

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

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8 **Abstract**

9         The adoption of liquid hydrogen (LH<sub>2</sub>) holds promise for decarbonising long-range  
10 aviation. LH<sub>2</sub> aircraft could weigh less than Jet-A aircraft, thereby reducing the thrust  
11 requirement. However, the lower volumetric energy density of LH<sub>2</sub> can adversely impact the  
12 aerodynamic performance and energy consumption of tube-wing aircraft. In a first, this work  
13 conducts an energy performance modelling of a futuristic (2030+) LH<sub>2</sub> blended-wing-body  
14 (BWB) aircraft (301 passengers and 13,890 km) using conceptual aircraft design-optimisation  
15 approach employing weight-sizing methods, while considering the realistic gravimetric and  
16 volumetric energy density effects of LH<sub>2</sub> on aircraft design, and the resulting reduction in  
17 aircraft thrust requirement. This study shows that at the design point the futuristic LH<sub>2</sub> BWB  
18 aircraft reduces the specific energy consumption (SEC, MJ/tonne-km) by 51.7 – 53.5% and 7.3  
19 – 10.8%, compared to (Jet-A) Boeing 777-200LR and Jet-A BWB, respectively. At the off-  
20 design points, this study shows that by increasing the load factor for a given range and/or  
21 increasing range for all load factor cases, the SEC (or energy efficiency) of this LH<sub>2</sub> BWB  
22 concept improves. The results of this work will inform future studies on use-phase emissions  
23 and contrails modelling, LH<sub>2</sub> aircraft operations for contrail reduction, estimation of operating  
24 costs, and lifecycle climate impacts.

## 1 **Keywords**

2 Hydrogen gas turbine, engine cycle performance, aviation fuel, climate neutral aircraft,  
3 decarbonising long-range aviation

## 4 **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 <sub>2</sub>	Liquid hydrogen
LNG	Liquid natural gas
LTA	Large twin aisle
<i>L/D</i>	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
RoC	rate of climb (in m/s)
<i>S</i>	Wing area (in m <sup>2</sup> )
SEC	Specific energy consumption (MJ/tonne-km)
SI	Supplementary information
SLS	Sea level static
SPK	Synthetic paraffin kerosene
<i>T</i>	Thrust (in N)
TOC	Top of climb
TSFC	Thrust specific fuel consumption
<i>T/W</i>	Thrust to weight ratio
UHB	Ultra-high bypass ratio
<i>V</i>	Flight speed (m/s)
VLTA	Very large twin aisle
<i>W</i>	Aircraft weight (in kg)

### *Greek symbols*

$\eta$	Gravimetric index
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### *Subscript*

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 <sup>2</sup> )
∞	Ambient or atmospheric (in service ceiling)

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## 1 **1. Introduction**

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

8           Most airlines retired their very large twin aisle (VLTAs: A380 and/or B747) aircraft  
9 during COVID-19 lockdown of 2020 and thus in the next few decades large twin aisle (LTA,  
10 such as B777, B787, A350, etc.) aircraft will likely be the most common air vehicles for long-  
11 range travel [6]. It was observed through authors' previous study [5] that decarbonising the  
12 long-range aviation domain is difficult, and of many alternative energy vectors and propulsion  
13 technologies explored (including batteries and fuel cells) only liquid hydrogen (LH<sub>2</sub>) and 100%  
14 synthetic paraffin kerosene (SPK) are the only two alternatives to Jet-A for a tube-wing  
15 (conventional) LTA aircraft.

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

21           Recently, industry efforts on hydrogen engine testing and hydrogen aircraft R&D has  
22 gained momentum [12–16], especially with the unveiling of the hydrogen powered blended-  
23 wing-body (BWB) Airbus ZEROe concept [17]. In authors' recent study [6], it was found that  
24 by enhancing aircraft aerodynamics and overall efficiency, the specific energy consumption  
25 (SEC) of LH<sub>2</sub> powered long-range tube-wing aircraft could be dramatically reduced, in

1 comparison with a present-day Jet-A aircraft. Previous studies [6,18–21] have qualitatively  
2 identified that employing a BWB airframe for LH<sub>2</sub> use could be a promising solution. In  
3 comparison with a tube-wing airframe, a BWB airframe enables better integration of LH<sub>2</sub>  
4 storage since it enhances aerodynamic performance and provides higher internal volume for  
5 cryogenic systems storage. Thus, a BWB airframe appears to be a better candidate for LH<sub>2</sub>  
6 aircraft.

7         Considering the above discussion, the scope of the present work is limited to the  
8 conceptual design-optimisation and energy performance evaluation of a combustion-based  
9 LTA [~300 passengers (PAX) and 7,500 nautical miles (13,890 km) design range] BWB LH<sub>2</sub>  
10 aircraft. Fuel cells are not explored or reviewed in this work. Furthermore, the literature review  
11 below is focussed only on the conceptual design-optimisation and energy performance  
12 evaluation of combustion-based LTA BWB LH<sub>2</sub> aircraft. The reader is advised to explore  
13 works by: Brewer [22] for tube-wing LH<sub>2</sub> aircraft design performance, cryogenic tanks, and  
14 other aircraft subsystems design; and review studies by Adler et al. [23] and Tiwari et al. [20]  
15 on LH<sub>2</sub> aircraft subsystems, combustors and fuel cell systems. None of the studies on hydrogen  
16 aircraft design and performance [5,6,18,22,24–81] provide a detailed design and optimisation  
17 and energy performance evaluation of a combustion-based LTA BWB LH<sub>2</sub> aircraft for a  
18 reduced thrust requirement, compared to its Jet-A variant (or a baseline). The literature review  
19 below concisely reports the studies with their shortcomings only for a long-range LTA  
20 category.

21         Study [72] considered designs for both tube-wing and BWB aircraft powered by LH<sub>2</sub>  
22 for short-, medium- and long-range. The analysis does not undertake original aerodynamic  
23 performance estimation and assumes similar lift-to-drag ratio for the hydrogen aircraft as that  
24 of the reference aircraft. It does not provide energy performance comparison for any of the LH<sub>2</sub>

1 BWB aircraft with the respective Jet-A BWB aircraft, and these LH<sub>2</sub> aircraft are infeasible  
2 designs as they do not meet the design range as that of the baseline.

3 Study [78] primarily models a 200 PAX aircraft powered by different alternative fuels  
4 including LH<sub>2</sub>, using both tube-wing and BWB airframe (in GENUS frameworks). The authors  
5 apply the method to a 400 PAX and 800 PAX aircraft. Overall, the authors analyse the life  
6 cycle effects and the aircraft range considerations are from 3,700 km to 15,700 km for each of  
7 the three (PAX) types of aircraft. However, no aircraft design details [gross take-off weight  
8 (GTOW), operating empty weight (OEW), wing area, span, etc.] are disclosed by the authors.  
9 Additionally, data on inflight energy consumption of BWB LH<sub>2</sub> aircraft and comparison with  
10 Jet-A BWB or tube-wing is not available.

11 Study [73] conducts design and energy performance examination of a (100%) LH<sub>2</sub>  
12 powered BWB aircraft (combustion based). However, this LH<sub>2</sub> BWB aircraft is a large quad  
13 or VLTA BWB aircraft type (PAX capacity similar to a Boeing 747 aircraft), which are retired  
14 by major airlines from the global fleet.

15 Studies on long-range LTA LH<sub>2</sub> aircraft focus only on tube-wing aircraft performance  
16 modelling [5,6,18,22,24–28,54,65,76,79–81], or conduct systems-level preliminary design  
17 consideration of a twin tube-wing LTA LH<sub>2</sub> aircraft concept [51], or the aircraft is not  
18 completely fuelled by LH<sub>2</sub> [51,74]. Other studies examining LH<sub>2</sub> (combustion) aircraft have:  
19 (i) considered smaller range and/or payload combinations than a typical design point of long-  
20 range LTA (class of) tube-wing and BWB aircraft [18,54,65,75,77]; (ii) substantially modified  
21 the cruise altitude and/or Mach number for the LH<sub>2</sub> tube-wing and BWB aircraft, thereby  
22 resulting in different aircraft design characteristics, in comparison with a typical baseline or  
23 long-range LTA aircraft [75,76,79]; and (iii) simulated the energy performance a two-fuel  
24 (100% SPK and LH<sub>2</sub>) BWB aircraft where LH<sub>2</sub> fuels a proportion of the aircraft energy  
25 requirement [74].

1 Overall, it is clear from the above discussion on an up-to-date literature review of  
2 different studies [5,6,18,22,24–81] that there is a requirement for a study which quantitatively  
3 evaluates the energy performance of a long-range LTA BWB aircraft powered by LH<sub>2</sub> with  
4 typical LTA aircraft design characteristics. This motivates the present work. Additionally, in  
5 authors' previous studies [5,6], they observed that the gross take-off weight (GTOW) of (tube-  
6 wing) LH<sub>2</sub> aircraft significantly reduces (on the order of 20+%, due to the use of lighter fuel),  
7 or the thrust requirement reduces, which necessitates a more detailed design and optimisation  
8 of an LH<sub>2</sub> aircraft for meeting the thrust ( $T$ ) to weight ( $W$ ) ratio ( $T/W$ ) of the reference aircraft.  
9 The primary research task in this work is to design and optimize a long-range LTA BWB  
10 aircraft powered by LH<sub>2</sub> employing conceptual design process, while considering the reduced  
11 thrust requirement for a lighter LH<sub>2</sub> aircraft. This enables a quantification of the energy  
12 performance of the long-range LTA BWB powered by LH<sub>2</sub>.

13 Moreover, in authors' previous study [5], they developed a power law equation that  
14 relates the operating empty weight (OEW) and GTOW for combustion based LH<sub>2</sub> aircraft based  
15 on a database of 31 aircraft (irrespective of the design range and architecture type) in published  
16 literature. Such an equation is useful for conceptual LH<sub>2</sub> aircraft design and weight sizing  
17 studies. Similar work is done by Roskam [82] but that is limited just to Jet-A aircraft. In this  
18 work, the authors will update their previous database of combustion based LH<sub>2</sub> aircraft from  
19 literature.

20 The above signify the novelty of this work. Utilizing low-carbon fuels and advanced  
21 aircraft technology is essential for mitigating the climate impact of aviation. The objectives of  
22 this work are to:

- 23 i. Conduct energy performance evaluation of an LTA (seating ~300 passengers) BWB  
24 aircraft powered by LH<sub>2</sub> at on-design and off-design points, using conceptual aircraft  
25 design process.

1 ii. Develop/update combustion based LH<sub>2</sub> aircraft database that helps to relate OEW to the  
2 GTOW. This database is based on LH<sub>2</sub> aircraft designed in this work and open  
3 literature.

4 The fulfilment of the above objectives be useful for future studies focused on use-phase  
5 emissions (like oxides of nitrogen) and contrails modelling, LH<sub>2</sub> aircraft operations (different  
6 cruise altitude and speed for contrail reduction), estimation of operating costs, and lifecycle  
7 climate impacts. Considering the above, this work is of significance to expand the pool of  
8 knowledge on LH<sub>2</sub> aircraft design and operations and lifecycle effects. Details excluded from  
9 the main body are included in the Supplementary Information (SI) document.

## 10 **2. Methodology**

11 This work models a futuristic (2030+ or N+2 timeframe) BWB aircraft (design range  
12 13,890 km) powered by two ultrahigh bypass ratio (UHB) geared turbofan engine (GTF)  
13 engines seating 301 passengers. This aircraft configuration is selected because a significant  
14 amount of information on the engine and aircraft design for conducting a conceptual design  
15 study is available from NASA's studies [83–86]. The performance characteristics of the engine  
16 used on the NASA N+2 BWB aircraft, at all flight mission points are unknown from NASA's  
17 studies. Therefore in authors' previous study [87], using the design requirements from NASA  
18 studies, the performance metrics of a future UHB GTF powered by LH<sub>2</sub> and Jet-A (and 100%  
19 SPK) (separately) is modelled at on-design and off-design points using conceptual engine  
20 design process. The current work is a low-order (or conceptual) design and performance of a  
21 futuristic BWB aircraft powered by LH<sub>2</sub>, and it does not consider detailed aircraft structural  
22 and stability examination. The conceptual design in this work is limited to standard aircraft  
23 weight sizing. A review of conceptual aircraft design process is included in SI §1. The reference  
24 aircraft is Boeing 777-200 LR.

## 1 2.1 Design cases

2 The BWB aircraft design cases that will be considered in this work are the Jet-A case  
3 and three cases of LH<sub>2</sub> fuel. The UHB GTF engine is modelled implementing NextGen  
4 materials (lighter, high-strength, and/or withstanding high temperatures) and is detailed in  
5 authors' previous study [87]. The overview of conditions in the three cases of LH<sub>2</sub> fuel analysed  
6 are as follows:

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

## 19 2.2 Design requirement

20 The design requirement/specification is a necessary step for initiating the aircraft design  
21 process (which can be observed from Figure SI 1). In terms of the future aircraft configuration  
22 as stated previously the NASA N+2 BWB aircraft powered by UHB GTF engine for 301  
23 passengers is selected because a significant amount of data on the aircraft design for conducting  
24 a conceptual design study is available from NASA's studies [83–86,91,92]. It is to be noted

1 that only the span of this aircraft is known and the length or other geometric details of the  
 2 NASA N+2 BWB-GTF aircraft are not known directly from NASA’s study [83]. NASA’s  
 3 project has evolved over a period of ten years and this project has been published through a  
 4 series of publications [83–86,91,92]. A study by June et al. [93] reveals three-view engineering  
 5 drawing of the NASA N+2 BWB-GTF aircraft that seats 301 passengers. The other geometric  
 6 information of the aircraft will be estimated via reverse engineering since the aircraft span is  
 7 known. The outer mould line of the aircraft is developed in SolidWorks (discussed ahead) using  
 8 the three-view engineering drawing. Additionally, the wetted area ( $S_{wet}$ ) of the NASA N+2  
 9 BWB-GTF aircraft is not known through studies [83–86,91,93]. Therefore, this work will  
 10 calculate  $S_{wet}$  from the geometric model developed in SolidWorks.

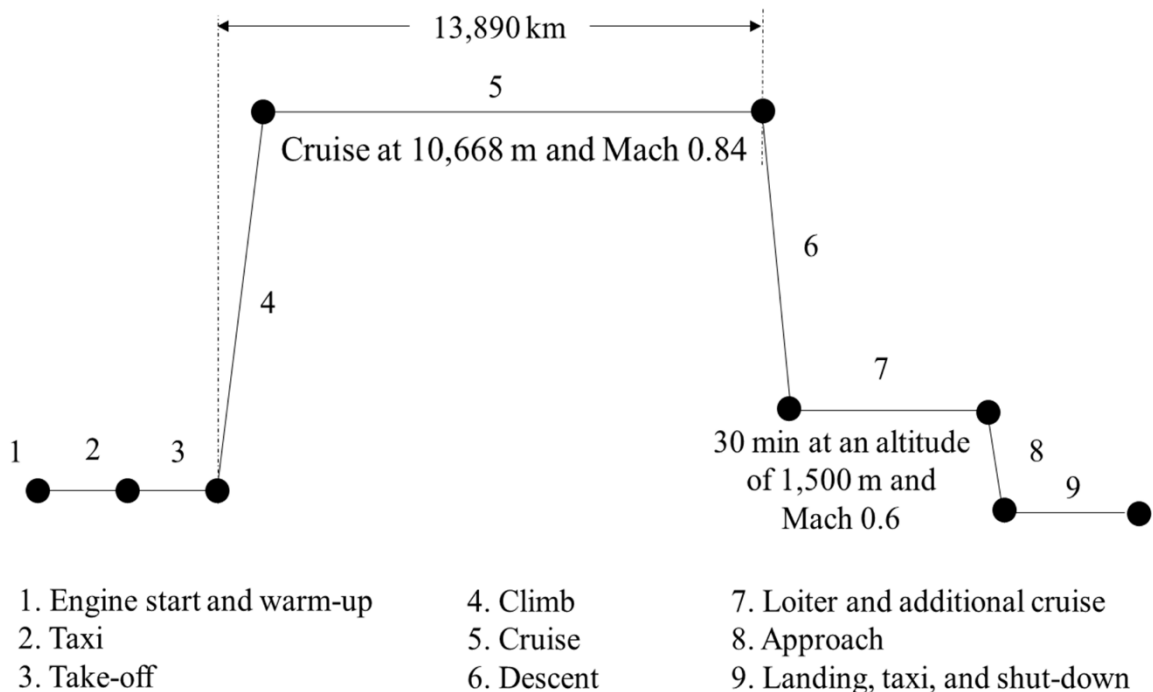
**Table 1. BWB aircraft design requirements**

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 <sub>2</sub>
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 <sup>2</sup>
Aspect ratio (AR)	6.1

11  
 12 The design requirement is to carry out a conceptual design of an LTA BWB aircraft for  
 13 transporting 301 passengers over a range of 7,500 nmi or 13,890 km. This aircraft should be  
 14 powered by LH<sub>2</sub> fuel. For developing the design of an LH<sub>2</sub> aircraft, a baseline case is required  
 15 where this BWB aircraft is powered by Jet-A. Modifications to the baseline case are made for  
 16 the use of LH<sub>2</sub> fuel, where the modifications are based on published literature. The BWB  
 17 aircraft design requirements are summarised in Table 1, and these are based on NASA’s study

1 [83]. It is to be noted that the GTOW and OEW from NASA’s study [83] are not listed in Table  
 2 1 because these are expected to change for different fuel cases and the weights of the two  
 3 engines decreases as observed in authors’ previous study [87] (use of lighter materials and  
 4 future component efficiencies). The block fuel weight ( $W_{F,block}$ ) is defined as the fuel weight  
 5 burnt during the flight mission. The ratio of  $W_{F,block}$  to total fuel weight at mission start ( $W_{F,total}$ )  
 6 of the Jet-A NASA N+2 BWB aircraft is 0.9 [83]. In this work, similar value for the said ratio  
 7 is used during the iteration process of the weight sizing method for estimating the aircraft  
 8 operational energy consumption (discussed in §2.5). For the BWB Jet-A (baseline) case, except  
 9 for the engine weights and  $W_{F,total}$ , there is no other change compared to the Jet-A NASA N+2  
 10 BWB aircraft [83]. For LH<sub>2</sub> fuel, modifications are required to the aircraft which changes OEW  
 11 and GTOW (discussed in §2.5).

12 2.3 Flight mission profile



13

14

**Figure 1. Multi-segment flight mission profile**

1           A simple multi-segment flight mission profile is considered in this work, which is  
2 represented in Figure 1. The mission begins with engine start and warm-up followed by taxi-  
3 out. Thereafter, the aircraft takes-off from the runway and climbs to the design cruise altitude  
4 of 10,668 m (or 35,000 ft as per set design requirements in Table 1). The mission design range  
5 is 13,890 km as discussed earlier, which is covered only during climb and cruise (primarily in  
6 cruise). After cruising, the aircraft descends to a loiter altitude. A standard value of 30 minutes  
7 loiter (or additional cruise) at an altitude of 5,000 feet (~1,500 m) at Mach 0.6 [94,95], is  
8 considered. The resulting loiter range is ~362 km as per calculations. After the loiter is  
9 completed, the aircraft approaches the runway for landing. Once the aircraft lands, it is taxied  
10 into the gate followed by engine shutdown. Overall, in this work, the contribution of flight  
11 range or distance to the total design range during flight segments except climb and cruise, is  
12 considered negligible. The loiter phase is an additional flight operation outside of the design  
13 range because it is carried out only when the aircraft has to wait for receiving clearance to land  
14 on the runway. The fuel consumed in the loiter phase is included in  $W_{F,block}$ . This flight mission  
15 profile is used for the calculation of  $W_{F,block}$  i.e., aircraft's block fuel consumption. A ratio of  
16  $W_{F,block}$  to  $W_{F,total}$  of 0.9 is used, as discussed previously, that accounts for reserve fuel  
17 requirement.

#### 18   2.4   Service ceiling equation

19           The service ceiling for a transport jet is defined as the altitude at which the maximum  
20 rate of climb (RoC) is 500 ft/min (2.54 m/s) for jet powered aircraft [96]. In the current work,  
21 the engine thrust requirement at top of climb (TOC) point for the LH<sub>2</sub> BWB aircraft is based  
22 on two separate calculations. The first method is using the service ceiling thrust equation i.e.,  
23 equation 1 below (based on resource [96]), and the second method is using  $T/W$  of the baseline  
24 (conventional jet fuel) BWB aircraft. Both predictions are found to be of similar magnitude,

1 however, the maximum of the two values is selected as the thrust required to be produced by  
2 the engines at TOC point. The aircraft thrust ( $T$ ) at service ceiling is given by,

$$T = W \left( \frac{\text{RoC}}{V_\infty} + \frac{\sqrt{1 - \left(\frac{\text{RoC}}{V_\infty}\right)^2}}{(L/D)_{\max}} \right) \quad \text{eq. (1) [source [96]]}$$

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

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

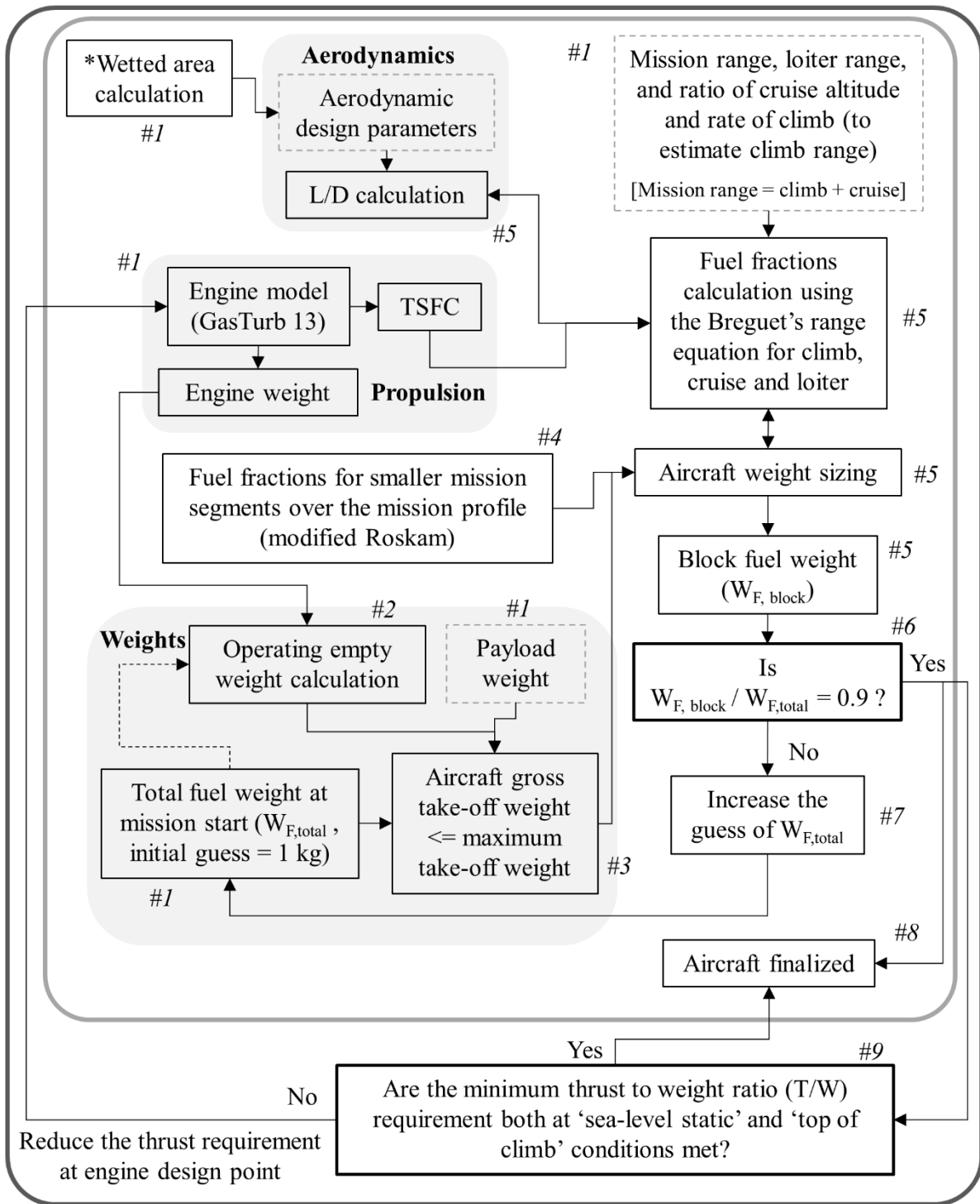
- 8 • An average climb speed of Mach 0.47 (calculation discussed in Part I SI §3.2 Table SI 13).
- 9 • The aircraft weight is an average weight of aircraft during climb (between the ‘end point  
10 of take-off’ and ‘beginning point of cruise’). This aircraft weight and  $(L/D)_{\max}$  are known  
11 from the weight sizing process.

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

## 14 2.5 Aircraft weight sizing method

15 The aircraft weight sizing process is not only iterative but also there is interaction  
16 between the different systems of aircraft with each other (viz. aerodynamics, propulsion,  
17 weight, etc.). The schematic/methodology is based on the standard sizing approach of Raymer  
18 [97] and Roskam [82]. The aircraft data (known and calculated) such as structural weight of  
19 different aircraft sections, tank weight for different fuels, and aircraft geometry and airfoils  
20 used are included in SI §2. In this work, three cases of LH<sub>2</sub> fuel are analysed.

21



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

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

#### 12 2.5.1 Convergence criteria

13           Referring to Figure 2, for all three fuelled BWB aircraft cases, the weight sizing  
14 process that estimates the aircraft operational energy consumption, a convergence criterion for  
15 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  
16 of LH<sub>2</sub> BWB aircraft cases begins with a guess value of  $W_{F,total}$  (other inputs are discussed in  
17 SI §3), and  $W_{F,block}$  is calculated from it for each fuel case. The guess value of  $W_{F,total}$  is iterated  
18 until the said ratio equals 0.9. This determines the GTOW of each of the BWB aircraft case.  
19 The GTOW of the Jet-A BWB aircraft (baseline case of this work) is set as the maximum take-  
20 off weight (MTOW) limit for all fuel cases. The specific energy consumption (SEC, in  
21 MJ/tonne-km) of the aircraft is estimated for different fuel cases since it is a significant  
22 performance parameter that enables the estimation of direct operating costs [5]. The SEC (eq.  
23 (2)) is given by,

SEC =

$$(W_{F,block} \times \text{fuel calorific value}) / (\text{payload weight} \times \text{aircraft range}) \cdot \text{eq. (2) [source [5]]}$$

1

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

7           For all three cases of LH<sub>2</sub> aircraft considered in this work, using the calculation  
8 process discussed in SI §2.3, the weight of LH<sub>2</sub> tank systems is calculated. In SI §2.3 the LH<sub>2</sub>  
9 tank weight is estimated from the gravimetric index ( $\eta$ ), which is defined as the ratio of  
10 cryogenic fuel weight to the sum of the dry tank weight and cryogenic fuel weight  
11 [18,80,89,98]. In authors' previous study [6], the effect of  $\eta$  on a long-range LH<sub>2</sub> aircraft energy  
12 performance is examined, and in the present work the authors assume an average  $\eta = 0.78$   
13 based on the study by Verstraete et al. [80] and authors' previous study [5] (details in SI §2.3).

14           The geometric model of the BWB aircraft is developed in SolidWorks [99], using the  
15 BWB geometry data discussed in SI §2.4. For the LH<sub>2</sub> aircraft cases, the geometric model is  
16 used for ensuring that the cryogenic tanks fit inside the BWB. The LH<sub>2</sub> tank systems must be  
17 adapted to the internal available space of the BWB aircraft in the inner wings and in aft body  
18 of the cabin (not affecting the aircraft cabin dimensions, the cabin layout and geometry are  
19 discussed in SI §2.4). The LH<sub>2</sub> tank systems are expected to be a tapered cylindrical tank,  
20 similar to the tapered cylindrical tank design or frustum-shaped tank design by Verstraete et al.  
21 [80] for the tube-wing aircraft. Verstraete et al. study is used for the design of the LH<sub>2</sub> fuel tank  
22 in this work (discussed in SI §2.3).

1 Post-convergence, the (minimum) required volume of LH<sub>2</sub> fuel is calculated from the  
2 total LH<sub>2</sub> fuel weight at the beginning of the mission (known from the weight sizing process)  
3 and the mass-density of LH<sub>2</sub> fuel (71 kg/m<sup>3</sup>). A tapered cylindrical tank integral to (and inside)  
4 the BWB structure is modelled in SolidWorks, using the insulation thickness (8.1 cm with  $\eta$  of  
5 0.78) and the (minimum) LH<sub>2</sub> fuel volume required to be stored (at the beginning of the  
6 mission). The tapered cylindrical LH<sub>2</sub> tank must be designed in a piece-wise manner for making  
7 maximum use of the internal space in the wings of a BWB aircraft. This is because the cross-  
8 sectional area of a BWB aircraft is variable both in the spanwise and lengthwise direction. The  
9 tapered cylindrical LH<sub>2</sub> tank shape can be considered as multiple small-tapered cylinders joined  
10 together. The tapered cylindrical shape resulting in this work could have negative structural  
11 and heat-transfer implications. The tank design volume is the volume formed by the ‘inner tank  
12 wall.’ The inner tank wall is separated from the outer tank surface by insulation. Therefore,  
13 care must be taken while designing the LH<sub>2</sub> tank systems such that the effect of the insulation  
14 thickness on volume calculation is accounted (details in SI §2.3). The weight sizing iteration  
15 continues until the end of convergence. The effect of  $T/W$  ratio of the aircraft is important  
16 during the convergence. However, it depends on the type of LH<sub>2</sub> aircraft case considered, which  
17 is discussed below.

## 18 2.5.2 LH<sub>2</sub> aircraft $T/W$ constraint

19 Referring to Figure 2, for Case 1 of the LH<sub>2</sub> aircraft, the sizing process begins with a  
20 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 LH<sub>2</sub> aircraft  
21 is calculated iteratively based on this guess value while employing the weight sizing process.  
22  $W_{F,\text{block}}$  of LH<sub>2</sub> fuel and  $W_{F,\text{total}}$  are calculated such that their ratio is 0.9. As discussed before,  
23 in case 1 the thrust production remains unchanged and therefore  $T/W$  is not a constraint in the  
24 weight sizing process. The  $T/W$  ratios at sea level static (SLS) and TOC are estimated using  
25 the thrust produced by engines (similar to Jet-A BWB aircraft case/design requirements) and

1 the aircraft weight estimated from the weight sizing process. An aircraft powered by LH<sub>2</sub> fuel  
2 will be lighter, compared to an aircraft powered by Jet-A considering only the effect of LH<sub>2</sub>'s  
3 higher gravimetric energy density, resulting in lower thrust requirement. The  $T/W$  ratios for  
4 Case 1 at SLS and TOC will be greater than the baseline case because in Case 1 the thrust  
5 production remains the same as the baseline case (Jet-A BWB aircraft). After the convergence  
6 criteria is met in the weight sizing process, the aircraft design is finalised. The main effect that  
7 is anticipated in Case 1 is the effect of lighter aircraft on the block fuel (energy) consumption  
8 reduction.

9 Referring to Figure 2 in Case 2 of LH<sub>2</sub>, the fan diameter is no longer a design  
10 constraint that is considered in Case 1 and thus the fan/engine diameter reduces (engine and  
11 aircraft weight reduces) because of lesser thrust requirement (due to a lighter aircraft because  
12 of lesser weight of high gravimetric energy density fuel and reduction in engine weight). Case  
13 2 of LH<sub>2</sub> aircraft begins with the (guess value of)  $W_{F,total}$  similar to Case 1. The convergence  
14 criteria for the weight sizing process remain similar to the process described for Case 1.  
15 However, the  $T/W$  ratio is an important factor considered in Case 2. The  $T/W$  ratio of the BWB  
16 Jet-A aircraft after the weight sizing process is calculated at SLS and TOC. The thrust value at  
17 on-design point is iteratively changed and the engine is designed along with its off-design  
18 performance (details in [87]). This is done in such a way that the  $T/W$  ratio at SLS and TOC is  
19 at least the respective calculated value for BWB Jet-A aircraft, or slightly higher. As discussed  
20 in §2.4, in the current work the engine thrust requirement at TOC for the LH<sub>2</sub> BWB aircraft is  
21 based on two separate calculations. The first method is using the service ceiling thrust equation,  
22 and the second method is using the  $T/W$  ratio of the baseline case (Jet-A BWB aircraft). Both  
23 predictions are of similar magnitude, however, the maximum of the two values is selected as  
24 the thrust required to be produced by engines at TOC point. It is to be noted that because this  
25 work designs aircraft at a conceptual level, the  $T/W$  ratios do not reach the exact values (as

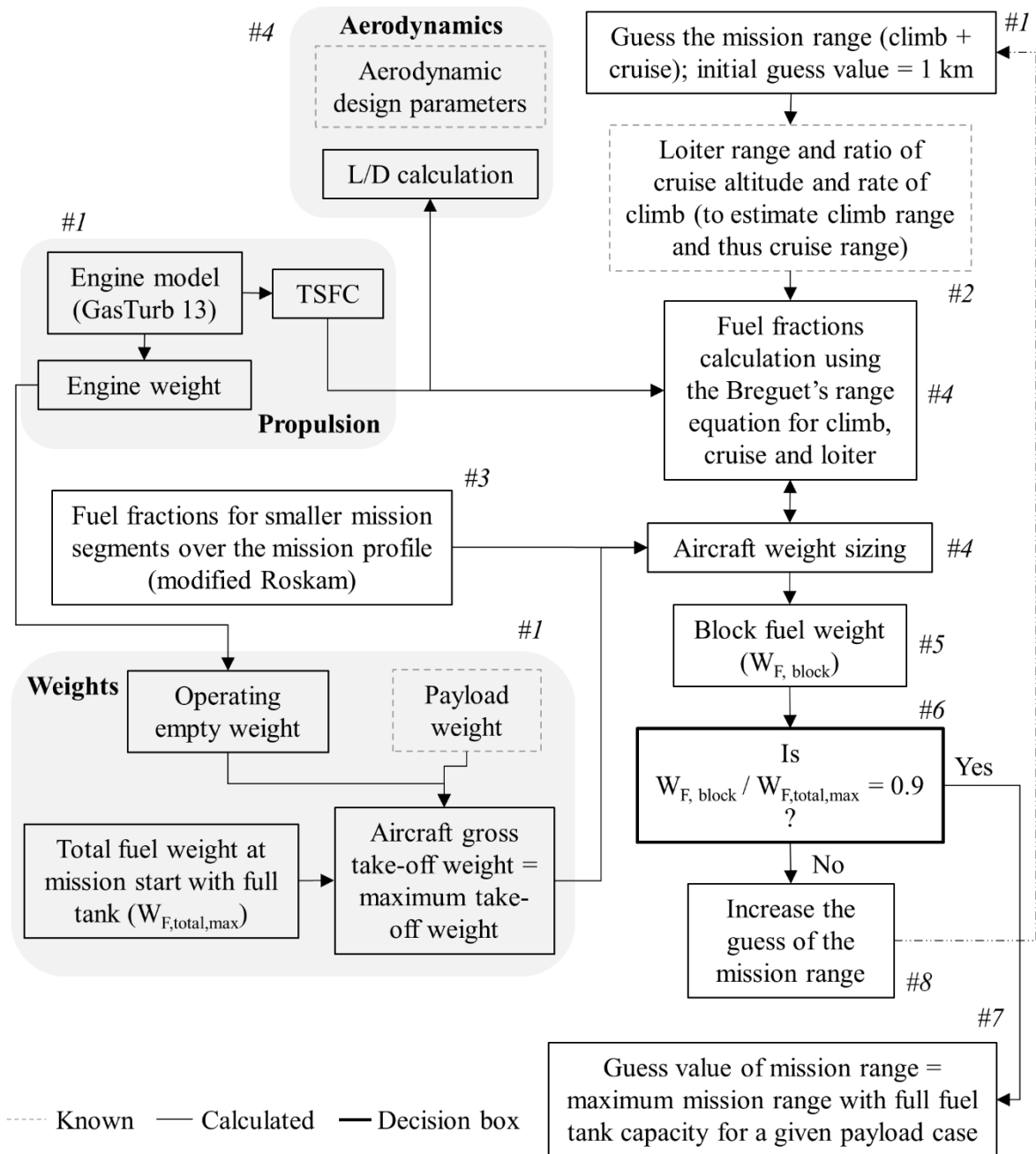
1 calculated for Jet-A BWB aircraft). Nevertheless, they are similar in magnitude to or are  
2 slightly higher than the  $T/W$  values for Jet-A BWB aircraft. Typically, during high-order  
3 modelling or high-fidelity analysis, a multi-point design and optimisation is carried out in a  
4 flight mission, such that the  $T/W$  are identical to the target values. While the thrust is iterated,  
5 the convergence criteria in the weight sizing process along with the sizing of the LH<sub>2</sub> fuel tank  
6 and its integration (structural penalty) within the BWB aircraft, remain same as described  
7 earlier. As thrust reduces, the following weights change along with it: the propulsion systems  
8 weights (smaller engine as compared to Case 1), the LH<sub>2</sub> fuel tank weight,  $W_{F,\text{total}}$  for LH<sub>2</sub> fuel,  
9 and GTOW of the aircraft (with aerodynamic parameters), as compared to Case 1. This  
10 interaction between different components of the weight-sizing process is shown in Figure 2.  
11 Only after the convergence criteria and the  $T/W$  ratio constraints are met, the aircraft design for  
12 Case 2 LH<sub>2</sub> aircraft is finalised.

13           Similarly, Case 3 of LH<sub>2</sub> aircraft is essentially Case 2 without engine cooling flows,  
14 because the engine operates colder and is smaller than the baseline (Jet-A) engine due to  
15 reduced thrust requirement. This further improves the thrust specific fuel consumption (TSFC),  
16 reduces propulsion systems weight, and therefore reduces  $W_{F,\text{block}}$  (as compared to Case 2). For  
17 the set convergence criteria and  $T/W$  ratio constraints, this results in reduction in  $W_{F,\text{total}}$ , the  
18 LH<sub>2</sub> fuel tank weight, propulsion systems weights, and GTOW of the aircraft (with effect on  
19 aerodynamics), as compared to Case 2. This interaction between different components of the  
20 weight-sizing process is shown in Figure 2. The methodology (including the convergence  
21 criteria and  $T/W$  effects) remains similar to Case 2. Only after the convergence criteria and the  
22  $T/W$  ratio constraints are met, the aircraft design for Case 3 LH<sub>2</sub> aircraft is finalised. The main  
23 effects that are anticipated in both Case 2 and Case 3 on block fuel (energy) consumption  
24 reduction are due to: the use of a high gravimetric energy density (LH<sub>2</sub>) fuel that reduces the  
25 aircraft weight; the effect of thrust requirement reduction due to a lighter aircraft; and the effect

1 of engine weight reduction (smaller engines due to thrust requirement reduction) on the aircraft  
2 weight; all of which result in block fuel (energy) consumption reduction. As can be observed,  
3 the conceptual design phase of the aircraft is not only iterative but also there is interaction  
4 between the different systems of aircraft with each other.

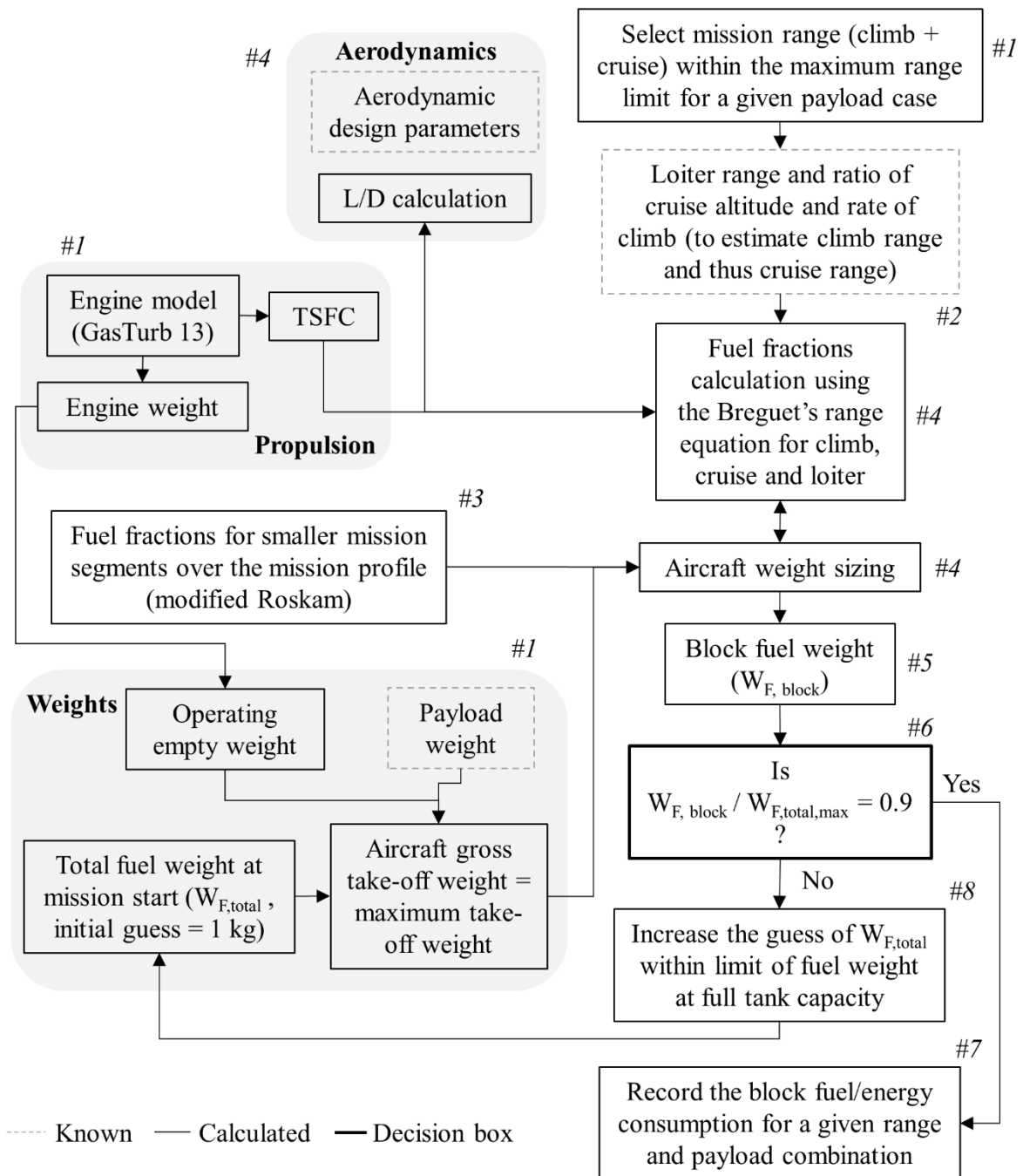
## 5 2.6 Off-design performance of aircraft

6 The aircraft performance for each fuel case at design point is known after following the  
7 aircraft weight sizing methodology described in previous section. The aircraft now becomes a  
8 ‘fixed’ aircraft. In real world applications, aircraft do not always fly with full design payload  
9 capacity, full fuel tank, and/or at design range. This work evaluates the performance of each of  
10 the aircraft powered by different fuels for typical range and payload combinations for long-  
11 range flights. Three payload cases are considered: 66.5% load factor (200 passengers or 35.59  
12 tonnes), 83.1% load factor (250 passengers or 44.49 tonnes), and 100% load factor (301  
13 passengers or 53.57 tonnes). The three load factor cases are evaluated for aircraft range between  
14 5,000 km and the maximum permissible range for a given load factor case flying with full tank  
15 capacity. The flowchart/schematic for the estimation of the maximum permissible range for a  
16 given load factor with full fuel tank is represented by Figure 3. Additionally, Figure 4 shows  
17 the flowchart/schematic for the estimation of the operational energy consumption of an aircraft  
18 for given range and load factor combinations.



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



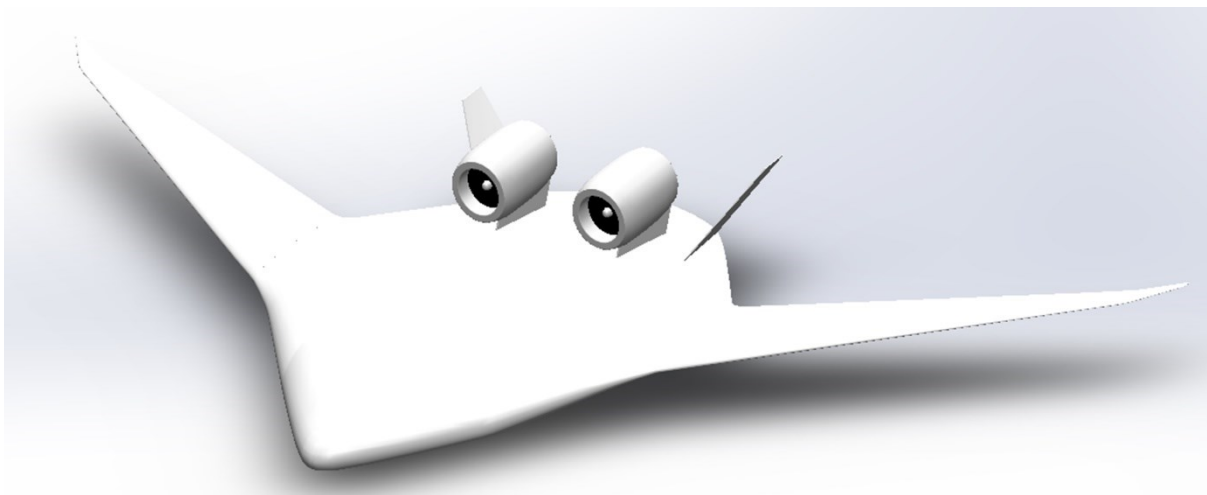
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**Figure 4. Schematic for the estimation of the operational energy consumption of an aircraft for given range and payload combination**

1    **3.    Results and discussion**

2    3.1    Design point

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



15

16            **Figure 5. Geometric model of BWB aircraft simulated using SolidWorks**

17

**Table 2. Performance comparison of Boeing 777-200 LR and future aircraft [Jet-A BWB aircraft and BWB LH<sub>2</sub> 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 <sub>2</sub> 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 $\eta$	-	-	-	0.78	0.78	0.78
$W_{F,total}$	kg	73,965	72,678	24,250	23,817	23,347
<i>Ratio of GTOW and GTOW<sub>NASA</sub></i>	-	1	0.975	0.806	0.801	0.795
$W_{F,block}$	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 <sup>2</sup> )	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])		

1

2 Table 2 provides the performance comparison of Boeing 777-200 LR and future aircraft

3 [Jet-A BWB aircraft and BWB LH<sub>2</sub> aircraft (all three cases)] over one flight mission. It can be

1 observed from Table 2 that  $T/W$  ratio at SLS and TOC for BWB LH<sub>2</sub> aircraft tend towards the  
2  $T/W$  ratios of BWB Jet-A aircraft at SLS and TOC, from case 1 to case 3 (from the unoptimized  
3 to the optimised aircraft). In all three cases of BWB LH<sub>2</sub> aircraft the minimum required  $T/W$  at  
4 SLS and TOC are met, for a flight to be possible with the same airframe used for Jet-A BWB  
5 aircraft (and NASA N+2 BWB 301 PAX aircraft).

6 The NASA N+2 BWB 301 PAX (Jet-A) aircraft provides 47% reduction in block fuel  
7 energy consumption, as compared to Boeing 777-200LR, which is known from Nickol et al.  
8 [83] study. The Jet-A BWB aircraft (designed in this work) is (1.74%) more efficient than  
9 NASA N+2 BWB 301 PAX (Jet-A). This energy efficiency improvement is attributable to  
10 TSFC improvement (high component efficiencies and engine weight reduction, details in [87])  
11 that reduces the GTOW.

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

17 It is important to note that the LH<sub>2</sub> fuel tank systems (for the designed mission) fit inside  
18 the BWB aircraft primarily because of the consideration of future aircraft technology that  
19 significantly reduces the fuel weight and fuel volume to be carried on the aircraft. For example:  
20 as discussed above, BWB LH<sub>2</sub> aircraft (all three cases) provides energy-efficiency  
21 improvement of approximately 50%, as compared to Boeing 777-200LR. Had there been no  
22 energy efficiency improvement due to the use of aircraft technology, the LH<sub>2</sub> fuel volume  
23 required would be at least twice the volume of fuel required by the N+2 BWB LH<sub>2</sub> aircraft  
24 cases. This fuel volume cannot be accommodated in the present airframe and significant  
25 modifications to the BWB geometry would be required (resulting in weight penalty) or a larger

1 BWB airframe would be required. The use of future aircraft technology (engine and airframe)  
2 enables successful and efficient use of LH<sub>2</sub> fuel in the aircraft. This is further supported by a  
3 study by Adler et al. [77] which designs both tube-wing and BWB powered by hydrogen using  
4 present-day aircraft technology. Adler et al. observe that hydrogen powered BWB (employing  
5 present-day aircraft technology) has a 3.8% energy penalty, compared to a Jet-A BWB. The  
6 energy penalty for a hydrogen powered tube-wing (employing present-day aircraft technology)  
7 is 5.1%, relative to Jet-A tube-wing. Adler et al. suggest that maturation in BWB technology  
8 can benefit the use of hydrogen, which is similar to the recommendations by CleanSky report  
9 [18].

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

17 Compared to the Jet-A BWB aircraft, BWB LH<sub>2</sub> aircraft case 1, 2, and 3 provide 7.3%,  
18 9%, and 10.8% reduction, respectively, in the block fuel energy consumption. As discussed  
19 before, the improvement in the block fuel energy consumption in all three cases of BWB LH<sub>2</sub>  
20 aircraft is primarily due to the improved TSFCs (details in [87]) and due to the aircraft weight  
21 reduction. In case 2 and 3 of BWB LH<sub>2</sub> aircraft the reduction in the thrust requirement (leading  
22 to engine weight reduction and therefore the reduction of aircraft GTOW) is an additional  
23 reason for the improved energy efficiency. It was observed in authors' previous studies [5,6],  
24 that tube-wing LH<sub>2</sub> aircraft requires increase in fuselage length to accommodate LH<sub>2</sub> fuel tanks  
25 which negatively impacts  $L/D$  and therefore the aircraft energy consumption, for maintaining

1 same range and payload as that of baseline case. This negative impact is not observed for this  
2 N+2 BWB aircraft because of their higher internal volume that enable storage of LH<sub>2</sub> tanks and  
3 energy efficiency. Overall, a BWB architecture is therefore more energy efficient and effective  
4 for LH<sub>2</sub> use, compared to a tube-wing architecture.

5 The relevant detailed results of the different components/sub-systems of the weight  
6 sizing process, for all fuel cases are included in the SI document. The iteration parameters,  
7 aerodynamic performance, propulsion results, characteristics of LH<sub>2</sub> tank systems (tank counts,  
8 shapes, and dimensions), and breakdown of aircraft weight and fuel consumed during one flight  
9 mission, are included in SI §4.1, 4.2, 4.3, 4.4, and 4.5, respectively.

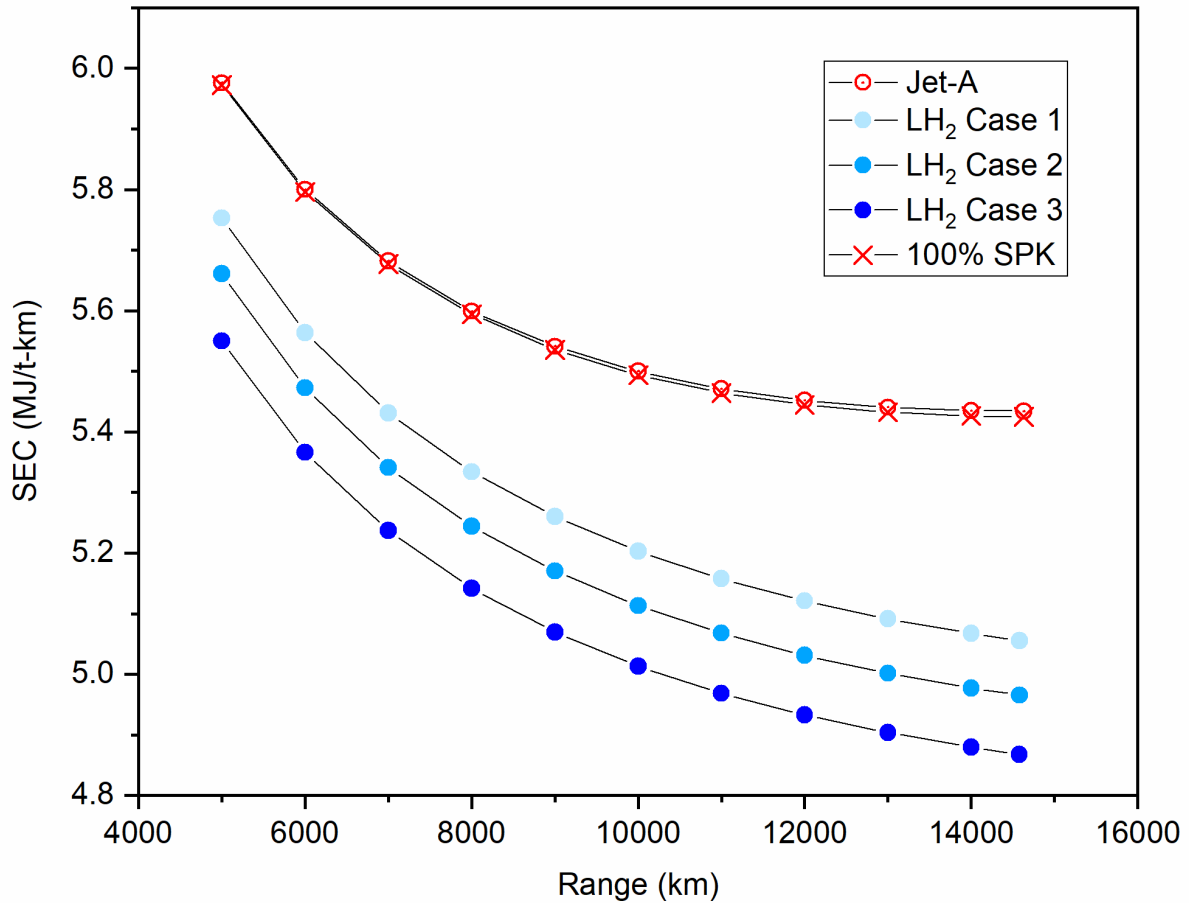
10 The significant reduction in the GTOW of LH<sub>2</sub> aircraft observed from Table 2 (greater  
11 than 19% reduction in GTOW depending on case) is of importance during emergency landing  
12 situations as a lighter aircraft will not necessitate jettison of a highly flammable LH<sub>2</sub> fuel  
13 (details in SI §4.6). A similar analysis is conducted for tube-wing LH<sub>2</sub> aircraft in authors'  
14 previous study [5] and similar observations were made. The reduction in GTOW and  
15 resultantly the take-off wing-loading (from baseline) for (N+2) BWB LH<sub>2</sub> aircraft in this work  
16 is observed to be ~20%, compared to NASA N+2 BWB, 44.6% compared to B777-200 LR,  
17 and 39% compared to A350-1000. For an N+3 tube-wing aircraft, based on authors' previous  
18 study [6] this reduction in GTOW is ~34%, compared to A350-1000. For the above two  
19 futuristic technology improvement scenarios, the GTOW reduction potential for LH<sub>2</sub> aircraft is  
20 much greater compared to the 15% reduction in GTOW observed in authors' previous study  
21 [5] for a LH<sub>2</sub> version of A350-1000 (tube-wing aircraft of present-day technology), relative to  
22 Jet-A A350-1000.

23 Lastly, a comparison of the change in the take-off wing-loading and cruise  $L/D$  with  
24 literature due to fuel switch from Jet-A to LH<sub>2</sub> in a BWB aircraft, is conducted. Of the limited  
25 number of studies on BWB [72,73,77,78], only the study by Adler et al. [77] enables such a

1 comparison. The study finds that the take-off wing-loading and cruise  $L/D$  drops by 17.2% and  
2 6%, respectively, for a switch of fuel from Jet-A to LH<sub>2</sub> in a BWB aircraft. This is similar to  
3 the findings in the present work where there is a reduction in take-off wing-loading and cruise  
4  $L/D$  of 19.4 – 20.5% and 5 – 5.7%, respectively. The design point characteristics of the 100%  
5 SPK BWB aircraft is included in SI §4.9 (Table SI 21).

### 6 3.2 Off design performance characteristics

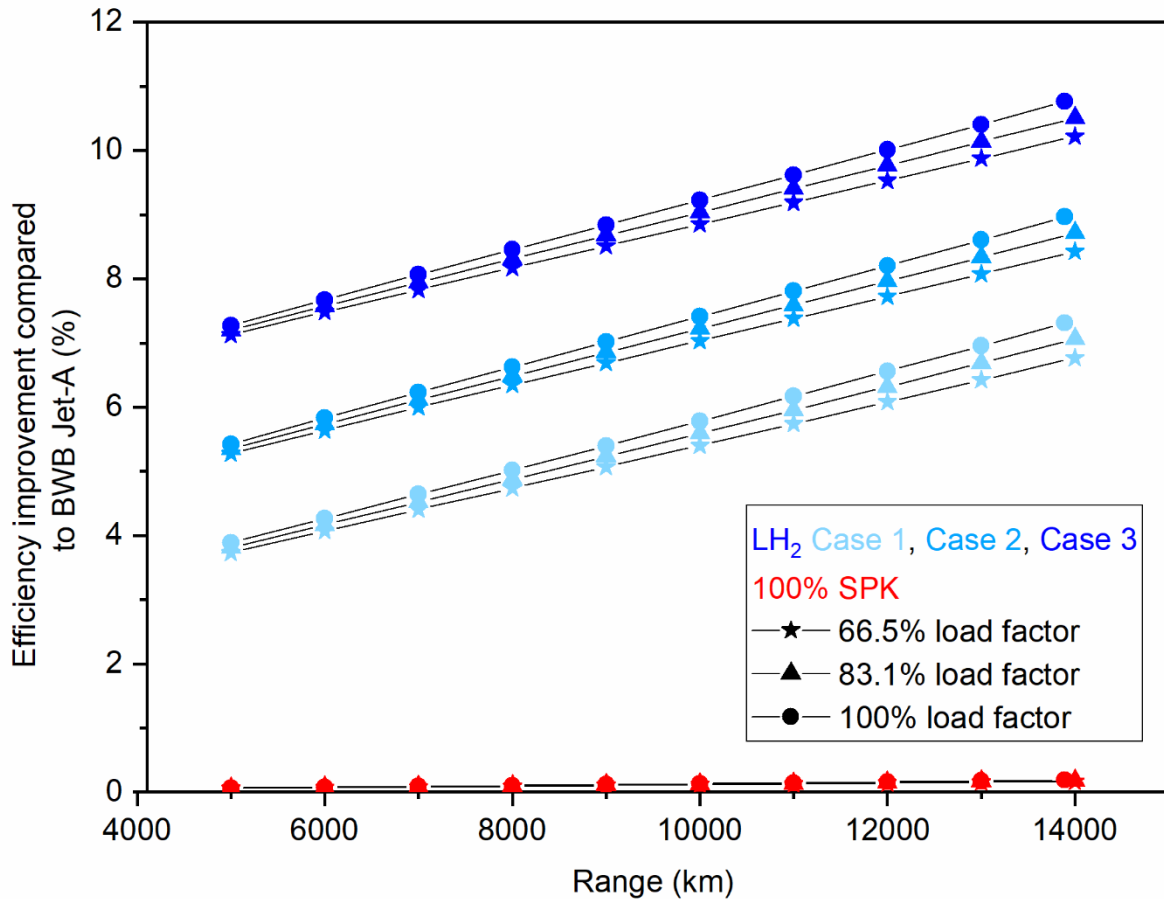
7 The methodology/flowchart for the aircraft off-design point performance estimation  
8 has been discussed in §2.6. Three payload (load factor) cases are considered: 66.5% load factor  
9 (200 passengers or 35.59 tonnes), 83.1% load factor (250 passengers or 44.49 tonnes), and  
10 100% load factor (301 passengers or 53.57 tonnes). The three load factor cases are evaluated  
11 for aircraft range between 5,000 km and the maximum permissible range for a given load factor  
12 case flying with full tank capacity. Figure 6, and (in SI §4.7) Figures SI 5 and SI 6 show the  
13 variation of SEC with range for BWB aircraft powered by different fuels for 66.5% load factor,  
14 83.1% load factor, and 100% load factor, respectively. In all three figures same trend is  
15 observed for SEC vs range i.e., with increasing range, the SEC decreases for each of the fuel  
16 case.



1

2 **Figure 6. Variation of SEC with range for BWB aircraft powered by different fuels for**  
 3 **66.5% load factor**

4 Additionally, at any given range, by increasing the load factor the absolute value of  
 5 SEC decreases for each of the fuel case. BWB LH<sub>2</sub> aircraft are more efficient at greater range  
 6 and the SEC curve appears to keep dipping with increasing range, as compared to Jet-A. This  
 7 (for BWB LH<sub>2</sub> aircraft) contrasts with the observations made in authors' previous study [5],  
 8 where the SEC of LH<sub>2</sub> 'tube-wing' aircraft, though decreases with range, is less sensitive  
 9 beyond (the range of) 10,000 km. SEC of Jet-A BWB (and 100% SPK) is less sensitive to  
 10 range beyond ~13,000 km. Of the three BWB LH<sub>2</sub> aircraft design cases, Case 3 offers the best  
 11 SEC at all range and load factor combinations.



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**Figure 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**

Insights from Figure 6, and (in SI §4.7) Figures SI 5 and SI 6 can be visualised through a single plot i.e., Figure 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 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 LH<sub>2</sub> aircraft, compared to the Jet-A BWB aircraft. The BWB LH<sub>2</sub> Case 3 aircraft is

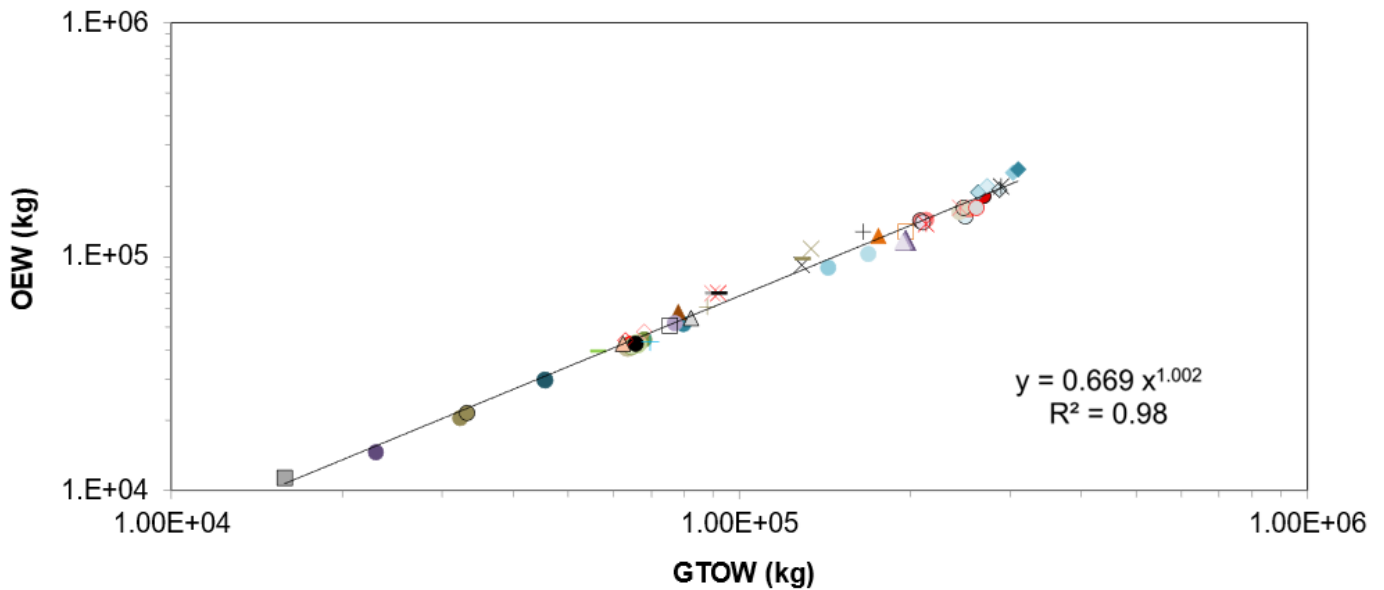
1 the most efficient aircraft at all range and load factor combinations, compared to the Jet-A  
2 BWB aircraft.

### 3 3.3 Relationship between OEW and GTOW for LH<sub>2</sub> aircraft

4 It is important to conduct a final evaluation, i.e. a sanity check, by analysing the  
5 relationship between OEW and GTOW for the transport aircraft designed in this work and the  
6 transport aircraft in literature (separately for each fuel type), through regression. In this work,  
7 the database of aircraft is updated relative to the authors' previous study [5]. Currently, there  
8 are 54 combustion-based LH<sub>2</sub> aircraft and 70 Jet-A (and 100% SPK) aircraft from literature,  
9 separately, inclusive of type of architecture (tube-wing and unconventional), class (regional,  
10 single aisle, small twin aisle, LTA, and VLTA) and/ combustion based or range (short, mid,  
11 and long range).

12 Figure 8 shows the relationship between OEW and GTOW of LH<sub>2</sub> aircraft (54 aircraft)  
13 from the present work and literature (all are tube-wing except six BWB as indicated). It can be  
14 observed that the relationship between OEW and GTOW for the aircraft designed in this work  
15 is similar to the LH<sub>2</sub> aircraft designs in literature, and the developed equation would facilitate  
16 conceptual LH<sub>2</sub> aircraft design and weight sizing studies. Similar work is done by Roskam [82]  
17 but that is limited just to Jet-A aircraft.

18 For Jet-A (and 100% SPK) aircraft, historical aircraft data and literature is used for the  
19 regression analysis, where the data is of different sizes of aircraft. Table SI 17 (SI §4.7) lists  
20 the OEW and GTOW of aircraft already into service, in literature, and aircraft designed in this  
21 work. Overall, 70 aircraft are listed in Table SI 17 (SI §4.7). 27 present-day aircraft (Jet-A) and  
22 nine futuristic aircraft (Jet-A and 100% SPK) are included in the database. An equation is  
23 developed in Figure SI 7 (in SI §4.7) which shows the relationship between OEW and GTOW  
24 of aircraft in service, of future (other studies), and future aircraft designed in this work (only  
25 Jet-A and 100% SPK).



- Jagtap et al. (2023) (366 PAX 13,870 km) tank index 0.78
- Jagtap et al. (2024) N+2 (366 PAX 13,870 km) tank index 0.88
- Jagtap et al. (2024) N+3 (366 PAX 13,870 km) tank index 0.88
- Brewer (130 PAX 2,778 km)
- Brewer (200 PAX 5,556 km)
- Brewer (400 PAX 5,556 km)
- Brewer (400 PAX 10,186 km)
- Brewer (400 PAX 18,520 km)
- ▲ Verstraete (150 PAX 4,000 km)
- ▲ Verstraete (300 PAX 9,000 km)
- ▲ Verstraete (400 PAX 14,000 km)
- Proesmans et al. ATR (67 PAX 2,410 km)
- Proesmans et al. COC (67 PAX 2,410 km)
- Proesmans et al. ATR (130 PAX 3,200 km)
- Proesmans et al. COC (130 PAX 3,200 km)
- Proesmans et al. ATR (253 PAX 10,800 km)
- Proesmans et al. COC (253 PAX 10,800 km)
- Silberhorn et al. (2019) (165 PAX 5,740 km) Rear tank
- Silberhorn et al. (2019) (165 PAX 5,740 km) Top tank
- Silberhorn et al. (2019) (165 PAX 5,740 km) Pod tank
- + Airbus Cryoplane (185 PAX 7,400 km)
- × Gomez et al. (194 PAX 9,000 km)
- × Silberhorn et al. (2022) (261 PAX, 7,220 km)
- + Lammen et al. (300 PAX, 3,704 km)
- Troeltsch et al. (400 PAX 11,853 km)
- Onorato et al. (72 PAX, 926 km)
- Onorato et al. (150 PAX, 4,560 km)
- Onorato et al. (295 PAX, 7,674 km)
- ◆ Mourouzidis et al. (332 PAX, 8,890 km) tank index 0.45
- ◆ Mourouzidis et al. (332 PAX, 8,890 km) tank index 0.67
- ◆ Huete et al. (232 PAX, 10,370 km)
- ◆ Huete et al. (388 PAX, 6,112 km)
- ◇ Huete et al. (720 PAX, 3,334 km)
- × Beck et al. BWB (524 PAX 11,408 km)
- Smith et al. (242 PAX, 4,250 km)
- Karpuk et al. (~210 PAX, 4,000 km)
- Karpuk et al. BWB (378 PAX, 10,580 km)
- △ Ramm et al.
- + Burschik et al. (250 PAX, 2,778 km)
- × Adler et al. (420 PAX, 10,186 km)
- × Adler et al. BWB (420 PAX, 10,186 km)
- ◇ Barton et al. (108 PAX, 3,000 km) 12.5 km cruise altitude
- ◇ Barton et al. (108 PAX, 3,000 km) 14 km cruise altitude
- Oak et al. (132 PAX, 5,740 km)
- VanLandingham et al. (~40 PAX, 1,948 km)
- VanLandingham et al. (~180 PAX, 6,575 km)
- ▲ Camboni (150 PAX, 3,000 km)
- × Palaia et al. (84 PAX, 7,810 km)
- × Palaia et al. (84 PAX, 9,770 km)
- Palaia et al. (116 PAX, 5,990 km)
- Palaia et al. (116 PAX, 7,730 km)
- ▲ This study BWB LH2 Case 1 (301 PAX 13,890 km)
- ▲ This study BWB LH2 Case 2 (301 PAX 13,890 km)
- ▲ This study BWB LH2 Case 3 (301 PAX 13,890 km)

2 **Figure 8. Relationship between OEW and GTOW of LH<sub>2</sub> aircraft (54 aircraft) from the**  
 3 **present work and literature (all are tube-wing except six BWB as indicated) (Source of**  
 4 **data [5,6,22,26–28,45,47,49,50,54,61–64,66–70,73,75–77,79,81])**

5 3.4 Other results, comments, and discussion

6 It was observed through the findings of the authors' previous study [5] (details in SI  
 7 §4.8) that liquid natural gas (LNG) powered aircraft showed a potential in terms of getting  
 8 closer to the design target range (10,895 km for LNG case 1, compared to target of 13,870 km).

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

9 In previous studies [5,6], a qualitative discussion on other significant aspects for LH<sub>2</sub>  
10 and 100% SPK powered flight are included. These include: (a) other necessary modifications  
11 to aircraft and aviation sub-systems (infrastructure), (b) effects on airline decision-making and  
12 planning of fleet, and (c) effects of fuel and life-cycle costs.

### 13 3.5 Limitations of the present work

14 The effect of cryogenic tank is not considered in detail and is based on other studies.  
15 Ideally, a separate design model for cryogenic tank is required that accounts for both internal  
16 and external mechanical and thermal stresses. Additionally, given the scope of this work being  
17 restricted to the conceptual design phase, the quantitative impacts of other necessary  
18 modifications to LH<sub>2</sub> aircraft sub-systems are not considered in this work. These include  
19 modifications to fuel lines and engine/combustor and installation of a heat exchanger for phase  
20 change of liquid to gaseous hydrogen, and for 100% SPK aircraft sub-systems such as change  
21 of seals in the high-pressure fuel systems, etc. (see SI §3.4.2 for assumptions). Based on other  
22 (unpublished) research efforts, this additional weight could be insignificant, compared to  
23 GTOW (on the order of <1% of GTOW).

24 The estimation of the aircraft's operational energy consumption is based on a simplified  
25 (multi-segment) mission in the weight sizing process, where the energy consumption in smaller

1 flight segments is calculated using the modifications to Roskam's fuel fraction. The impact of  
2 headwinds/tailwinds are not accounted in this work. Additionally,  $L/D$  ratios during climb,  
3 cruise, and loiter are average values for respective segments based on the aircraft weight during  
4 respective segment's beginning and end. The  $L/D$  ratio calculation for cruise and loiter assumes  
5 constant speed and angle of attack. Moreover, in the estimation of the drag coefficient, wave  
6 drag is considered to be negligible which is typically considered in high-fidelity analysis.

7 The estimation of aircraft performance characteristics in this work is constrained to the  
8 aircraft use-phase only and these comprise of aerodynamic, weight, and energy performance.  
9 Compared to Jet-A, LH<sub>2</sub> fuel combustion generates more water vapour at typical cruise altitude  
10 and might increase contrail formation which negatively impacts the climate [5]. Additionally,  
11 fuel costs which depend on the feedstock and/or pathway used to manufacture fuel, and life-  
12 cycle impacts, are not accounted in this work. Also, emission performance, and flight  
13 economics (comparison for different fuels) and its impact on airline decision-making and  
14 planning of fleet are not considered in this work. Lastly, aircraft stability and stress/structural  
15 analysis are not conducted in this work. Overall, the weight sizing process in this work is a  
16 low-order or low-fidelity analysis and errors in aircraft performance metrics are expected.

#### 17 **4. Conclusions**

18 LH<sub>2</sub> is a promising fuel for decarbonizing long-haul aviation, primarily due to its  
19 potential for zero carbon emissions during flight. However, the low volumetric energy density  
20 of LH<sub>2</sub> can negatively impact the energy consumption of tube-wing aircraft. In contrast, the  
21 BWB airframe offers a more efficient integration of LH<sub>2</sub> systems, as it enhances aerodynamic  
22 performance and provides greater internal volume for accommodating cryogenic storage. As a  
23 result, the BWB design may be a more suitable option for LH<sub>2</sub> powered aircraft.

24 In a first, this work conducts the energy performance modelling of LH<sub>2</sub> and 100% SPK  
25 (separately) powered BWB aircraft (301 passengers and 13,890 km) of future (2030+ or N+2)

1 BWB aircraft using conceptual aircraft design approach. The conceptual design phase in this  
2 work is limited to the LH<sub>2</sub> aircraft weight-sizing process. In terms of the methodology, this  
3 work provides a structured weight sizing process for a hydrogen powered BWB aircraft using  
4 future technology.

5 At the design point, the energy consumption of the N+2 BWB powered by Jet-A, 100%  
6 SPK, and LH<sub>2</sub> is observed to be reduced by 47.9%, 48%, and 51.7 – 53.5% (depending on  
7 optimisation case), respectively, compared to Boeing 777-200LR. LH<sub>2</sub> fuel tank systems  
8 designed in this work fit inside the BWB aircraft primarily because of the consideration of  
9 future (N+2) aircraft technology that significantly reduces the fuel weight and fuel volume to  
10 be carried on the aircraft. The SEC of N+3 tube-wing LH<sub>2</sub> aircraft known from literature could  
11 be 33% lesser and requires a fuselage length increase of 22%, compared to A350-1000 Jet-A  
12 aircraft. For the A350-1000 LH<sub>2</sub> aircraft modelled in literature using present-day aircraft  
13 technology, the SEC is 11% greater and requires 37% increase in fuselage length, compared to  
14 A350-1000 Jet-A aircraft. The (N+2) BWB LH<sub>2</sub> aircraft (case 3) modelled in this work  
15 provides energy consumption improvement of approximately 53.5%, as compared to Boeing  
16 777-200LR, or 48.5% compared to A350-1000 Jet-A aircraft. Without the energy consumption  
17 benefits from future aircraft technology, the LH<sub>2</sub> fuel volume required would be at least double  
18 that of the volumes needed in the N+2 BWB LH<sub>2</sub> cases modelled here. The adoption of future  
19 (2030+) aircraft technology (engine and airframe) enables successful, effective, and efficient  
20 use of LH<sub>2</sub> fuel in the aircraft. Compared to the Jet-A BWB aircraft, BWB LH<sub>2</sub> aircraft case 1,  
21 2, and 3 provide 7.3%, 9%, and 10.8% reduction, respectively, in the energy consumption at  
22 the design point.

23 Additionally, at off-design points, for a given fuel case, an increase in load factor of the  
24 BWB LH<sub>2</sub> aircraft leads to a reduction in the maximum achievable range. For a given fuel case,  
25 increasing the load factor of the BWB LH<sub>2</sub> aircraft, improves the SEC, compared to a Jet-A

1 BWB aircraft. Moreover, for a given fuel case and load factor, the SEC improves with  
2 increasing range, compared to a Jet-A BWB aircraft. This improvement in SEC is observed  
3 prominently for all three cases of BWB LH<sub>2</sub> aircraft, compared to the Jet-A BWB aircraft. The  
4 BWB LH<sub>2</sub> Case 3 aircraft is the most energy efficient aircraft at all range and load factor  
5 combinations, compared to the Jet-A BWB aircraft.

6         Moreover, at the design point the OEW and GTOW for LH<sub>2</sub> aircraft, as derived from  
7 both prior literature and the present study, are found to be related by a power law equation.  
8 This relationship will facilitate future research on the conceptual design and weight sizing of  
9 LH<sub>2</sub> powered aircraft. Overall, purely based on the energy performance, the BWB LH<sub>2</sub> aircraft  
10 emerges as a preferred long-range transport aircraft type for long-haul travel, as supported by  
11 various studies in the literature comparing LH<sub>2</sub> powered tube-wing and BWB aircraft.

12         The BWB LH<sub>2</sub> aircraft has a clear advantage over Jet-A BWB aircraft in terms of energy  
13 consumption (use-phase) and that this BWB LH<sub>2</sub> aircraft in the use-phase would emit only  
14 water vapour and small amounts of oxides of nitrogen. In terms of future work, the aircraft  
15 energy consumption and performance estimation from this work would help studies on: (i) use-  
16 phase emissions and contrails modelling; (ii) further development in aircraft technology to  
17 enable long-range LH<sub>2</sub> flight; (iii) aircraft operations such as changes in cruise altitude and  
18 flight speed for contrail mitigation; (iv) estimation of fuel pathways and/or feedstocks that  
19 could enable climate-neutral long-range aviation on a lifecycle basis; and (v) estimation of  
20 ticket cost as the direct operating cost depends on fuel production process and aircraft energy  
21 consumption; (vi) comparative study of life-cycle socio-environmental costs of flight powered  
22 by alternative fuels, compared to Jet-A, thereby facilitating aviation policy making.

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5 **Declaration of competing interest**

6           The authors declare that they have no known competing financial interests or personal  
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8

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