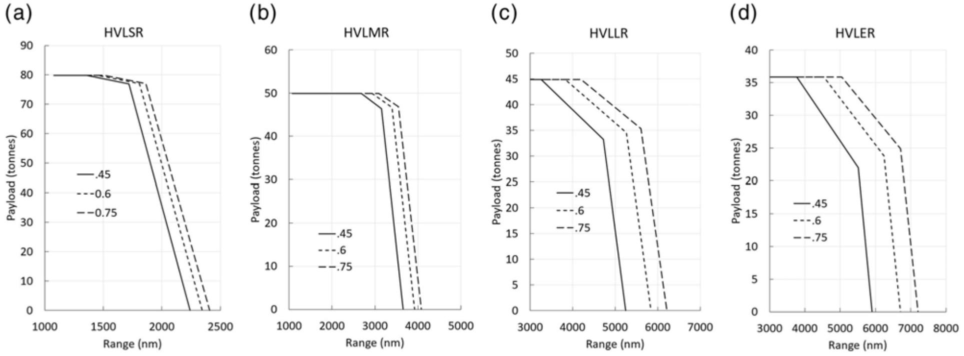

Figure 7. *Influence of* η_{grav} *on the payload range diagrams of the aircraft family.*

weight has been taken into account. Its indirect effect on aircraft operational empty weight though fuselage reinforcements and arrangements has not been accounted for. Therefore, the sensitivity to range shown in this paper should be considered a lower limit, being by and large the expected variation of aircraft performance larger than estimated here due to fuselage arrangement and other nonlinear effects. The results are shown at two levels: change of the design range for the designed passenger capacity and modified payload range diagrams.

Figure 6 shows the range variation of the aircraft with gravimetric efficiency of the tanks. (For each aircraft, the amount of fuel does not change, only the weight of the tanks.) For small tanks, such as those of HVLSR, the impact of changing tank weight is small because the tank weight is a small fraction of the total aircraft weight. This is shown in Table 1. As tanks become larger, heavier they comprise a larger weight fraction. So, for aircraft designs with longer range the increase in range due enhanced gravimetric efficiency is larger. In the case of HVLER the increase in design range is of about 20% from the baseline gravimetric efficiency of 0.45 to the optimistic value of 0.85.

Figure 7 shows three specific examples of the parametric evaluation for each member of the aircraft family and the impact of gravimetric efficiency on the payload range diagram. The cases shown correspond to three values of gravimetric efficiency. The first case is for 0.45; this is compatible with the first evaluation [8] and what was used as a pessimistic baseline. The next value, of 0.60, corresponds to the value of gravimetric efficiency the authors believe is appropriate for the first generation of hydrogen-fuelled aircraft to enter service. The third value of 0.75 corresponds to gravimetric efficiencies that could be implemented in the second or third generation of aircraft [6, 12]. This value of 0.75 is not considered a ceiling; it is rather viewed by the authors as a goal achievable after three decades of development and experience with hydrogen- fuelled airliners. Beyond this the law of diminishing returns sets in and the curves shown in Fig. 6 flatten considerably.

3.0 Conclusion

This paper describes a techno-philosophical investigation into a family of four derivatives of a propulsion integration design for the first innovation wave. The models are based on the careful integration of a large twin deck civil transport with the wings and engines of a long-range widebody twinjet. The investigation is backed by detailed calculations. These four hypothetical configurations have different tank locations for storing liquid hydrogen fuel to achieve different payload range objectives. The impact of hydrogen tank weight on the attributes of this family of civil aircraft using hydrogen fuel in gas turbine engines is carried out could be developed using the main components of two existing aircraft as a basis for the design. The baseline was conceived with a gravimetric efficiency of 0.45.

This family exhibits a payload and range that is significantly smaller than the ‘donor’ aircraft; however, its characteristics are sufficiently attractive to be considered as a launch option for a first generation zero carbon aircraft. The baseline range of HVLER is strategically chosen to allow flights from any point on the planet to any other with just one stop. The focus of this study is the impact of the liquid hydrogen tank weight on the performance of the aircraft. A range of tank gravimetric efficiencies was analysed based on a detailed evaluation and the parametric analysis. The range chosen was from a pessimistic 0.3 to an optimistic of 0.85. The authors consider that a gravimetric efficiency of 0.7 is a feasible proposition for an entry into service in 12–15 years.

With a gravimetric efficiency of 0.7 the HVLLR would be able to have a range of over 5,500 nm, giving it the capability of reaching any point on the planet with a single stop. With this gravimetric efficiency, HVLER’s range would extend to more than 6,500 nm, offering a wide scope for service. With this gravimetric efficiency the family would be able to cover nearly 98–99% of existing large capacity requirements.

It must be noted that airport and aircraft safety can be managed with careful attention to detail and appropriate investments, and there is the need to adapt certification rules. This will give rise to a longer platform development process because in parallel with the development of the aircraft, certification rules will need to be adapted. This family of aircraft could be of fundamental assistance in the certification process given that certification rules will need to be updated. Their similarity with existing platforms is such that it will allow the focus of adapting certification rules on the hydrogen-related systems. This is, of course, not a trivial task, but the concept could give rise to the acceleration of decarbonisation.

At the beginning a small number of hubs would be fitted with the capability of refuelling hydrogen. However, one useful feature of hydrogen is its light weight, so the penalty for carrying extra fuel is much smaller than that for conventional fuel. This would permit the aircraft to serve many destinations without refuelling, i.e. having pre-loaded the fuel at a hydrogen hub, land, disembark and embark passengers without refuelling in a conventional airport and flying on to another hydrogen hub. The authors strongly believe that seawater electrolysis with green electricity is required, requiring coastal hydrogen production stations. Preliminary investigations show that with two hubs, whole continents can be covered with these arrangements, and even single hub operations are attractive. A certified interaircraft refuelling kit for land operations would need to be designed to fit in the large cargo hold of HVLLR. This could be loaded onto an aircraft to rescue another in the case of a ‘stranded’ situation in a conventional airport.

Undoubtedly all these developments will cost hundreds of billions of pounds (or euros or US dollars). In fact, the more the details of this first generation of hydrogen aircraft are explored, the stronger becomes the view of the authors that the main obstacle for developing green civil aviation is the short-term cost of the transition. However, the authors firmly believe these costs are acceptable to migrate to zero-carbon, an industry that brings so many technical, social and economic benefits.

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