

Conceptual design-optimisation of a subsonic hydrogen-powered long-range blended-wing-body aircraft

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ABSTRACT

The adoption of liquid hydrogen (LH₂) holds promise for decarbonising long-range aviation. LH₂ aircraft could weigh less than Jet-A aircraft, thereby reducing the thrust requirement. However, the lower volumetric energy density of LH₂ can adversely impact the aerodynamic performance and energy consumption of tube-wing aircraft. In a first, this work conducts an energy performance modelling of a futuristic (2030+) LH₂ blended-wing-body (BWB) aircraft (301 passengers and 13,890 km) using conceptual aircraft design-optimisation approach employing weight-sizing methods, while considering the realistic gravimetric and volumetric energy density effects of LH₂ on aircraft design, and the resulting reduction in aircraft thrust requirement. This study shows that at the design point the futuristic LH₂ BWB aircraft reduces the specific energy consumption (SEC, MJ/tonne-km) by 51.7–53.5% and 7.3–10.8%, compared to (Jet-A) Boeing 777-200LR and Jet-A BWB, respectively. At the off-design points, this study shows that by increasing the load factor for a given range and/or increasing range for all load factor cases, the SEC (or energy efficiency) of this LH₂ BWB concept improves. The results of this work will inform future studies on use-phase emissions and contrails modelling, LH₂ aircraft operations for contrail reduction, estimation of operating costs, and lifecycle climate impacts.

Nomenclature

Abbreviations	
AR	Aspect ratio
ATR	Average temperature response
BWB	Blended wing body
COC	Cash operating cost
GTF	Geared turbofan
GTOW	Gross take-off weight (in kg)
LH ₂	Liquid hydrogen
LNG	Liquid natural gas
LTA	Large twin aisle
L/D	Lift to drag ratio
MTOW	Maximum take-off weight (in kg)
N+2	2030+ timeframe
N+3	2035+ timeframe
OEW	Operating empty weight (in kg)
PAX	Passengers

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RoC	rate of climb (in m/s)
S	Wing area (in m ²)
SEC	Specific energy consumption (MJ/tonne-km)
SI	Supplementary information
SLS	Sea level static
SPK	Synthetic paraffin kerosene
T	Thrust (in N)
TOC	Top of climb
TSFC	Thrust specific fuel consumption
T/W	Thrust to weight ratio
UHB	Ultra-high bypass ratio
V	Flight speed (m/s)
VLTA	Very large twin aisle
W	Aircraft weight (in kg)
Greek symbols	
η	Gravimetric index
Subscript	

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F	Fuel (weight) (in kg)
F _{block}	Block fuel weight (in kg)
F _{total}	Total fuel weight carried at mission start (in kg)
F _{total, max}	Maximum weight of total fuel carried at mission start (in kg)
max	Maximum value
NASA	NASA BWB aircraft
wet	Aircraft wetted area (in m ²)
∞	Ambient or atmospheric (in service ceiling)

1. Introduction

Currently, the aviation industry's share to the total man-made climate forcing is ca. 3.5% [1,2]. Despite considering the effects of COVID-19, air-traffic is expected to double between 2023 and 2042 [3], thereby exacerbating aviation's climate footprint considering the business as usual scenario. Industry forecasts suggest that a combination of low-carbon fuels and advanced technology could address 80% of the measures needed for aviation to achieve carbon-neutral growth [4,5].

Most airlines retired their very large twin aisle (VLTAs: A380 and/or B747) aircraft during COVID-19 lockdown of 2020 and thus in the next few decades large twin aisle (LTA, such as B777, B787, A350, etc.) aircraft will likely be the most common air vehicles for long-range travel [6]. It was observed through authors' previous study [5] that decarbonising the long-range aviation domain is difficult, and of many alternative energy vectors and propulsion technologies explored (including batteries and fuel cells) only liquid hydrogen (LH₂) and 100% synthetic paraffin kerosene (SPK) are the only two alternatives to Jet-A for a tube-wing (conventional) LTA aircraft.

Different blending ratios of SPK [7–10] and/or 100% SPK show a maximum improvement in energy consumption of 0.3% [5,11]. Currently, only blended SPK from different manufacturing pathways (maximum 50% blending) is approved as an alternative fuel for civil aviation use as drop-in fuel (no aircraft modifications required for its use) and 100% SPK is a non-drop-in fuel [5,7–10].

Recently, industry efforts on hydrogen engine testing and hydrogen aircraft R&D has gained momentum [12–16], especially with the unveiling of the hydrogen powered blended-wing-body (BWB) Airbus ZEROe concept [17]. In authors' recent study [6], it was found that by enhancing aircraft aerodynamics and overall efficiency, the specific energy consumption (SEC) of LH₂ powered long-range tube-wing aircraft could be dramatically reduced, in comparison with a present-day Jet-A aircraft. Previous studies [6,18–21] have qualitatively identified that employing a BWB airframe for LH₂ use could be a promising solution. In comparison with a tube-wing airframe, a BWB airframe enables better integration of LH₂ storage since it enhances aerodynamic performance and provides higher internal volume for cryogenic systems storage. Thus, a BWB airframe appears to be a better candidate for LH₂ aircraft.

Considering the above discussion, the scope of the present work is limited to the conceptual design-optimisation and energy performance evaluation of a combustion-based LTA [~300 passengers (PAX) and 7,500 nautical miles (13,890 km) design range] BWB LH₂ aircraft. Fuel cells are not explored or reviewed in this work. Furthermore, the literature review below is focussed only on the conceptual design-optimisation and energy performance evaluation of combustion-based LTA BWB LH₂ aircraft. The reader is advised to explore works by: Brewer [22] for tube-wing LH₂ aircraft design performance, cryogenic tanks, and other aircraft subsystems design; and review studies by Adler et al. [23] and Tiwari et al. [20] on LH₂ aircraft subsystems, combustors and fuel cell systems. None of the studies on hydrogen aircraft design and performance [5,6,17,21,23–50,50–82] provide a detailed design and optimisation and energy performance evaluation of a combustion-based LTA BWB LH₂ aircraft for a reduced thrust requirement, compared to its Jet-A variant (or a baseline). The literature review

below concisely reports the studies with their shortcomings only for a long-range LTA category.

Study [72] considered designs for both tube-wing and BWB aircraft powered by LH₂ for short-, medium- and long-range. The analysis does not undertake original aerodynamic performance estimation and assumes similar lift-to-drag ratio for the hydrogen aircraft as that of the reference aircraft. It does not provide energy performance comparison for any of the LH₂ BWB aircraft with the respective Jet-A BWB aircraft, and these LH₂ aircraft are infeasible designs as they do not meet the design range as that of the baseline.

Study [78] primarily models a 200 PAX aircraft powered by different alternative fuels including LH₂, using both tube-wing and BWB airframe (in GENUS framework). The authors apply the method to a 400 PAX and 800 PAX aircraft. Overall, the authors analyse the life cycle effects and the aircraft range considerations are from 3,700 km to 15,700 km for each of the three (PAX) types of aircraft. However, no aircraft design details [gross take-off weight (GTOW), operating empty weight (OEW), wing area, span, etc.] are disclosed by the authors. Additionally, data on inflight energy consumption of BWB LH₂ aircraft and comparison with Jet-A BWB or tube-wing is not available.

Study [73] conducts design and energy performance examination of a (100%) LH₂ powered BWB aircraft (combustion based). However, this LH₂ BWB aircraft is a large quad or VLTA BWB aircraft type (PAX capacity similar to a Boeing 747 aircraft), which are retired by major airlines from the global fleet.

Studies on long-range LTA LH₂ aircraft focus only on tube-wing aircraft performance modelling [5,6,18,22,24–28,54,65,76,79–81], or conduct systems-level preliminary design consideration of a twin tube-wing LTA LH₂ aircraft concept [51], or the aircraft is not completely fuelled by LH₂ [51,74]. Other studies examining LH₂ (combustion) aircraft have: (i) considered smaller range and/or payload combinations than a typical design point of long-range LTA (class of) tube-wing and BWB aircraft [18,54,65,75,77]; (ii) substantially modified the cruise altitude and/or Mach number for the LH₂ tube-wing and BWB aircraft, thereby resulting in different aircraft design characteristics, in comparison with a typical baseline or long-range LTA aircraft [75,76,79]; and (iii) simulated the energy performance a two-fuel (100% SPK and LH₂) BWB aircraft where LH₂ fuels a proportion of the aircraft energy requirement [74].

Overall, it is clear from the above discussion on an up-to-date literature review of different studies [5,6,29–38,17,39–48,21,49–58,23,59–68,24,69–78,25,79–82,26–28] that there is a requirement for a study which quantitatively evaluates the energy performance of a long-range LTA BWB aircraft powered by LH₂ with typical LTA aircraft design characteristics. This motivates the present work. Additionally, in authors' previous studies [5,6], they observed that the gross take-off weight (GTOW) of (tube-wing) LH₂ aircraft significantly reduces (on the order of 20+%, due to the use of lighter fuel), or the thrust requirement reduces, which necessitates a more detailed design and optimisation of an LH₂ aircraft for meeting the thrust (*T*) to weight (*W*) ratio (*T/W*) of the reference aircraft. The primary research task in this work is to design and optimize a long-range LTA BWB aircraft powered by LH₂ employing conceptual design process, while considering the reduced thrust requirement for a lighter LH₂ aircraft. This enables a quantification of the energy performance of the long-range LTA BWB powered by LH₂.

Moreover, in authors' previous study [5], they developed a power law equation that relates the operating empty weight (OEW) and GTOW for combustion based LH₂ aircraft based on a database of 31 aircraft (irrespective of the design range and architecture type) in published literature. Such an equation is useful for conceptual LH₂ aircraft design and weight sizing studies. Similar work is done by Roskam [82] but that is limited just to Jet-A aircraft. In this work, the authors will update their previous database of combustion based LH₂ aircraft from literature.

The above signify the novelty of this work. Utilizing low-carbon fuels and advanced aircraft technology is essential for mitigating the climate

impact of aviation. The objectives of this work are to:

- i. Conduct energy performance evaluation of an LTA (seating ~300 passengers) BWB aircraft powered by LH_2 at on-design and off-design points, using conceptual aircraft design process.
- ii. Develop/update combustion based LH_2 aircraft database that helps to relate OEW to the GTOW. This database is based on LH_2 aircraft designed in this work and open literature.

The fulfilment of the above objectives will be useful for future studies focused on use-phase emissions (like oxides of nitrogen) and contrails modelling, LH_2 aircraft operations (different cruise altitude and speed for contrail reduction), estimation of operating costs, and lifecycle climate impacts. Considering the above, this work is of significance to expand the pool of knowledge on LH_2 aircraft design and operations and lifecycle effects. Details excluded from the main body are included in the Supplementary Information (SI) document.

2. Methodology

This work models a futuristic (2030+ or N+2 timeframe) BWB aircraft (design range 13,890 km) powered by two ultrahigh bypass ratio (UHB) geared turbofan engine (GTF) engines seating 301 passengers. This aircraft configuration is selected because a significant amount of information on the engine and aircraft design for conducting a conceptual design study is available from NASA's studies [83–86]. The performance characteristics of the engine used on the NASA N+2 BWB aircraft, at all flight mission points are unknown from NASA's studies. Therefore in authors' previous study [87], using the design requirements from NASA studies, the performance metrics of a future UHB GTF powered by LH_2 and Jet-A (and 100% SPK) (separately) is modelled at on-design and off-design points using conceptual engine design process. The current work is a low-order (or conceptual) design and performance of a futuristic BWB aircraft powered by LH_2 , and it does not consider detailed aircraft structural and stability examination. The conceptual design in this work is limited to standard aircraft weight sizing. A review of conceptual aircraft design process is included in SI §1. The reference aircraft is Boeing 777-200 LR.

2.1. Design cases

The BWB aircraft design cases that will be considered in this work are the Jet-A case and three cases of LH_2 fuel. The UHB GTF engine is modelled implementing NextGen materials (lighter, high-strength, and/or withstanding high temperatures) and is detailed in authors' previous study [87]. The overview of conditions in the three cases of LH_2 fuel analysed are as follows.

- Case 1 is where the aircraft thrust production remains unchanged from the Jet-A case. As LH_2 fuel is 2.78 times more energy dense than Jet-A, smaller mass of LH_2 fuel is needed at the mission start. Thus, for similar T/W (of the baseline aircraft), the thrust requirements decrease. Studies [88–90] support that thrust requirements of LH_2 powered aircraft decrease and as a result engines become smaller in size. This reduction in thrust production is not accounted in this case but is considered in Case 2.
- Case 2 is where the aircraft thrust requirements (and production) and engine size decrease for maintaining similar T/W of the baseline Jet-A aircraft case. The use of T/W is a standard approach in aircraft design and it is supported by studies [75,77].
- Case 3 is Case 2 without engine cooling flows. This is because the engines are expected to run colder relative to the baseline case due to reduced thrust requirements (and production), and engines use NextGen materials for withstanding high temperatures.

2.2. Design requirement

The design requirement/specification is a necessary step for initiating the aircraft design process (which can be observed from Figure SI 1). In terms of the future aircraft configuration, as stated previously, the NASA N+2 BWB aircraft powered by UHB GTF engine for 301 passengers is selected because a significant amount of data on the aircraft design for conducting a conceptual design study is available from NASA's studies [83–86,91,92]. It is to be noted that only the span of this aircraft is known and the length or other geometric details of the NASA N+2 BWB-GTF aircraft are not known directly from NASA's study [83]. NASA's project has evolved over a period of ten years and this project has been published through a series of publications [83–86,91,92]. A study by June et al. [93] reveals three-view engineering drawing of the NASA N+2 BWB-GTF aircraft that seats 301 passengers. The other geometric information of the aircraft will be estimated via reverse engineering since the aircraft span is known. The outer mould line of the aircraft is developed in SolidWorks (discussed ahead) using the three-view engineering drawing. Additionally, the wetted area (S_{wet}) of the NASA N+2 BWB-GTF aircraft is not known through studies [83–86,91,93]. Therefore, this work will calculate S_{wet} from the geometric model developed in SolidWorks.

The design requirement is to carry out a conceptual design of an LTA BWB aircraft for transporting 301 passengers over a range of 7,500 nmi or 13,890 km. This aircraft should be powered by LH_2 fuel. For developing the design of an LH_2 aircraft, a baseline case is required where this BWB aircraft is powered by Jet-A. Modifications to the baseline case are made for the use of LH_2 fuel, where the modifications are based on published literature. The BWB aircraft design requirements are summarised in Table 1, and these are based on NASA's study [83]. It is to be noted that the GTOW and OEW from NASA's study [83] are not listed in Table 1 because these are expected to change for different fuel cases and the weights of the two engines decreases as observed in authors' previous study [87] (use of lighter materials and future component efficiencies). The block fuel weight ($W_{\text{F,block}}$) is defined as the fuel weight burnt during the flight mission. The ratio of $W_{\text{F,block}}$ to total fuel weight at mission start ($W_{\text{F,total}}$) of the Jet-A NASA N+2 BWB aircraft is 0.9 [83]. In this work, similar value for the said ratio is used during the iteration process of the weight sizing method for estimating the aircraft operational energy consumption (discussed in §2.5). For the BWB Jet-A (baseline) case, except for the engine weights and $W_{\text{F,total}}$, there is no other change compared to the Jet-A NASA N+2 BWB aircraft [83]. For LH_2 fuel, modifications are required to the aircraft which changes OEW and GTOW (discussed in §2.5).

2.3. Flight mission profile

A simple multi-segment flight mission profile is considered in this work, which is represented in Fig. 1. The mission begins with engine start and warm-up followed by taxi-out. Thereafter, the aircraft takes-off from the runway and climbs to the design cruise altitude of 10,668 m (or

Table 1
BWB aircraft design requirements.

Characteristics	Value
Range	7,500 nautical miles (nmi) or 13,890 km
Passengers (PAX)	301
Powerplant	Two ultrahigh geared turbofan (UHB GTF) engines
Fuel type	1. Conventional jet fuel (Jet-A) 2. LH_2
Cruise Mach and altitude	0.84 at 10,668 m (35,000 ft)
Payload weight	53,570 kg
Wingspan	76.2 m
Length	37.465 m
Wing area (S)	944.73 m ²
Aspect ratio (AR)	6.1

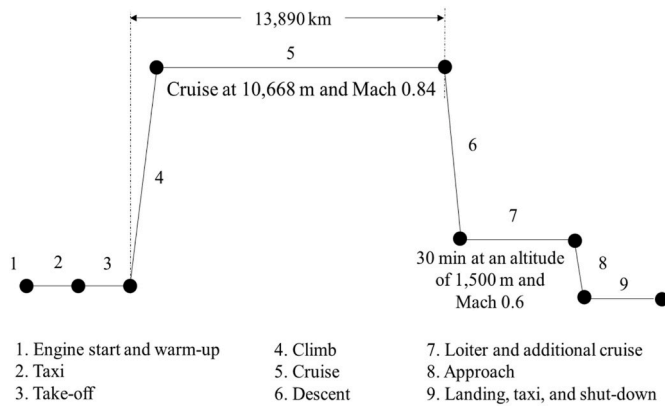


Fig. 1. Multi-segment flight mission profile.

35,000 ft as per set design requirements in Table 1). The mission design range is 13,890 km as discussed earlier, which is covered only during climb and cruise (primarily in cruise). After cruising, the aircraft descends to a loiter altitude. A standard value of 30 min loiter (or additional cruise) at an altitude of 5,000 feet (~1,500 m) at Mach 0.6 [94, 95], is considered. The resulting loiter range is ~362 km as per calculations. After the loiter is completed, the aircraft approaches the runway for landing. Once the aircraft lands, it is taxied into the gate followed by engine shutdown. Overall, in this work, the contribution of flight range or distance to the total design range during flight segments except climb and cruise, is considered negligible. The loiter phase is an additional flight operation outside of the design range because it is carried out only when the aircraft has to wait for receiving clearance to land on the runway. The fuel consumed in the loiter phase is included in $W_{F,block}$. This flight mission profile is used for the calculation of $W_{F,block}$ i.e., aircraft's block fuel consumption. A ratio of $W_{F,block}$ to $W_{F,total}$ of 0.9 is used, as discussed previously, that accounts for reserve fuel requirement.

2.4. Service ceiling equation

The service ceiling for a transport jet is defined as the altitude at which the maximum rate of climb (RoC) is 500 ft/min (2.54 m/s) for jet powered aircraft [96]. In the current work, the engine thrust requirement at top of climb (TOC) point for the LH₂ BWB aircraft is based on two separate calculations. The first method is using the service ceiling thrust equation i.e., equation (1) below (based on resource [96]), and the second method is using T/W of the baseline (conventional jet fuel) BWB aircraft. Both predictions are found to be of similar magnitude, however, the maximum of the two values is selected as the thrust required to be produced by the engines at TOC point. The aircraft thrust (T) at service ceiling is given by, [source [96]]

$$T = W \left(\frac{RoC}{V_{\infty}} + \frac{\sqrt{1 - \left(\frac{RoC}{V_{\infty}} \right)^2}}{(L/D)_{max}} \right) \quad \text{eq. (1)}$$

where V_{∞} is flight speed, W is aircraft weight at service ceiling, and $(L/D)_{max}$ is the maximum value of lift to drag ratio (L/D).

It can be observed from equation (1) that the thrust equation depends on four parameters: aircraft weight, rate of climb, flight speed, and the maximum lift to drag ratio of the aircraft. Accordingly, this work uses first order modelling methods, for climb with:

- An average climb speed of Mach 0.47 (calculation discussed in Part I SI §3.2 Table SI 13).

- The aircraft weight is an average weight of aircraft during climb (between the 'end point of take-off' and 'beginning point of cruise'). This aircraft weight and $(L/D)_{max}$ are known from the weight sizing process.

The RoC at service ceiling conditions for a transport jet, by definition (discussed above), is 500 ft/min (2.54 m/s).

2.5. Aircraft weight sizing method

The aircraft weight sizing process is not only iterative but also there is interaction between the different systems of aircraft with each other (viz. aerodynamics, propulsion, weight, etc.). The schematic/methodology is based on the standard sizing approach of Raymer [97] and Roskam [82]. The aircraft data (known and calculated) such as structural weight of different aircraft sections, tank weight for different fuels, and aircraft geometry and airfoils used are included in SI §2. In this work, three cases of LH₂ fuel are analysed.

Fig. 2 shows the weight sizing process schematic for aircraft powered by Jet-A (and 100% SPK), and LH₂ (all three cases). In the case of aircraft powered by Jet-A BWB, the sizing is straightforward using the standard approach of Raymer [97] and Roskam [82] because of data availability. For using LH₂, there are modifications required to be made to the baseline (Jet-A) aircraft structure. Therefore, the LH₂ aircraft sizing has some new sub-components within the process schematic as observed from Fig. 2, though it includes the steps covered in the sizing of conventional jet fuel aircraft. It can be observed that Fig. 2 includes T/W consideration in the iteration process for case 2 and case 3 of hydrogen aircraft, which is not included for case 1 LH₂, as per definition of each LH₂ aircraft case. The sub-components of Fig. 2 viz. propulsion, aerodynamics, fuel fractions, and aircraft systems weight are detailed case by case in SI §3 (also see SI §3.4.2 for assumptions).

2.5.1. Convergence criteria

Referring to Fig. 2, for all three fuelled BWB aircraft cases, the weight sizing process that estimates the aircraft operational energy consumption, a convergence criterion for the ratio of $W_{F,block}$ and $W_{F,total}$, is set to 0.9. The weight sizing process for Jet-A, and three cases of LH₂ BWB aircraft cases begins with a guess value of $W_{F,total}$ (other inputs are discussed in SI §3), and $W_{F,block}$ is calculated from it for each fuel case. The guess value of $W_{F,total}$ is iterated until the said ratio equals 0.9. This determines the GTOW of each of the BWB aircraft case. The GTOW of the Jet-A BWB aircraft (baseline case of this work) is set as the maximum take-off weight (MTOW) limit for all fuel cases. The specific energy consumption (SEC, in MJ/tonne-km) of the aircraft is estimated for different fuel cases since it is a significant performance parameter that enables the estimation of direct operating costs [5]. The SEC (eq. (2)) is given by, [source [5]]

$$SEC = (W_{F,block} \times \text{fuel calorific value}) / (\text{payload weight} \times \text{aircraft range}) \quad \text{eq. (2)}$$

The authors choose to constrain the aircraft GTOW for different fuel cases, to be less than or equal to the MTOW limit of the baseline Jet-A BWB aircraft structure (observed in Fig. 2), similar to the approach in previous studies [5,6]. This constraint is applied since a detailed structural analysis is not conducted in this work. Therefore, the MTOW determines the design limit on the $W_{F,total}$ for all fuel cases.

For all three cases of LH₂ aircraft considered in this work, using the calculation process discussed in SI §2.3, the weight of LH₂ tank systems is calculated. In SI §2.3 the LH₂ tank weight is estimated from the gravimetric index (η), which is defined as the ratio of cryogenic fuel weight to the sum of the dry tank weight and cryogenic fuel weight [18, 80,89,98]. In authors' previous study [6], the effect of η on a long-range LH₂ aircraft energy performance is examined, and in the present work the authors assume an average $\eta = 0.78$ based on the study by Verstraete

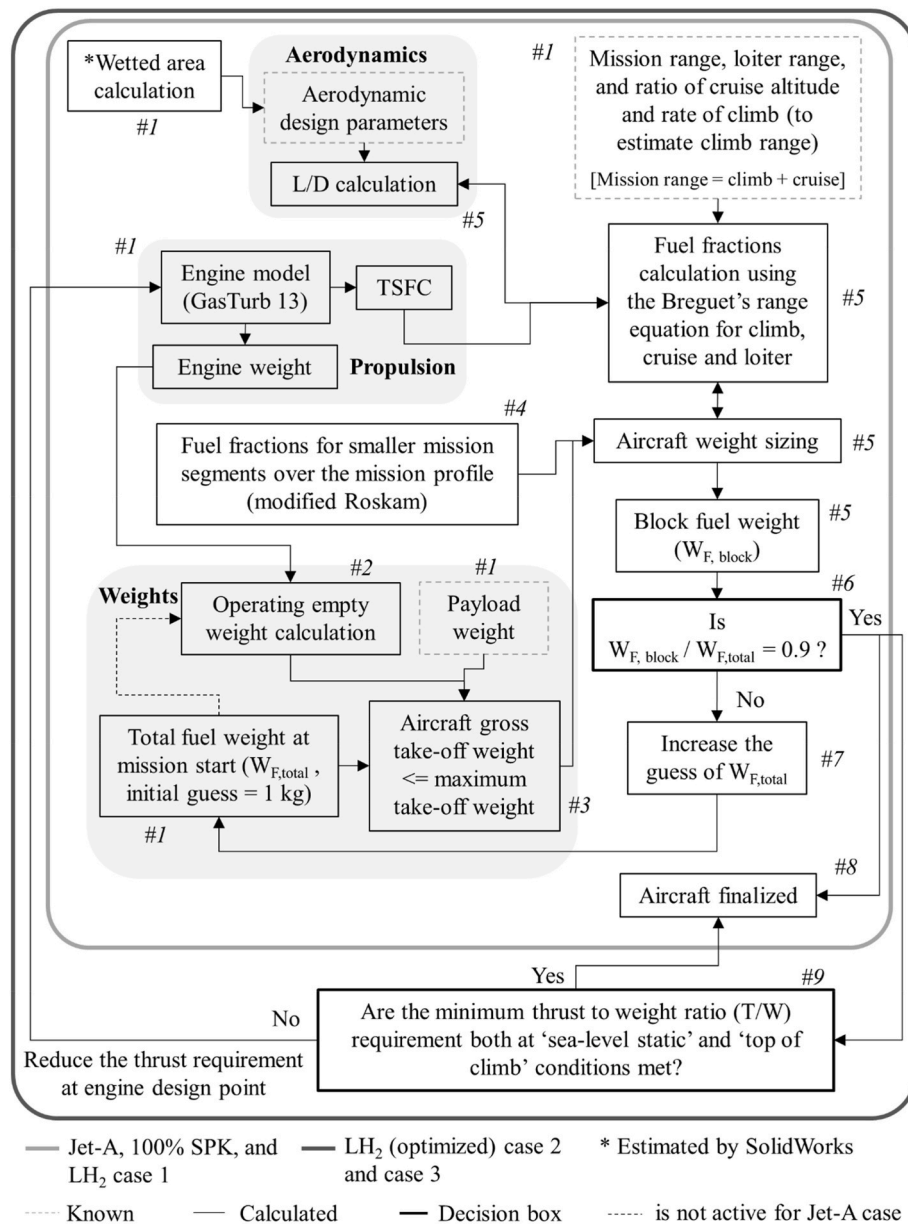


Fig. 2. Weight sizing process schematic for aircraft powered by Jet-A (and 100% SPK), and liquid hydrogen (all three cases).

et al. [80] and authors' previous study [5] (details in SI §2.3).

The geometric model of the BWB aircraft is developed in SolidWorks [99], using the BWB geometry data discussed in SI §2.4. For the LH₂ aircraft cases, the geometric model is used for ensuring that the cryogenic tanks fit inside the BWB. The LH₂ tank systems must be adapted to the internal available space of the BWB aircraft in the inner wings and in aft body of the cabin (for not affecting the aircraft cabin dimensions, the cabin layout and geometry, and these are discussed in SI §2.4). The LH₂ tank systems are expected to be a tapered cylindrical tank, similar to the tapered cylindrical tank design or frustum-shaped tank design by Verstraete et al. [80] for the tube-wing aircraft. Verstraete et al. study is used for the design of the LH₂ fuel tank in this work (discussed in SI §2.3).

Post-convergence, the (minimum) required volume of LH₂ fuel is calculated from the total LH₂ fuel weight at the beginning of the mission (known from the weight sizing process) and the mass-density of LH₂ fuel (71 kg/m³). A tapered cylindrical tank integral to (and inside) the BWB structure is modelled in SolidWorks, using the insulation thickness (8.1 cm with η of 0.78) and the (minimum) LH₂ fuel volume required to be

stored (at the beginning of the mission). The tapered cylindrical LH₂ tank must be designed in a piece-wise manner for making maximum use of the internal space in the wings of a BWB aircraft. This is because the cross-sectional area of a BWB aircraft is variable both in the spanwise and lengthwise direction. The tapered cylindrical LH₂ tank shape can be considered as multiple small-tapered cylinders joined together. The tapered cylindrical shape resulting in this work could have negative structural and heat-transfer implications. The tank design volume is the volume formed by the 'inner tank wall.' The inner tank wall is separated from the outer tank surface by insulation. Therefore, care must be taken while designing the LH₂ tank systems such that the effect of the insulation thickness on volume calculation is accounted (details in SI §2.3). The weight sizing iteration continues until the end of convergence. The effect of T/W ratio of the aircraft is important during the convergence. However, it depends on the type of LH₂ aircraft case considered, which is discussed below.

2.5.2. LH₂ aircraft T/W constraint

Referring to Fig. 2, for Case 1 of the LH₂ aircraft, the sizing process

begins with a guess weight of $W_{F, \text{total}}$, where the guess value of $W_{F, \text{total}}$ is 1 kg. $W_{F, \text{block}}$ for Case 1 LH₂ aircraft is calculated iteratively based on this guess value while employing the weight sizing process. $W_{F, \text{block}}$ of LH₂ fuel and $W_{F, \text{total}}$ are calculated such that their ratio is 0.9. As discussed before, in case 1 the thrust production remains unchanged and therefore T/W is not a constraint in the weight sizing process. The T/W ratios at sea level static (SLS) and TOC are estimated using the thrust produced by engines (similar to Jet-A BWB aircraft case/design requirements) and the aircraft weight estimated from the weight sizing process. An aircraft powered by LH₂ fuel will be lighter, compared to an aircraft powered by Jet-A considering only the effect of LH₂'s higher gravimetric energy density, resulting in lower thrust requirement. The T/W ratios for Case 1 at SLS and TOC will be greater than the baseline case because in Case 1 the thrust production remains the same as the baseline case (Jet-A BWB aircraft). After the convergence criteria is met in the weight sizing process, the aircraft design is finalised. The main effect that is anticipated in Case 1 is the effect of lighter aircraft on the block fuel (energy) consumption reduction.

Referring to Fig. 2 in Case 2 of LH₂, the fan diameter is no longer a design constraint that is considered in Case 1 and thus the fan/engine diameter reduces (engine and aircraft weight reduces) because of lesser thrust requirement (due to a lighter aircraft because of lesser weight of a high gravimetric energy density fuel and reduction in engine weight). Case 2 of LH₂ aircraft begins with the (guess value of) $W_{F, \text{total}}$ similar to Case 1. The convergence criteria for the weight sizing process remain similar to the process described for Case 1. However, the T/W ratio is an important factor considered in Case 2. The T/W ratio of the BWB Jet-A aircraft is calculated at SLS and TOC after the weight sizing process. The thrust value at on-design point is iteratively changed and the engine is designed along with its off-design performance (details in Ref. [87]). This is done in such a way that the T/W ratio at SLS and TOC is at least the respective (calculated) value for BWB Jet-A aircraft, or slightly higher. As discussed in §2.4, in the current work the engine thrust requirement at TOC for the LH₂ BWB aircraft is based on two separate calculations. The first method is using the service ceiling thrust equation, and the second method is using the T/W ratio of the baseline case (Jet-A BWB aircraft). Both predictions are of similar magnitude, however, the maximum of the two values is selected as the thrust required to be produced by engines at TOC point. It is to be noted that because this work designs aircraft at a conceptual level, the T/W ratios do not reach the exact values (as calculated for Jet-A BWB aircraft). Nevertheless, they are similar in magnitude to or are slightly higher than the T/W values for Jet-A BWB aircraft. Typically, during high-order modelling or high-fidelity analysis, a multi-point design and optimisation is carried out in a flight mission, such that the T/W are identical to the target values. While the thrust is iterated, the convergence criteria in the weight sizing process along with the sizing of the LH₂ fuel tank and its integration (structural penalty) within the BWB aircraft, remain same as described earlier. As thrust reduces, the following weights change along with it: the propulsion systems weights (smaller engine as compared to Case 1), the LH₂ fuel tank weight, $W_{F, \text{total}}$ for LH₂ fuel, and GTOW of the aircraft (with aerodynamic parameters), as compared to Case 1. This interaction between different components of the weight-sizing process is shown in Fig. 2. Only after the convergence criteria and the T/W ratio constraints are met, the aircraft design for Case 2 LH₂ aircraft is finalised.

Similarly, Case 3 of LH₂ aircraft is essentially Case 2 without engine cooling flows, because the engine operates colder and is smaller than the baseline (Jet-A) engine due to reduced thrust requirement. This further improves the thrust specific fuel consumption (TSFC), reduces propulsion systems weight, and therefore reduces $W_{F, \text{block}}$ (as compared to Case 2). For the set convergence criteria and T/W ratio constraints, this results in reduction in $W_{F, \text{total}}$, the LH₂ fuel tank weight, propulsion systems weights, and GTOW of the aircraft (with effect on aerodynamics), as compared to Case 2. This interaction between different components of the weight-sizing process is shown in Fig. 2. The methodology (including

the convergence criteria and T/W effects) remains similar to Case 2. Only after the convergence criteria and the T/W ratio constraints are met, the aircraft design for Case 3 LH₂ aircraft is finalised. The main effects that are anticipated in both Case 2 and Case 3 on block fuel (energy) consumption reduction are due to: the use of a high gravimetric energy density (LH₂) fuel that reduces the aircraft weight; the effect of thrust requirement reduction due to a lighter aircraft; and the effect of engine weight reduction (smaller engines due to thrust requirement reduction) on the aircraft weight; all of which result in block fuel (energy) consumption reduction. As can be observed, the conceptual design phase of the aircraft is not only iterative but also there is interaction between the different systems of aircraft with each other.

2.6. Off-design performance of aircraft

The aircraft performance for each fuel case at the design point is known after following the aircraft weight sizing methodology described in previous section. The aircraft now becomes a 'fixed' aircraft. In real world applications, aircraft do not always fly with full design payload capacity, full fuel tank, and/or at the design range. This work evaluates the performance of each of the aircraft powered by different fuels for typical range and payload combinations for long-range flights. Three payload cases are considered: 66.5% load factor (200 passengers or 35.59 tonnes), 83.1% load factor (250 passengers or 44.49 tonnes), and 100% load factor (301 passengers or 53.57 tonnes). The three load factor cases are evaluated for aircraft range between 5,000 km and the maximum permissible range for a given load factor case flying with full tank capacity. The flowchart/schematic for the estimation of the maximum permissible range for a given load factor with full fuel tank is represented by Fig. 3. Additionally, Fig. 4 shows the flowchart/schematic for the estimation of the operational energy consumption of an aircraft for given range and load factor combinations.

3. Results and discussion

3.1. Design point

Fig. 5 provides the pictorial representation of the BWB aircraft for all fuel cases. It is to be noted that Jet-A (100% SPK) and three cases of LH₂ have the same outer BWB frame/skin (outer mould) as illustrated by Fig. 5. For LH₂ BWB aircraft, this is in contrast with the observations made for a tube-wing LH₂ aircraft [5,6] where the aircraft length increases to accommodate the fuel. A BWB airframe has greater internal volume as compared to a tube-wing aircraft (of similar size and class) and this enables effective utilisation of space for LH₂ storage within the wings. In addition, N+2 aircraft and engine technologies are employed that reduce the energy demand, thereby reducing volume requirement which can be accommodated within the BWB internal volume. This aspect is further elaborated next. The aircraft length and S_{wet} are calculated to be 35 m and 2,132 m² (22,944 ft²), respectively, using the SolidWorks geometric model (required for the estimation of the aerodynamics performance during the weight sizing process).

Table 2 provides the performance comparison of Boeing 777-200 LR and future aircraft [Jet-A BWB aircraft and BWB LH₂ aircraft (all three cases)] over one flight mission. It can be observed from Table 2 that T/W ratio at SLS and TOC for BWB LH₂ aircraft tend towards the T/W ratios of BWB Jet-A aircraft at SLS and TOC, from case 1 to case 3 (from the unoptimized to the optimised aircraft). In all three cases of BWB LH₂ aircraft, the minimum required T/W at SLS and TOC are met, for a flight to be possible with the same airframe used for Jet-A BWB aircraft (and NASA N+2 BWB 301 PAX aircraft).

The NASA N+2 BWB 301 PAX (Jet-A) aircraft provides 47% reduction in block fuel energy consumption, as compared to Boeing 777-200LR, which is known from Nickol et al. [83] study. The Jet-A BWB aircraft (designed in this work) is (1.74%) more efficient than NASA N+2 BWB 301 PAX (Jet-A). This energy efficiency improvement is

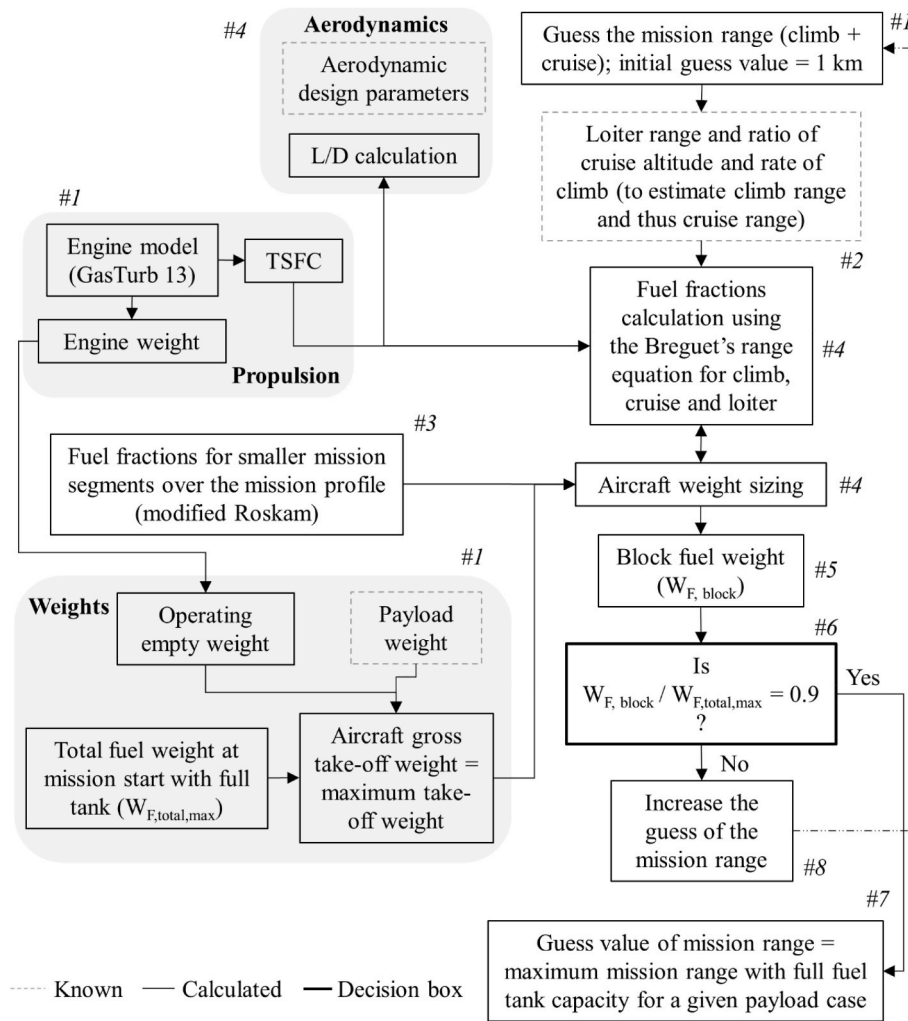


Fig. 3. Schematic for the estimation of the maximum permissible range for a given payload case.

attributable to TSFC improvement (high component efficiencies and engine weight reduction, details in Ref. [87]) that reduces the GTOW.

The Jet-A BWB aircraft provides 47.9% reduction in the block fuel energy consumption, as compared to Boeing 777-200LR. The performance of BWB LH₂ aircraft is better than both NASA N+2 BWB 301 PAX (Jet-A) aircraft and Jet-A BWB aircraft (present work). Case 1, 2, and 3 of BWB LH₂ aircraft provide 51.7%, 52.6%, and 53.5% reduction, respectively, in the block fuel energy consumption, as compared to Boeing 777-200LR.

It is important to note that the LH₂ fuel tank systems (for the designed mission) fit inside the BWB aircraft primarily because of the consideration of future aircraft technology that significantly reduces the fuel weight and fuel volume to be carried on the aircraft. For example: as discussed above, BWB LH₂ aircraft (all three cases) provides energy-efficiency improvement of approximately 50%, as compared to Boeing 777-200LR. Had there been no energy efficiency improvement due to the use of aircraft technology, the LH₂ fuel volume required would be at least twice the volume of fuel required by the N+2 BWB LH₂ aircraft cases. This fuel volume cannot be accommodated in the present airframe and significant modifications to the BWB geometry would be required (resulting in weight penalty) or a larger BWB airframe would be required. The use of future aircraft technology (engine and airframe) enables successful and efficient use of LH₂ fuel in the aircraft. This is further supported by a study by Adler et al. [77] which designs both tube-wing and BWB powered by hydrogen using present-day aircraft technology. Adler et al. observe that hydrogen powered BWB

(employing present-day aircraft technology) has a 3.8% energy penalty, compared to a Jet-A BWB. The energy penalty for a hydrogen powered tube-wing (employing present-day aircraft technology) is 5.1%, relative to Jet-A tube-wing. Adler et al. suggest that maturation in BWB technology can benefit the use of hydrogen, which is similar to the recommendations by CleanSky report [18].

Furthermore, in authors' previous study [6], the N+3 (2035+) tube-wing LH₂ aircraft shows 33% improvement in energy consumption, compared to A350 Jet-A aircraft. Using the same baseline case (A350 Jet-A aircraft) instead of Boeing 777-200LR, the energy consumption of (N+2 technology) BWB LH₂ aircraft would improve by 48.5%. Therefore, from this analysis it can be clearly observed that a N+2 BWB airframe has energy consumption benefits for LH₂ use (despite lagging by one technology generation i.e., of N+2 technology), compared to a (N+3) tube-wing aircraft.

Compared to the Jet-A BWB aircraft, BWB LH₂ aircraft case 1, 2, and 3 provide 7.3%, 9%, and 10.8% reduction, respectively, in the block fuel energy consumption. As discussed before, the improvement in the block fuel energy consumption in all three cases of BWB LH₂ aircraft is primarily due to the improved TSFCs (details in Ref. [87]) and due to the aircraft weight reduction. In case 2 and 3 of BWB LH₂ aircraft the reduction in the thrust requirement (leading to engine weight reduction and therefore the reduction of aircraft GTOW) is an additional reason for the improved energy efficiency. It was observed in authors' previous studies [5,6], that tube-wing LH₂ aircraft requires increase in fuselage length to accommodate LH₂ fuel tanks which negatively impacts L/D

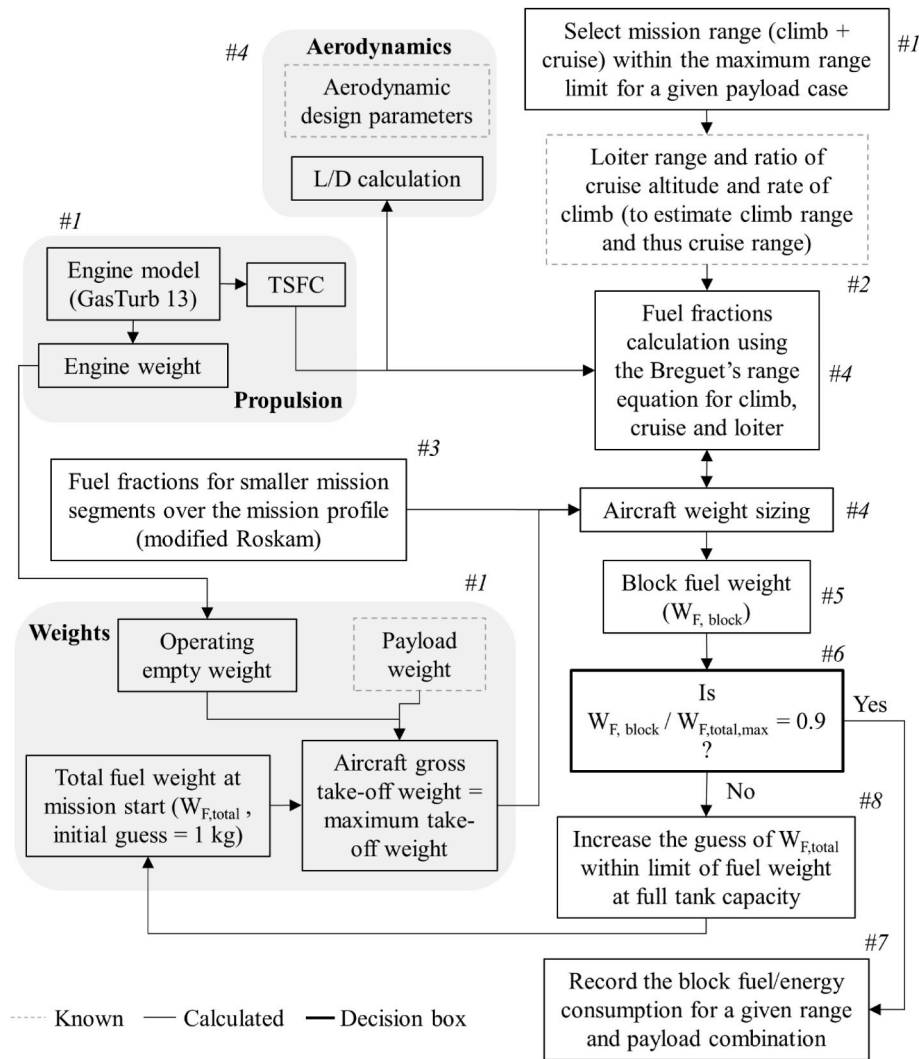


Fig. 4. Schematic for the estimation of the operational energy consumption of an aircraft for given range and payload combination.

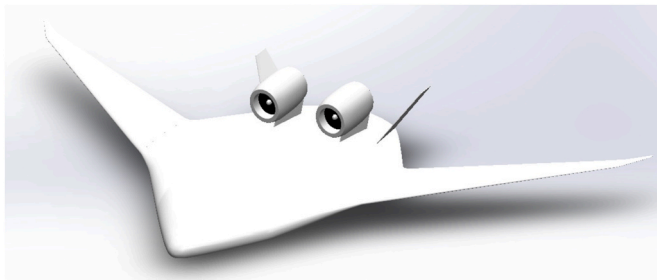


Fig. 5. Geometric model of BWB aircraft simulated using SolidWorks.

and therefore the aircraft energy consumption, for maintaining same range and payload as that of baseline case. This negative impact is not observed for this N+2 BWB aircraft because of their higher internal volume that enables storage of LH₂ tanks and energy efficiency. Overall, a BWB architecture is more energy efficient and effective for LH₂ use, compared to a tube-wing architecture.

The relevant detailed results of the different components/sub-systems of the weight sizing process, for all fuel cases are included in the SI document. The iteration parameters, aerodynamic performance, propulsion results, characteristics of LH₂ tank systems (tank counts, shapes, and dimensions), and breakdown of aircraft weight and fuel

consumed during one flight mission, are included in SI §4.1, 4.2, 4.3, 4.4, and 4.5, respectively.

The significant reduction in the GTOW of LH₂ aircraft observed from Table 2 (greater than 19% reduction in GTOW depending on case) is of importance during emergency landing situations as a lighter aircraft will not necessitate jettison of a highly flammable LH₂ fuel (details in SI §4.6). A similar analysis is conducted for tube-wing LH₂ aircraft in authors' previous study [5] and similar observations were made. The reduction in GTOW and resultantly the take-off wing-loading (from baseline) for (N+2) BWB LH₂ aircraft in this work is observed to be ~20%, compared to NASA N+2 BWB, 44.6% compared to B777-200 LR, and 39% compared to A350-1000. For an N+3 tube-wing aircraft, based on authors' previous study [6], this reduction in GTOW is ~34%, compared to A350-1000. For the above two futuristic technology improvement scenarios, the GTOW reduction potential for LH₂ aircraft is much greater compared to the 15% reduction in GTOW observed in authors' previous study [5] for a LH₂ version of A350-1000 (tube-wing aircraft of present-day technology), relative to Jet-A A350-1000.

Lastly, a comparison of the change in the take-off wing-loading and cruise *L/D* with literature due to fuel switch from Jet-A to LH₂ in a BWB aircraft, is conducted. Of the limited number of studies on LH₂ BWB [72, 73, 77, 78], only the study by Adler et al. [77] enables such a comparison. The study finds that the take-off wing-loading and cruise *L/D* drops by 17.2% and 6%, respectively, for a switch of fuel from Jet-A to LH₂ in a BWB aircraft. This is similar to the findings in the present work where

Table 2

Performance comparison of Boeing 777-200 LR and future aircraft [Jet-A BWB aircraft and BWB LH₂ aircraft (all three cases)] over one flight mission.

Aircraft range: 13,890 km (Current scenario)						
Aircraft		Jet-A block fuel consumption (kg)		Jet-A block fuel energy consumption (TJ)		
Boeing 777-200LR [83] and MTOW of 347,450 kg [100]		125,705		5.43		
Aircraft range: 13,890 km (Future scenarios)						
Parameters	Units	Nickol et al. [83]	Jet-A BWB aircraft	BWB LH ₂ aircraft		
				Case 1	Case 2	Case 3
GTOW	kg	242,441	236,398	195,325	194,177	192,677
OEW	kg	114,907	110,150	117,505	116,790	115,760
Payload weight	kg	53,570	53,570	53,570	53,570	53,570
Cryogenic tank η	–	–	–	0.78	0.78	0.78
$W_{F, \text{total}}$	kg	73,965	72,678	24,250	23,817	23,347
Ratio of GTOW and GTOW _{NASA}	-	1	0.975	0.806	0.801	0.795
$W_{F, \text{block}}$	kg	66,683	65,523	21,863	21,473	21,049
Block fuel energy	TJ	2.88	2.83	2.62	2.58	2.53
Block fuel energy reduction as compared to Boeing 777-200LR	%	47%	47.88%	51.69%	52.55%	53.49%
Block fuel energy reduction as compared to Jet-A BWB aircraft	%	–		7.31%	8.97%	10.76%
(L/D) at cruise	–	23.7	23.7	22.51	22.45	22.36
Block fuel weight/total fuel weight	–	0.9	0.9	0.9	0.9	0.9
Wing loading at take-off	(kg/m ²)	256.62	250.23	206.75	205.54	203.95
T/W (SLS)	–	0.252	0.262	0.318	0.277	0.276
T/W (TOC)	–	–	0.04851	0.058	0.0487	0.0489
Structurally (average) permissible ratio of aircraft landing weight and GTOW, for transport jet			0.84 (according to Roskam [82])			

there is a reduction in take-off wing-loading and cruise L/D of 19.4–20.5% and 5–5.7%, respectively. The design point characteristics of the 100% SPK BWB aircraft is included in SI §4.9 (Table SI 21).

3.2. Off design performance characteristics

The methodology/flowchart for the aircraft off-design point performance estimation has been discussed in §2.6. Three payload (load factor) cases are considered: 66.5% load factor (200 passengers or 35.59 tonnes), 83.1% load factor (250 passengers or 44.49 tonnes), and 100% load factor (301 passengers or 53.57 tonnes). The three load factor cases are evaluated for aircraft range between 5,000 km and the maximum permissible range for a given load factor case flying with full tank capacity. Fig. 6, and (in SI §4.7) Figures SI 5 and SI 6 show the variation of SEC with range for BWB aircraft powered by different fuels for 66.5% load factor, 83.1% load factor, and 100% load factor, respectively. In all

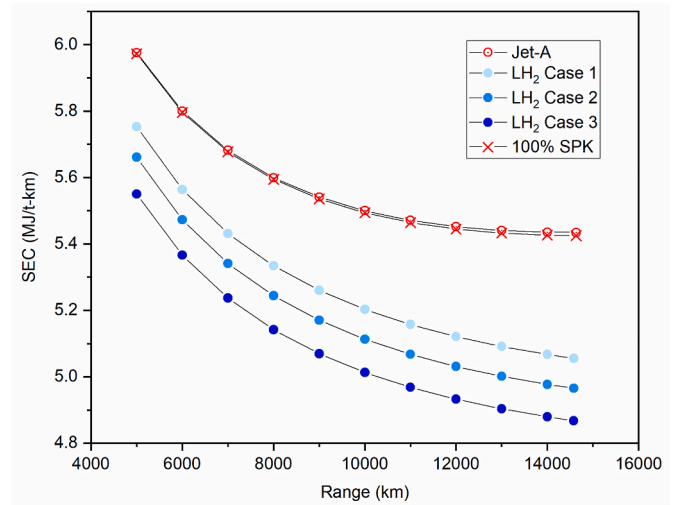


Fig. 6. Variation of SEC with range for BWB aircraft powered by different fuels for 66.5% load factor.

three figures same trend is observed for SEC vs range i.e., with increasing range, the SEC decreases for each of the fuel case.

Additionally, at any given range, by increasing the load factor the absolute value of SEC decreases for each of the fuel case. BWB LH₂ aircraft are more efficient at greater range and the SEC curve appears to keep dipping with increasing range, as compared to Jet-A. This (for BWB LH₂ aircraft) contrasts with the observations made in authors' previous study [5], where the SEC of LH₂ 'tube-wing' aircraft, though decreases with range, is less sensitive beyond (the range of) 10,000 km. SEC of Jet-A BWB (and 100% SPK) is less sensitive to range beyond ~13,000 km. Of the three BWB LH₂ aircraft design cases, Case 3 offers the best SEC at all range and load factor combinations.

Insights from Fig. 6, and (in SI §4.7) Figures SI 5 and SI 6 can be visualised through a single plot i.e., Fig. 7 which demonstrates the energy efficiency improvement of BWB powered by different fuel cases, as compared to Jet-A BWB aircraft, for varying range and load factor combinations. For a given fuel case, with increasing load factor, the maximum range that can be travelled decreases. Additionally, for a given fuel case, increasing the load factor improves the energy efficiency, compared to a Jet-A BWB aircraft. Moreover, for a given fuel and

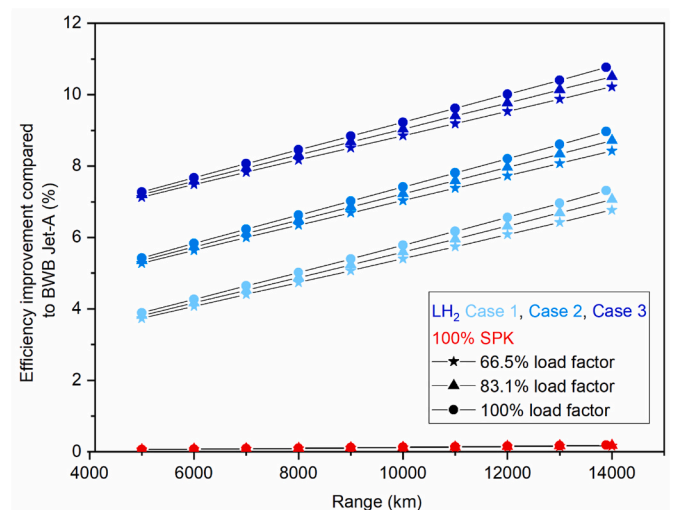


Fig. 7. Energy efficiency improvement of BWB powered by different fuel cases as compared to Jet-A BWB aircraft for varying range and load factor combinations.

load factor case, the energy efficiency improves with increasing range, compared to a Jet-A BWB aircraft. This increase in energy efficiency is observed prominently for all three cases of BWB LH₂ aircraft, compared to the Jet-A BWB aircraft. The BWB LH₂ Case 3 aircraft is the most efficient aircraft at all range and load factor combinations, compared to the Jet-A BWB aircraft.

3.3. Relationship between OEW and GTOW for LH₂ aircraft

It is important to conduct a final evaluation, i.e. a sanity check, by analysing the relationship between OEW and GTOW for the transport aircraft designed in this work and the transport aircraft in literature (separately for each fuel type), through regression. In this work, the database of aircraft is updated relative to the authors' previous study [5]. Currently, there are 54 combustion-based LH₂ aircraft and 70 Jet-A (and 100% SPK) aircraft from literature, separately, inclusive of type of architecture (tube-wing and unconventional), class (regional, single aisle, small twin aisle, LTA, and VLTA) and/or range (short, mid, and long range).

Fig. 8 shows the relationship between OEW and GTOW of LH₂ aircraft (54 aircraft) from the present work and literature (all are tube-wing except six BWB as indicated). It can be observed that the relationship between OEW and GTOW for the aircraft designed in this work is similar to the LH₂ aircraft designs in literature, and the developed equation would facilitate conceptual LH₂ aircraft design and weight sizing studies. Similar work is done by Roskam [82] but that is limited just to Jet-A aircraft.

For Jet-A (and 100% SPK) aircraft, historical aircraft data and literature is used for the regression analysis, where the data is of different sizes of aircraft. Table SI 17 (SI §4.7) lists the OEW and GTOW of aircraft already into service, in literature, and aircraft designed in this

work. Overall, 70 aircraft are listed in Table SI 17 (SI §4.7). 27 present-day aircraft (Jet-A) and nine futuristic aircraft (Jet-A and 100% SPK) are included in the database. An equation is developed in Figure SI 7 (in SI §4.7) which shows the relationship between OEW and GTOW of aircraft in service, of future (other studies), and future aircraft designed in this work (only Jet-A and 100% SPK).

3.4. Other results, comments, and discussion

It was observed through the findings of the authors' previous study [5] (details in SI §4.8) that liquid natural gas (LNG) powered aircraft showed a potential in terms of getting closer to the design target range (10,895 km for LNG case 1, compared to target of 13,870 km). Since this work considers weight sizing of a BWB aircraft that has greater internal volume, as compared to a tube-wing aircraft, it is worth to also examine the performance of LNG fuel in a BWB. The details of the LNG aircraft weight sizing process are included in SI §4.8. Similar to authors' previous study [5], two LNG cases (of cryogenic tank η of 0.78 and 0.63) are considered for a BWB powered by LNG. For LNG case of $\eta = 0.78$, which has highest cryogenic tank η of the two cases, the aircraft reaches a range of 12,052 km. Therefore, LNG is not identified as an alternative fuel for use in (N+2 technology) BWB aircraft (since target design range of 13,890 km is not met).

In previous studies [5,6], a qualitative discussion on other significant aspects for LH₂ and 100% SPK powered flight are included. These include: (a) other necessary modifications to aircraft and aviation sub-systems (infrastructure), (b) effects on airline decision-making and planning of fleet, and (c) effects of fuel and life-cycle costs.

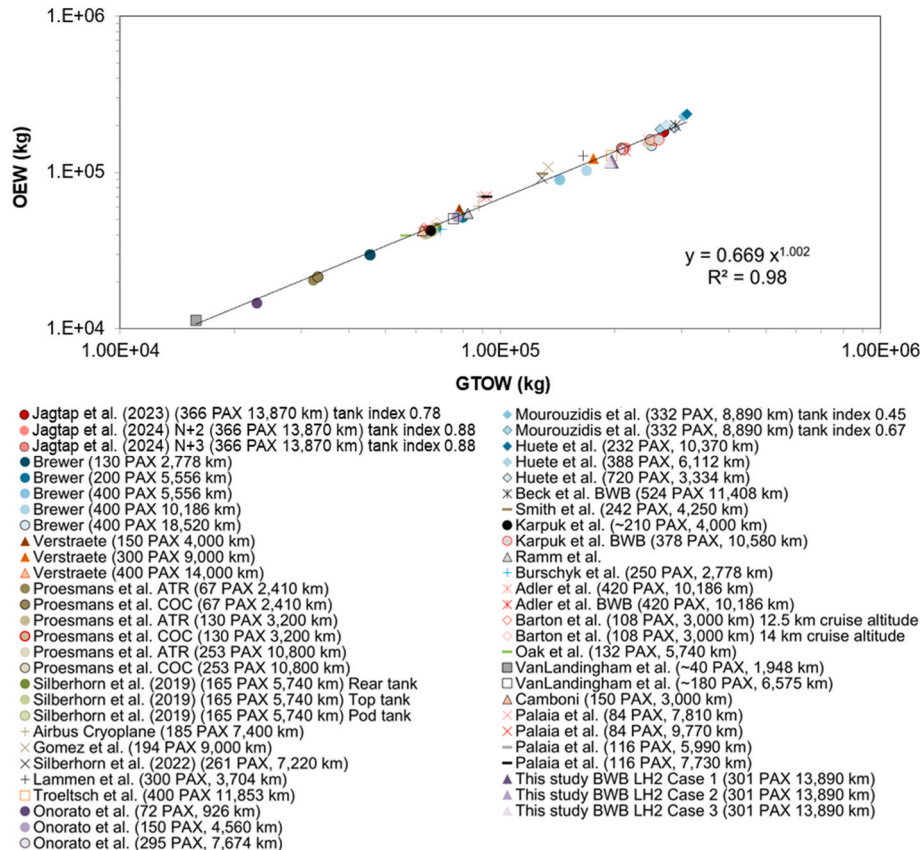


Fig. 8. Relationship between OEW and GTOW of LH₂ aircraft (54 aircraft) from the present work and literature (all are tube-wing except six BWB as indicated) (Source of data [5,6,22,26–28,45,47,49,50,54,61–64,66–70,73,75–77,79,81]).

3.5. Limitations of the present work

The effect of cryogenic tank is not considered in detail and is based on other studies. Ideally, a separate design model for cryogenic tank is required that accounts for both internal and external mechanical and thermal stresses. Additionally, given the scope of this work being restricted to the conceptual design phase, the quantitative impacts of other necessary modifications to LH₂ aircraft sub-systems are not considered in this work. These include modifications to fuel lines and engine/combustor and installation of a heat exchanger for phase change of liquid to gaseous hydrogen, and for 100% SPK aircraft sub-systems such as change of seals in the high-pressure fuel systems, etc. (see SI §3.4.2 for assumptions). Based on other (unpublished) research efforts, this additional weight could be insignificant, compared to GTOW (on the order of <1% of GTOW).

The estimation of the aircraft's operational energy consumption is based on a simplified (multi-segment) mission in the weight sizing process, where the energy consumption in smaller flight segments is calculated using the modifications to Roskam's fuel fraction. The impact of headwinds/tailwinds are not accounted in this work. Additionally, L/D ratios during climb, cruise, and loiter are average values for respective segments based on the aircraft weight during respective segment's beginning and end. The L/D ratio calculation for cruise and loiter assumes constant speed and angle of attack. Moreover, in the estimation of the drag coefficient, wave drag is considered to be negligible which is typically considered in high-fidelity analysis.

The estimation of aircraft performance characteristics in this work is constrained to the aircraft use-phase only and these comprise of aerodynamic, weight, and energy performance. Compared to Jet-A, LH₂ fuel combustion generates more water vapour at typical cruise altitude and might increase contrail formation which negatively impacts the climate [5]. Additionally, fuel costs (which depend on the feedstock and/or pathway used to manufacture fuel), and life-cycle impacts, are not accounted in this work. Also, emission performance, and flight economics (comparison for different fuels) and its impact on airline decision-making and planning of fleet are not considered in this work. Lastly, aircraft stability and stress/structural analysis are not conducted in this work. Overall, the weight sizing process in this work is a low-order or low-fidelity analysis and errors in aircraft performance metrics are expected.

4. Conclusions

LH₂ is a promising fuel for decarbonizing long-haul aviation, primarily due to its potential for zero carbon emissions during flight. However, the low volumetric energy density of LH₂ can negatively impact the energy consumption of a tube-wing aircraft. In contrast, the BWB airframe offers a more efficient integration of LH₂ systems, as it enhances aerodynamic performance and provides greater internal volume for accommodating cryogenic storage. As a result, the BWB design may be a more suitable option for LH₂ powered aircraft.

In a first, this work conducts the energy performance modelling of LH₂ and 100% SPK (separately) powered BWB aircraft (301 passengers and 13,890 km) of future (2030+ or N+2) BWB aircraft using conceptual aircraft design approach. The conceptual design phase in this work is limited to the LH₂ aircraft weight-sizing process. In terms of the methodology, this work provides a structured weight sizing process for a hydrogen powered BWB aircraft using future technology.

At the design point, the energy consumption of the N+2 BWB powered by Jet-A, 100% SPK, and LH₂ reduces by 47.9%, 48%, and 51.7–53.5% (depending on optimisation case), respectively, compared to Boeing 777-200LR. LH₂ fuel tank systems designed in this work fit inside the BWB aircraft primarily because of the consideration of future (N+2) aircraft technology that significantly reduces the fuel weight and fuel volume to be carried on the aircraft. The SEC of N+3 tube-wing LH₂ aircraft known from literature could be 33% lesser and requires a

fuselage length increase of 22%, compared to A350-1000 Jet-A aircraft. For the A350-1000 LH₂ aircraft modelled in literature using present-day aircraft technology, the SEC is 11% greater and requires 37% increase in fuselage length, compared to A350-1000 Jet-A aircraft. The (N+2) BWB LH₂ aircraft (case 3) modelled in this work provides energy consumption improvement of approximately 53.5%, as compared to Boeing 777-200LR, or 48.5% compared to A350-1000 Jet-A aircraft. Without the energy consumption benefits from the use of future aircraft technology, the LH₂ fuel volume required would be at least double than the volume needed in each of the N+2 BWB LH₂ cases modelled here. The adoption of future (2030+) aircraft technology (engine and airframe) enables successful, effective, and efficient use of LH₂ fuel in the aircraft. Compared to the Jet-A BWB aircraft, BWB LH₂ aircraft case 1, 2, and 3 provide 7.3%, 9%, and 10.8% reduction in the energy consumption, respectively, at the design point.

Additionally, at off-design points, for a given fuel case, an increase in load factor of the BWB LH₂ aircraft leads to a reduction in the maximum achievable range. For a given fuel case, increasing the load factor of the BWB LH₂ aircraft, improves the SEC, compared to a Jet-A BWB aircraft. Moreover, for a given fuel case and load factor, the SEC improves with increasing range, compared to a Jet-A BWB aircraft. This improvement in SEC is observed prominently for all three cases of BWB LH₂ aircraft, compared to the Jet-A BWB aircraft. The BWB LH₂ Case 3 aircraft is the most energy efficient aircraft at all range and load factor combinations, compared to the Jet-A BWB aircraft.

Moreover, at the design point the OEW and GTOW for LH₂ aircraft, as derived from both prior literature and the present study, are found to be related by a power law equation. This relationship will facilitate future research on the conceptual design and weight sizing of LH₂ powered aircraft. Overall, purely based on the energy performance, the BWB LH₂ aircraft emerges as a preferred long-range transport aircraft type for long-haul travel, as supported by various studies in the literature comparing LH₂ powered tube-wing and BWB aircraft.

The BWB LH₂ aircraft has a clear advantage over Jet-A BWB aircraft in terms of energy consumption (use-phase) and that this BWB LH₂ aircraft in the use-phase would emit only water vapour and small amounts of oxides of nitrogen. In terms of future work, the aircraft energy consumption and performance estimation from this work would help studies on: (i) use-phase emissions and contrails modelling; (ii) further development in aircraft technology to enable long-range LH₂ flight; (iii) aircraft operations such as changes in cruise altitude and flight speed for contrail mitigation; (iv) estimation of fuel pathways and/or feedstocks that could enable climate-neutral long-range aviation on a lifecycle basis; and (v) estimation of ticket cost as the direct operating cost depends on fuel production process and aircraft energy consumption; (vi) comparative study of life-cycle socio-environmental costs of flight powered by alternative fuels, compared to Jet-A, thereby facilitating aviation technology development and policy making.

CRedit authorship contribution statement

Swapnil S. Jagtap: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Peter R.N. Childs:** Writing – review & editing, Supervision, Methodology. **Marc E.J. Stettler:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.ijhydene.2024.11.331>.

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