Energy performance evaluation of alternative energy vectors for subsonic long-range tube-wing aircraft

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Abstract

Decarbonising long-range aviation is challenging. This study evaluates the performance of six low-carbon fuels and their realistic impacts on aircraft design for a large long-range passenger aircraft using Breguet's range equation. Liquid hydrogen (LH_2) and 100% synthetic paraffin kerosene (SPK) are the only two alternative fuels found to be viable. Using present-day technology, we find that the design-point specific energy consumption (SEC, MJ/tonne-km) of tube-wing aircraft powered by LH_2 and 100% SPK are 11% higher and 0.2% lower relative to Jet-A, respectively. At off-design points, SEC of 100% SPK and LH_2 are always similar to and greater than Jet-A, respectively. LH_2 aircraft SEC decreases with increasing range and is less sensitive beyond 10,000 km. In a first, we develop an equation that enables LH_2 aircraft weight-sizing. Our results should inform studies on LH_2 and 100% SPK aircraft operating costs and lifecycle emissions.

Keywords

Alternative fuels; low-carbon aviation; liquid hydrogen aircraft; decarbonising long-range flight

Nomenclature

AR	Aspect ratio
ATR	Average temperature response
C and D	Regression coefficients
COC	Cash operating cost
C_D	Total drag coefficient
$C_{D,O}$	Zero-lift drag coefficient
C_f	Skin friction coefficient
C_L	Lift coefficient
d_f	Fuselage diameter
e	Oswald's Skin friction coefficient efficiency factor
FCH	Fuel cells and hydrogen
g	Acceleration due to gravity
GTOW	Gross take-off weight
h	Lower calorific value
l_f	Fuselage length
LTA	Large twin aisle
LH_2	Liquid hydrogen
LNG	Liquid natural gas
LNH_3	Liquid ammonia
L/D	Lift to drag ratio
$\dot{m}_f$	Fuel consumption rate
MTOW	Maximum take-off weight
OEW	Operating empty weight
PAX	Passengers
R	Aircraft range
RF	Radiative forcing
S	Wing area
SEC	Specific energy consumption
SPK	Synthetic paraffin kerosene
S_{wet}	Aircraft wetted area
$S_{wet, Fuselage}$	Fuselage wetted area
V	Cruise speed of aircraft
VLTA	Very large twin aisle
$W_{aircraft}$	Aircraft weight in cruise
$W_{initial}$	Initial cruise aircraft weight
W_{final}	End of cruise aircraft weight
$W_{Fuselage}$	Aircraft fuselage weight
$W_{F,block}$	Block fuel weight
$W_{F,total}$	Total fuel weight carried at mission start
W_p	Passenger payload weight
ΔL	Additional fuselage length for alternative liquid fuels
η	Gravimetric index
η_o	Overall efficiency
λ	Ratio of dry tank weight and cryogenic fuel weight
ω	Weight reduction factor for fuselage weight and OEW
ρ	Fuel density
ρ_a	Density of air at cruise altitude

1. Introduction

Currently aviation accounts for ~3.5% of the total anthropogenic radiative forcing (RF), including the effects of aviation induced cirrus (Lee et al., 2021) . The aviation industry anticipates a doubling of air-traffic by 2040 (Boeing, 2020), despite the COVID-19 pandemic (Boeing, 2020; IATA, 2021a) and therefore aviation's total contribution to anthropogenic radiative forcing is forecast to increase by 2050 (IATA, 2021b; International Civil Aviation Organization Secretariat, 2010; Lee, 2018; Lee et al., 2021; Vedantham, 1999). In response, the aviation industry has set a target for 'carbon neutral growth' from 2020. Considering the projected growth in air traffic, the industry expects that emissions reductions will result from low-carbon alternative fuels, improved aircraft technologies and operational improvements, contributing 50%, 30% and 20% to the carbon neutral growth target, respectively (Hupe, 2020).

Long-range aircraft are either: large twin aisle (LTA) aircraft seating approximately 300 passengers (PAX) over 14,000 km at design point, such as the Boeing 777 and 787, and Airbus A350; or very large twin aisle (VLTA) aircraft seating at least 400 PAX for more than 14,000 km at design point, such as the Boeing 747 and Airbus A380. Long-range passenger aircraft (range > 5,000 km, seating approximately 250 PAX) contribute to 27% of the global aviation CO_2 emissions (Graver et al., 2019; Ritchie, 2020). More recent LTA aircraft have enabled 235 new point-to-point routes (Boeing, 2016). During the 2020 COVID-19 lockdown, a number of major airlines retired their VLTAs (A380 and/or B747) (Clinch, 2020; Polek, 2020; Qubein, 2020). Therefore, it appears that LTAs will likely be the most common means of intercontinental or long-range travel in the coming decades. There are all single-decker LTA aircraft (in the present fleet) with a typical fuselage diameter of ~ 6 m.

Long-haul aviation is an extremely difficult sector to decarbonise as there are a limited alternative energy vectors that can match the energy density (both gravimetric and volumetric) of Jet-A fuel (World Economic Forum, 2022). Liquid hydrogen (LH_2), liquid natural gas

(LNG), liquid ammonia (LNH_3), ethanol, and methanol appear to be alternatives to Jet-A fuel according to a study by Bicer et al. (Bicer and Dincer, 2017), in addition to 100% synthetic paraffin kerosene (SPK) according to studies by Hileman et al. and Proesmans et al. (Proesmans and Vos, 2022). Moreover, studies by Huete et al. (Huete et al., 2022, 2021), Verstraete (Verstraete, 2015), Brewer (Brewer, 2017), and the Airbus Cryoplane study (Reinhard Faass, 2001), model the performance of a long-range large aircraft completely powered by LH_2 but using a double-decker tube-wing airframe. Studies by Troeltsch et al. (Troeltsch et al., 2020) and Proesmans et al. (Proesmans and Vos, 2022) simulate the performance of a long-range large LH_2 aircraft which cruises at a lower altitude and Mach number, which would directly affect journey time.

It is clear from the above discussion that there is a need to examine and compare the aircraft performance of the six identified alternative fuels to check whether they could enable a typical long-range flight with an LTA aircraft while considering both gravimetric and volumetric energy density effects on aircraft design (associated weight, aerodynamics, and energy performance penalties), especially for cryogenic fuels like LH_2, LNG, and LNH_3. Furthermore, there is a scarcity of literature on the design of an LTA long-range single-decker aircraft completely powered by the combustion of LH_2, to the same design specification as that of the baseline Jet-A aircraft. The literature review is further detailed in §2.

The use of low-carbon energy vectors and/or alternative fuels is critical to the mitigation of aviation's climate impact. The objectives of this work are to: (i) quantitatively evaluate the energy performance characteristics of six alternative fuels – methanol, ethanol, 100% SPK, LH_2, LNG and LNH_3 – to identify fuels that enable the typical design target for future single-decker LTA aircraft (similar to Jet-A); (ii) conduct off-design point analysis for the identified fuel(s) and evaluate sensitivity of specific energy consumption (SEC in MJ/tonne-km) to range and payload combinations, especially for LH_2 aircraft; and (iii) quantify the relationship between the operating empty weight (OEW) and gross take-off weight (GTOW) for combustion based LH_2 aircraft based on regression analysis of the data obtained from the present work and literature to inform future studies on LH_2 aircraft weight sizing. The above three research items are missing from literature and thus are novel contributions of this work. The above analysis will be conducted using Breguet's range equation, a fundamental equation in aeronautics which predicts the aircraft range from fuel type (or calorific value), aircraft aerodynamics, overall efficiency, and structural weight (Waitz., 2008).

2. Literature review

Studies on disruptive technologies like solar-electric (Voß et al., 2020), ion propulsion (Xu et al., 2018), electric aircraft (turbo-electric, battery electric – hybrid and/or full electric) (Ashcraft et al., 2011; Brelje and Martins, 2019; Dietl et al., 2018; Druot et al., 2022; Felder et al., 2011; Friedrich and Robertson, 2015; Grönstedt et al., 2016; Jagtap, 2019a; Job et al., 2022; Pornet and Isikveren, 2015; Schäfer et al., 2019; Voskuijl et al., 2018; Voß et al., 2020) and fuel cell liquid hydrogen (LH_2) powered aircraft (Abu Kasim et al., 2022; Ashcraft et al., 2011; Brelje and Martins, 2021; Delgado Gosálvez et al., 2018; DLR, 2020; Job et al., 2022; Nicolay et al., 2021; Nicolosi et al., 2022; Pastra et al., 2022; Thoennes et al., 2014; Vonhoff, 2021; Waddington et al., 2021) suggest that these technologies are infeasible for typical long-range Mach 0.85 flight of an LTA aircraft, considering future technology developments trend.

There is a growing interest in LH_2 as an aviation fuel because of its high gravimetric energy density and its potential to emit zero carbon emissions in the use-phase. The aviation industry has begun investments and R&D on fuel infrastructure, cryogenic tank testing, conceptualizing aircraft design and plans of fuel testing in aircraft (Airbus, 2020, 2021a, 2021b; DLR, 2021). Studies on combustion-based LH_2 aircraft (Hoelzen et al., 2022; Lammen et al., 2022; Onorato et al., 2022; Prewitz et al., 2020; Silberhorn et al., 2019; Svensson, 2005a; Yang et al., 2022) model the energy performance of a regional/small- to mid-size aircraft for a short- to medium-range application. Other literature evaluating combustion based LH_2 aircraft includes studies that have: (i) evaluated smaller payload and range combinations below what is typical for long-range LTA aircraft (Cipolla et al., 2022; Gomez and Smith, 2019); (ii) significantly change the cruise Mach number and/or altitude, leading to different aircraft design characteristics compared to the typical baseline long-range LTA aircraft (Proesmans and Vos, 2022; Troeltsch et al., 2020); and (iii) investigated bi-fuel aircraft where LH_2 provides a proportion of the required fuel (Grewe et al., 2017).

A study by Onorato et al. (Onorato et al., 2022) designed a large LH_2 aircraft (295 passengers, 7,674 km) considering five different tank installation configurations, and found that the front and aft tank installation in both single deck and double deck seating type provides energy consumption improvement of 4.2% (37.1% increase in fuselage length) and 7% respectively, compared to a single-deck Jet-A aircraft. Additionally, studies by Huete et al. (Huete et al., 2022, 2021) examine the performance of (double-decker) large aircraft (different range and payload combinations), but their energy performance characteristics are unknown.

Verstraete (Verstraete, 2015) and Brewer (Brewer, 2017) modelled the use of LH_2 in a 400 passenger double-decker (greater fuselage diameter) aircraft (conventional tube-wing architecture) with 14,000 km and 18,500 km range respectively. Verstraete and Brewer reported 12% and 33% improvement in SEC compared to a baseline Jet-A aircraft, respectively. Both studies considered the additional structural weight resulting from integral LH_2 fuel tank systems and changes in aerodynamic performance resulting from a longer fuselage length, required to accommodate LH_2. However, in contrast to these two studies, the Airbus Cryoplane study (Bauen et al., 2020; Reinhard Faass, 2001) showed a 9% increase in SEC due to larger wetted area to accommodate LH_2 tank, in a double-decker long-range large aircraft (14,000 km design range seating approximately 300 PAX) (Airbus, 2003).

Troeltsch et al. (Troeltsch et al., 2020) designed an LH_2 aircraft (range 11,853 km with 400 passengers) with reduced cruise Mach speed of 0.7 (from 0.82 of the reference Jet-A aircraft), which shows a 9% increase in SEC compared to the reference aircraft. Proesmans et al. (Proesmans and Vos, 2022) conducted a pareto-optimal design examination of LH_2 powered aircraft for long-range aircraft, where each fuel and aircraft type was designed separately to minimise climate impact or operating costs. When minimising climate impact, for a long-range LTA aircraft, the optimal cruise altitude (6.1 km) and cruise Mach (0.6) are similar for their Jet-A and LH_2, (present-day Jet-A aircraft cruise at typical altitude of ~10.5-12.8 km and Mach of up to ~0.9). The SEC of LH_2 aircraft is 12.9% greater than the baseline Jet-A aircraft.

Different approved blends (with Jet-A) of drop-in SPK (no modifications to aircraft required for use) are currently the alternative to Jet-A fuel. These include a 10% blend for sugar-to-jet, and 50% blends for hydro-processed ester and fatty acid, Fischer-Tropsch, and alcohol-to-jet pathways (EASA, 2018; IATA, 2020; Jagtap, 2019b, 2019c, 2019d, 2016). 100% SPK (biomass-based and power-to-liquid (Schmidt et al., 2018)) is not strictly a drop-in fuel as it has not yet been approved (Jagtap, 2016; Lokesh, 2015). Studies by Hileman et al. (Hileman et al., 2010) and Proesmans et al. (Proesmans and Vos, 2022) found that a 100% SPK aircraft had similar energy consumption as that of a Jet-A aircraft.

Bicer et al. (Bicer and Dincer, 2017) examined small twin aisle aircraft of conventional tube-wing architecture (like Boeing 767) with a mid-range flight of 5,600 km, where the aircraft is operated by Jet-A, LH_2, liquid natural gas (LNG), liquid ammonia (LNH_3), ethanol, and methanol. However, it is unclear how the volumetric energy density of these alternative fuels and the subsequent impacts on aircraft design and energy performance were accounted for. The above five alternative fuels and 100% SPK appear to be the principal future alternatives to the Jet-A fuel, and there is a need to quantitatively evaluate the performance of these six fuels to determine if they could enable long-range travel with an LTA aircraft considering their realistic effects on aircraft design.

In summary, there are a limited number of studies that design an LTA long-range single-decker aircraft completely powered by the combustion of LH_2, to the same design specification as that of today's baseline Jet-A aircraft. A more detailed review (with relevant quantification) of the above different aircraft propulsion technologies and energy vectors, and alternative fuels is provided in the Supplementary Information file (SI) (in SI §1).

The present work is a low-order evaluation of the aircraft energy performance using different fuels. The methodology for the performance evaluation is detailed in §3 followed by results and discussion in §4. Details omitted from the main text are included in the SI document.

3. Methodology

We use Breguet's range equation for the performance evaluation of methanol, ethanol, 100% SPK, LH_2, LNG, and LNH_3. The Airbus 350-1000 aircraft is used as a baseline and it is modified for the use of the six fuels accounting for both volumetric and gravimetric energy density effects of each fuel on the aircraft aerodynamics and structure. We assume that typical cruise Mach number, altitude and necessary fuel reserves are maintained.

3.1 Design-point analysis

3.1.1 Breguet's range equation

Breguet's range equation is a fundamental equation in aeronautics which estimates the aircraft range given the lower calorific value of the fuel (h), lift to drag ratio (L/D), overall efficiency (η_0), and aircraft initial and final weight. Equation 1 shows an adaptation of the equation (Waitz., 2008), where the range of an aircraft, R, is given by,

$$R = \left(\frac{h}{g}\right)\left(\frac{L}{D}\right)\eta_{\mathrm{o}}\ln\left(\frac{W_{\mathrm{initial}}}{W_{\mathrm{final}}}\right). \tag{1}$$

g is gravitational acceleration, and W_{initial} and W_{final} are the aircraft weight at the beginning and end of cruise, respectively. The Breguet range equation is applicable to cases where η_{o}, L/D, and flight speed are constant over the flight and can therefore be used to give a first order estimate for typical cruise conditions (Waitz., 2008). We evaluate the accuracy of the Breguet range by predicting the performance characteristics of two in-service aircraft (Airbus A320-200 and Boeing B767-300F) in SI §7.3, where the aircraft range is predicted for two separate payload cases for both aircraft types. The performance characteristics predicted using the range equation for these four points are in reasonable agreement with the published data (within ±5%, a criterion defined for low-order aircraft performance modelling (Kirby, 2001; Kundu et al., 2019)).

3.1.2 Flight mission profile and iteration process

Figure 1 and Figure 2 show the process schematic of the range equation analysis for the Jet-A fuel case and alternative liquid fuel (cryogenic and non-cryogenic) cases, respectively. The SEC (in MJ/tonne-km) is calculated for the different fuels as it is an important performance parameter that facilitates the calculation of direct operating costs. The A350-1000 aircraft (Jet-A) is the baseline case and all alternative fuels will be evaluated for the same payload weight and design target range. The total fuel weight carried at mission start ($W_{\mathrm{F,total}}$), determines the volume needed to store that fuel and therefore the operating empty weight (OEW) of the aircraft. The aircraft GTOW is the sum of the OEW, W_{p} and $W_{\mathrm{F,total}}$. We choose to constrain the aircraft GTOW to be less than or equal to the maximum take-off weight (MTOW) limit of the baseline aircraft structure, which is 316 tonnes (weight breakdown in SI §4.4). This constraint is applied as we have not conducted a detailed structural analysis in this study. Therefore, the MTOW determines the design limit on the $W_{\mathrm{F,total}}$. In other words, for the alternative fuel cases, the $W_{\mathrm{F,total}}$ is iterated and estimated such that the aircraft GTOW does not exceed the MTOW. The details of calculation steps for η_{o} (and lost fuel value), aerodynamics and additional fuselage characteristics, and additional systems weight for alternative fuels are included in SI §4.1, §4.2, and §4.3, respectively. The passenger payload weight (W_{p}) and other A350-1000 aircraft (Jet-A) data is included in SI §4.4.

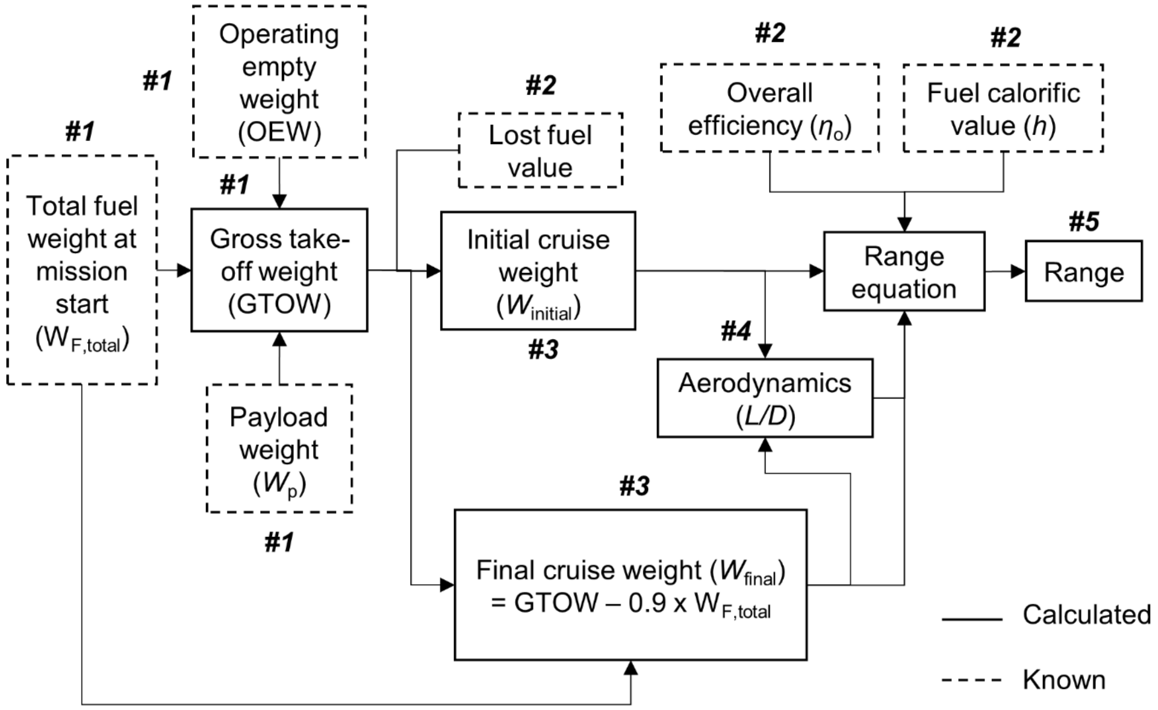

Figure 1. Process schematic of the range equation analysis for Jet-A (baseline) case. Boxes with dashed borders represent known values, boxes with solid border represent a calculation step, and # represent the calculation step number.

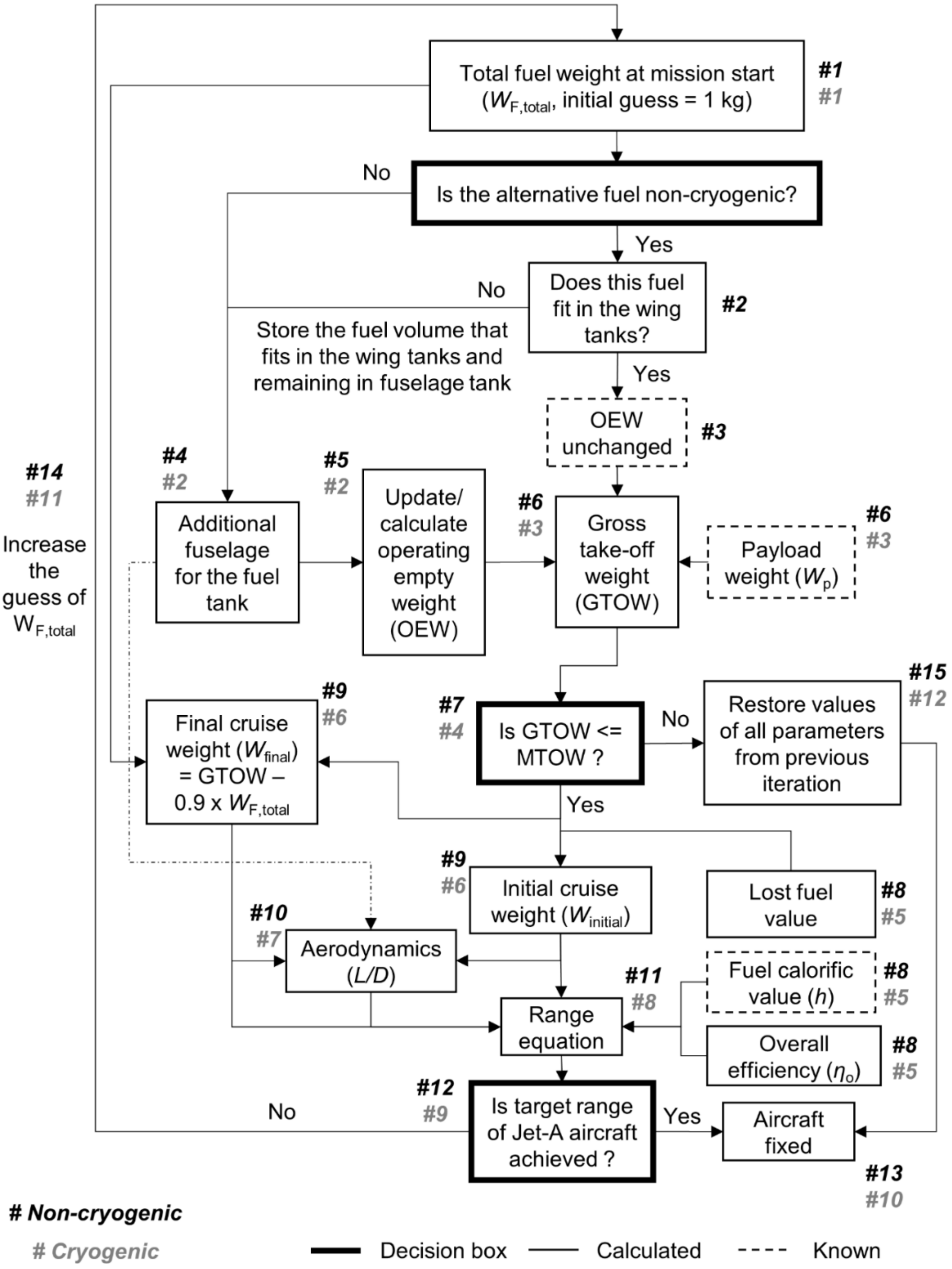

Figure 2. Process schematic of the range equation analysis for alternative fuel cases. Boxes with dashed borders represent known values, boxes with thin solid border represent a calculation step, boxes with solid thick border represent a decision box, and # represent the calculation step number. Grey and black colours are used for cryogenic and non-cryogenic fuel cases, respectively.

For the baseline Jet-A aircraft, the MTOW, OEW, and $W_{\mathrm{F,total}}$ are known for a given W_{p}. For alternative fuel cases, the wing planform (area, span and/or aspect ratio [AR]) is maintained from the baseline aircraft, which is similar to the approach used in the Cryoplane study (Bauen et al., 2020). To accommodate greater volumes of fuel that could be required for alternative fuels, we allow for extensions of the fuselage length. Additional fuselage length penalises aircraft fuel/energy performance via increased wetted area, drag and weight (via increased OEW). For cryogenic fuels (LH_2, LNG and LNH_3), $W_{\mathrm{F,total}}$ needs to be stored in cryogenic tank systems that are installed in the fuselage. For non-cryogenic fuels (100% SPK, methanol, ethanol), a substantial fraction of $W_{\mathrm{F,total}}$ fits inside the existing tank in the wings of the baseline aircraft. The remainder of the fuel (if any) must be accommodated in the (additional) fuselage. These calculation steps are detailed in SI §4.2 and §4.3.

The sum of the fuel consumed during non-cruise and cruise operation in a typical mission is defined here as block fuel consumption. For all fuels a ratio of 0.9 of the block fuel weight ($W_{\mathrm{F,block}}$) and $W_{\mathrm{F,total}}$ is maintained, which accounts for reserve or additional fuel, as used by Nickol et al. for both tube-wing and blended wing body long-range LTA aircraft (Nickol and Haller, 2016). The SEC is calculated from the $W_{\mathrm{F,block}}$ for each fuel case [SEC = $(W_{\mathrm{F,block}}\, h) / (W_{\mathrm{p}}\, R)$].

The lift to drag ratio for all fuel cases are calculated using method described in SI §4.2. Using the lost fuel factors for different fuels, the aircraft weight at the beginning of cruise [W_{initial} = (1 – lost fuel factor) x GTOW] is calculated. The aircraft weight at the end of cruise [W_{final} = GTOW – 0.9 x $W_{\mathrm{F,total}}$] is calculated by subtracting 90% of $W_{\mathrm{F,total}}$ from the GTOW. Therefore, all parameters of equation 1 are known and the aircraft range can be calculated. The stepwise procedure of the range equation analysis for the baseline and alternative fuel cases is described in SI §5 (referencing the step numbers shown in Figure 1 and Figure 2). The effects of headwinds/tailwinds are not considered in this analysis and the range calculated is the distance flown and not the greater circle distance.

3.2 Off-design analysis

By using the discussed methodology in §3.1, the aircraft performance at design point is known for different fuel cases. The aircraft now becomes a 'fixed' aircraft with fixed OEW, fuselage length and maximum fuel capacity for each fuel under consideration. However, in real world applications, airlines do not always operate their aircraft with full design payload capacity, design range and/or full fuel tank. For example, with a full fuel tank and reduced payload or load factor (compared to design payload i.e. 100% load factor), the aircraft can fly greater distance compared to the design range. Such operation is known as the off-design point performance of the aircraft.

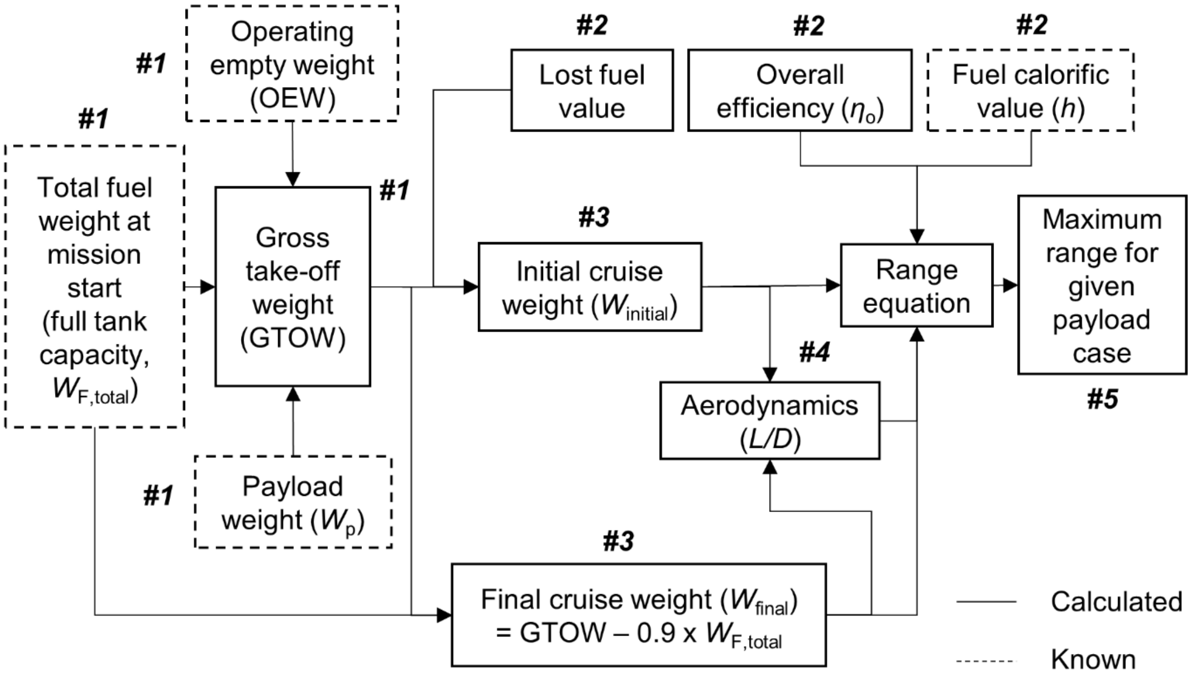

Figure 3. Schematic for the estimation of the maximum permissible range with full fuel tank for a given payload case. Boxes with dashed borders represent known values,

boxes with solid border represent a calculation step, and # represent the calculation step number.

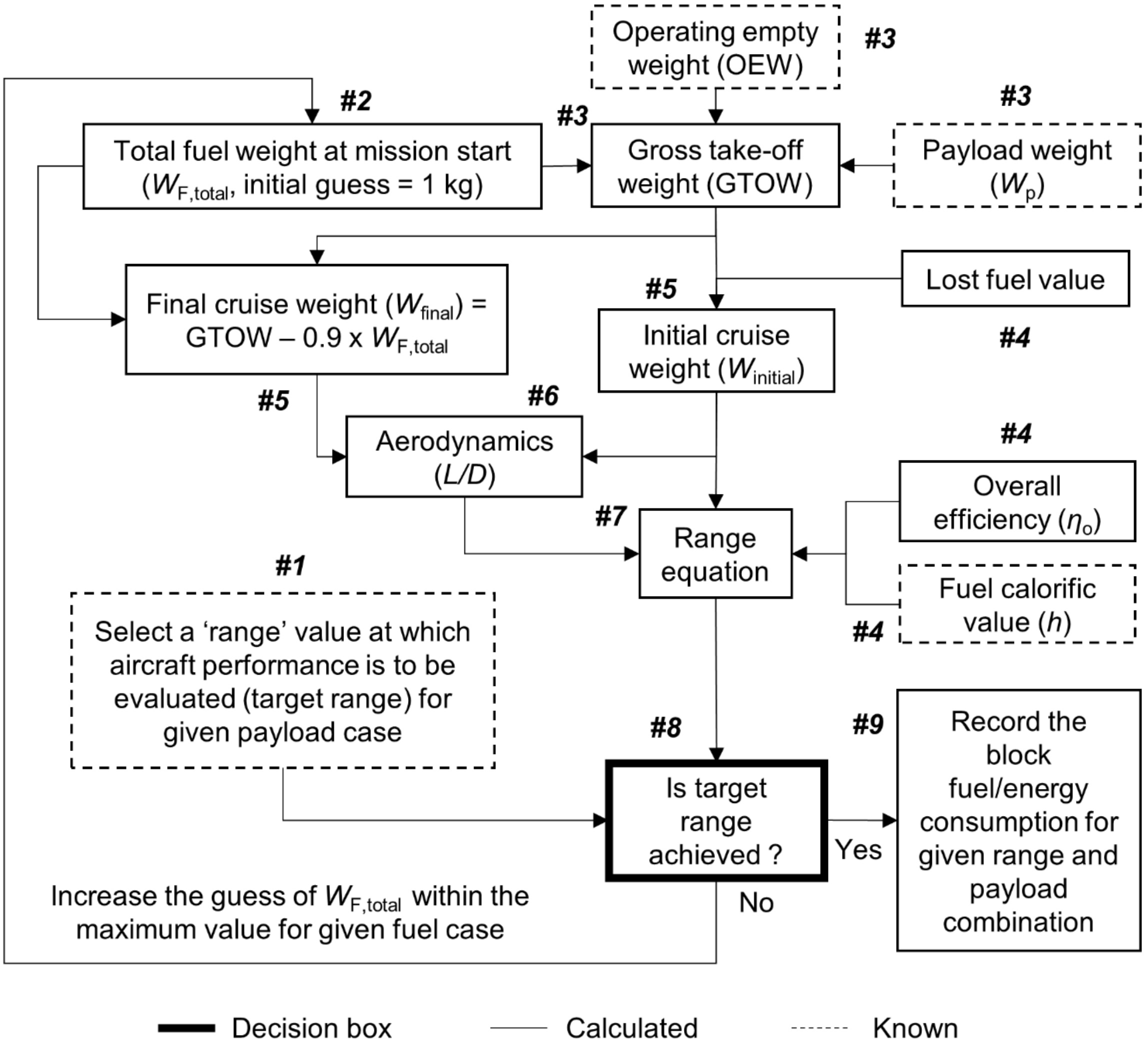

Figure 4. Schematic for the estimation of the $W_{F,block}$ of an aircraft for given range and payload combination. Boxes with dashed borders represent known values, boxes with thin solid border represent a calculation step, boxes with solid thick border represent a decision box, and # represent the calculation step number.

In this study, after identifying the alternative fuels that meet the design target range of the baseline Jet-A aircraft within the MTOW limit, the off-design aircraft performance for such fuel(s) is evaluated for typical range and payload (load factor) combinations for long-range flights. Three off-design passenger – load factor cases are considered for A350-1000 aircraft, other than its design reference point (366 PAX, 34.8 tonne passenger payload): (i) 200 PAX (19 tonne passenger payload, 55% load factor); (ii) 250 PAX (23.8 tonne passenger payload, 68% load factor); and (iii) 301 PAX (28.6 tonne passenger payload, 82% load factor). These different payload cases are evaluated for aircraft range between 5,000 km and the maximum range for a given load factor case flying with full tank capacity. The flowchart/schematic for the estimation of the maximum range with full fuel tank for a given load factor case using Breguet's range equation is shown in Figure 3. Additionally, Figure 4 shows the schematic for the estimation of the $W_{\mathrm{F,block}}$ of an aircraft for given range and payload combination using Breguet's range equation. The stepwise process in Figure 3 and Figure 4 is detailed in SI §6.

4. Results and discussion

The results of the performance evaluation of the six fuels at design point are analysed in §4.1 and the off-design performance analysis results of the identified alternative fuels that meet the baseline aircraft range within the MTOW limit are discussed in §4.2. Lastly, a relationship between OEW and GTOW for LH_2 aircraft is presented in §4.3.

4.1 Performance evaluation of alternative liquid fuels at design point

Figure 5 shows the comparison of different alternative fuels for their SEC and range performance within the MTOW limit of the baseline Jet-A aircraft carrying 366 passenger-payload (34,770 kg). It is to be noted that 100% SPK fuel has similar properties as that of Jet-A fuel, and thus its SEC is similar to Jet-A. The SEC points for 100% SPK and Jet-A fuel overlap, thus in Figure 5 these two points are combined and labelled as 'Jet fuel'.

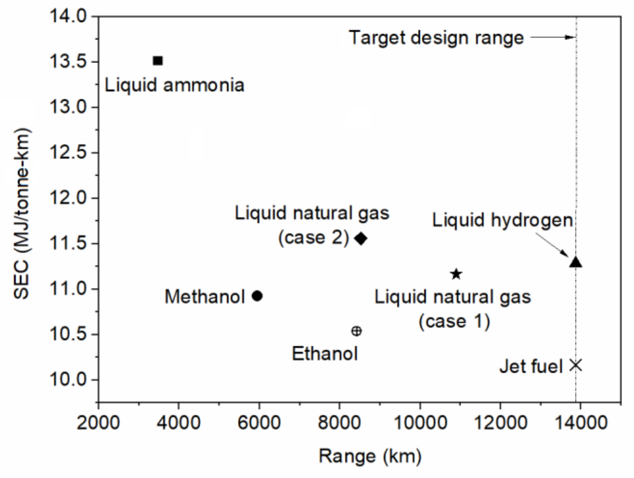

Figure 5. Comparison of different alternative fuels for their SEC and maximum range within the MTOW limit of the baseline Jet-A aircraft carrying 366 passenger-payload (34,770 kg)

We observe from Figure 5 that of the six alternative fuels only 100% SPK and LH_2 powered LTA aircraft (single decker tube-wing) enable the typical long-range flight distance as that of the Jet-A aircraft (baseline) of 13,870 km for 366 passenger-payload of 34,770 kg, within the limit of MTOW (of 316 tonne). Thus, 100% SPK and LH_2 are quantitatively identified alternative liquid fuels from this study that enable a long-range air travel with an LTA aircraft. Further details of the performance characteristics of the baseline aircraft modified for the use of six alternative liquid fuels (for same payload of 34,770 kg i.e. 366 passenger payload) is included in SI §8.1. Additionally, SI §8.1 includes comparison of the aircraft and systems characteristics (such as fuselage length, wing loading, etc. for similar tank η) for LH_2 aircraft with other studies in literature. Table 1 shows the SEC performance of identified alternative liquid fuels that enable long-range travel with an LTA aircraft. ΔL represents the additional fuselage length for accommodating the alternative fuel.

Table 1. Nominal SEC of LTA aircraft at 13,870 km range for payload of 34,770 kg with Jet A, 100% SPK and LH_2

Fuel	h (MJ/kg)	ΔL (%)	$W_{F,block}$ (kg)	L/D	GTOW (kg)	OEW/GTOW	SEC (MJ/tonne-km)
Jet A	43.2	-	113,491	18.63	315,999	0.49	10.17
100% SPK	44.1	0.3	110,988	18.57	313,404 *(-0.82%)*	0.50	10.15 *(-0.17%)*
LH_2	120	37.2	45,338	16.09	268,516 *(-15%)*	0.68	11.28 *(+10.97%)*

A study by Proesmans et al. (Proesmans and Vos, 2022) found that the 100% SPK aircraft energy consumption was similar to a Jet-A aircraft. According to the findings of Hileman et al. (Hileman et al., 2010), 100% SPK offers a 0.3% improvement in energy consumption relative to Jet-A while considering that the fuel gravimetric energy density is a significant aspect compared to the volumetric energy density. In the present work, both gravimetric and volumetric energy densities are equally important. Considering this, the energy consumption benefits due to slightly better gravimetric energy density performance of 100% SPK gets reduced due to its slightly poor volumetric energy density performance (increase of fuselage length by 0.25 m or by 0.3%), compared to Jet-A. It can be observed from Table 1 that 100% SPK offers an insignificant net improvement (of 0.17%) in energy consumption as compared to Jet-A, which is similar to the findings of Hileman et al and Proesmans et al. For non-cryogenic fuel, especially 100% SPK it is observed that the fuselage length increases insignificantly (by 0.3%) to store additional fuel and this fuel could be accommodated in future aircraft designs with minor changes to the aircraft wing design instead of storing the fuel in fuselage as considered in this study.

From Table 1, we observe that LH_2 aircraft consumes more energy than Jet-A aircraft due to its poor volumetric energy density performance compared to Jet-A and higher OEW due to cryogenic systems requirements, thereby resulting in longer and heavier fuselage (negative impact on *L/D*). The LH_2 aircraft fuselage length increases by 26.87 m (or by 37.2%) compared to Jet-A case. This finding is similar to the observation made in the studies by: (i) Verstraete (Verstraete, 2015), where there is 38.2% increase in fuselage length for a single-decker 300 passenger LH_2 aircraft (using similar cryogenic tank η) but has a shorter design range of 9,000 km; and (ii) Proesmans et al. (Proesmans and Vos, 2022), where there is 38.4 – 41.1% increase in fuselage length for a 253 passenger (long-range LTA) aircraft with design range of 10,800 km. In terms of absolute value, for a single decker 400 passenger aircraft with a design range of 14,000 km, the study by Verstraete (Verstraete, 2015) finds that the LH_2 aircraft (similar cryogenic tank η) fuselage length is greater than 95 m which is of the similar order as that of the finding of this work (of approximately 99 m). More design details of this single-decker 400 passenger aircraft by Verstraete (Verstraete, 2015) are not known in sufficient detail to enable further comparison. Moreover, according to a study by Onorato et al. (Onorato et al., 2022), for a large LH_2 aircraft (295 passengers, 7,674 km), the authors found that there was a 37.1% increase in fuselage length (similar to the findings of the present work), compared to a single-deck Jet-A aircraft.

For LH_2 aircraft, it is observed that relative to the baseline Jet-A aircraft, for a high energy dense (by weight) LH_2 fuel there is a net reduction in the aircraft GTOW of 15% (OEW/GTOW = 0.683) and 10.97% increase in SEC (for η of 0.78). These findings are similar to the observations made in the Cryoplane study which uses foam based insulation tanks (exact tank η not known but is expected to be of the similar order used in this study), where the SEC of the long-range LH_2 powered aircraft (using conventional tube-wing architecture) increases by 9% and GTOW reduces by 14.8% (OEW/GTOW = 0.68) relative to the Jet-A aircraft

(Airbus, 2003). Additionally, this finding is similar to the observations made in a study by Troeltsch et al. (Troeltsch et al., 2020) where the authors design an LH_2 aircraft (range 11,853 km with 400 PAX) with foam-based LH_2 tanks (front and aft), and this aircraft shows a 9% increase in energy consumption compared to the reference aircraft..

The significant reduction in the GTOW of LH_2 aircraft is of importance during emergency landing situations as a lighter aircraft will not necessitate jettison of a highly flammable LH_2 fuel (see SI §8.2 for details). In addition to the several comparisons made in this work with published studies on LH_2 powered long-range LTA aircraft, an attempt is made to validate the long-range LH_2 aircraft design in the Clean Sky 2 - FCH joint project (CleanSky2-FCH, 2020), and this is included in SI §7.4.

4.2 Off-design performance analysis

Figure 6 shows the SEC comparison of different fuel cases at different range and payload (load factor) combinations. The SEC for 100% SPK is similar to Jet-A and thus it is not shown in Figure 6 due to overlapping points (can be observed from Figure SI 4 included in SI §8.3). We observe that reducing the load factor increases the maximum aircraft range for all fuels (points on extreme right). Additionally, for any given load factor, the trend of SEC variation with range and the absolute values of SEC for Jet-A and 100% SPK are similar. For both fuels we observe a minimum point at ~7000 km. On an absolute scale, the LH_2 aircraft consumes more energy than Jet-A aircraft at all combinations of range and load factor. For the LH_2 aircraft, the SEC decreases with increasing range, though the SEC variation with range is less sensitive beyond ~10,000 km. Increasing the load factor improves the SEC, for all three fuels. The difference in SEC variation with range for Jet-A (and 100% SPK) and LH_2 aircraft is due to the high OEW/GTOW ratio for the LH_2 aircraft. The high OEW and lighter GTOW of the LH_2 aircraft than Jet-A case, makes the LH_2 aircraft consume more energy at lower range. Further details on the OEW/GTOW and aerodynamic performance variation with range for different load factor cases is included in SI §8.3.

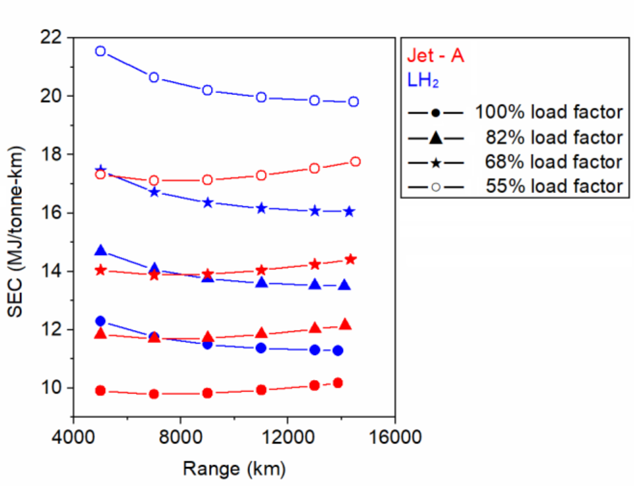

Figure 6. SEC comparison for Jet-A (and/or 100% SPK) and LH_2 aircraft at different range and payload (load factor) combinations

Figure 7 shows the comparison of percent change in SEC for LH_2 relative to the Jet-A aircraft at different range and payload (load factor) combinations. The percent difference in SEC between LH_2 and Jet-A aircraft decreases with increasing range for all load factor cases, and this reduction is greater at higher load factor cases. In other words, the effect of load factor on the percent difference in SEC between LH_2 and Jet-A aircraft increases with increasing range. For 100% SPK the percent difference in SEC relative to Jet-A aircraft is insignificant and is constant for all load factor and range combinations. Thus, 100% SPK is not included in Figure 7, and the said insignificant change in SEC can be observed from Figure SI 5 included in SI §8.3. In summary, 100% SPK can be used across all range and load factor combinations with similar SEC as that of Jet-A, whereas the SEC of LH_2 is lower at higher range and greater load factor combination though it is always greater than the SEC of Jet-A for all load factor cases i.e. tube-wing single-decker LH_2 aircraft is less energy efficient than Jet-A aircraft at all combinations of payload (load factor) and range.

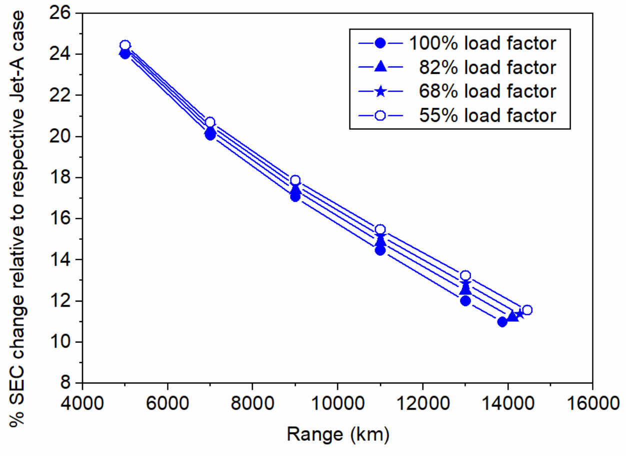

Figure 7. Comparison of percent change in SEC for LH_2 relative to the Jet-A aircraft at different range and payload (load factor) combinations

4.3 Relationship between OEW and GTOW for LH_2 aircraft

Figure 8 shows the relationship between OEW and GTOW of tube-wing LH_2 aircraft from the present study and literature (Brewer (Brewer, 2017), Verstraete (Verstraete, 2015), Troeltsch et al. (Troeltsch et al., 2020), Beck et al. (Beck et al., 2018), Proesmans et al. (Proesmans and Vos, 2022), Gomez et al. (Gomez and Smith, 2019), Silberhorn et al. (Silberhorn et al., 2019) (2019), Silberhorn et al. (Silberhorn et al., 2022) (2022), Lammen et al. (Lammen et al., 2022), Onorato et al. (Onorato et al., 2022), and Huete et al. (Huete et al., 2022)). For data from Proesmans et al. (Proesmans and Vos, 2022), ‘ATR’ and ‘COC’ denote LH_2 aircraft optimised for average temperature response and cash operating cost, respectively. Additionally, in the study by Silberhorn et al. (Silberhorn et al., 2019) (2019), the authors design three versions of LH_2 aircraft, where each version has a distinct tank installation location (rear, top, and pod) and these are included in Figure 8.

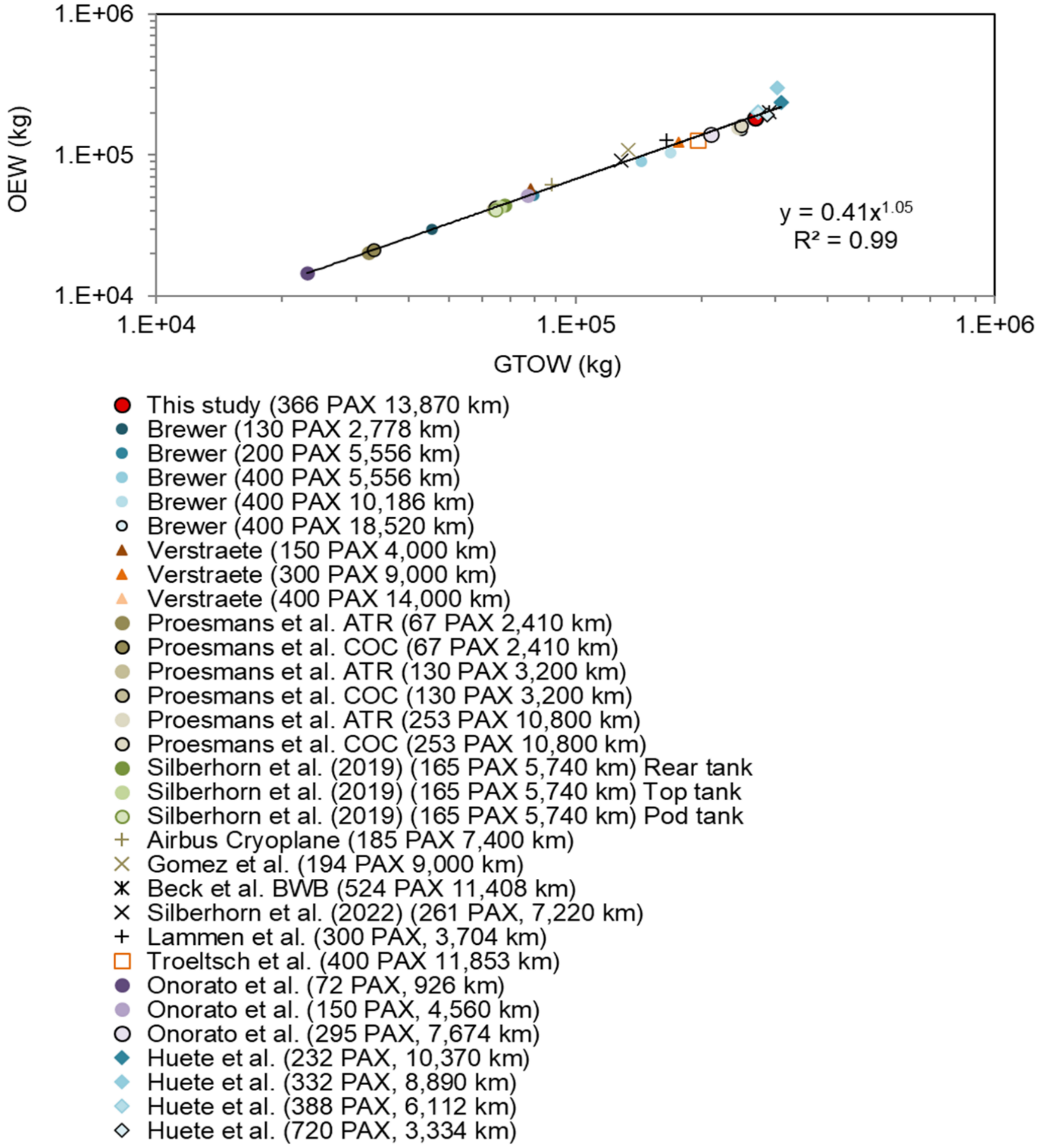

Figure 8. Relationship between OEW and GTOW of LH_2 aircraft from the literature [except Beck et al. data point (BWB), all aircraft are tube-wing] and present study (Brewer (Brewer, 2017), Verstraete (Verstraete, 2015), Troeltsch et al. (Troeltsch et al., 2020), Beck et al. (Beck et al., 2018), Proesmans et al. (Proesmans and Vos, 2022), Gomez et al. (Gomez and Smith, 2019), Silberhorn et al. (Silberhorn et al., 2019) (2019), Silberhorn et al. (Silberhorn et al., 2022) (2022), Lammen et al. (Lammen et al., 2022), Onorato et al. (Onorato et al., 2022), and Huete et al. (Huete et al., 2022))

We observe from Figure 8 that the relationship between OEW and GTOW for the LH_2 aircraft designed in this research and earlier literature follow a consistent trend, which can be approximated by a power law. We suggest that this trend could facilitate a more rapid weight sizing studies on LH_2 aircraft designs using low-order modelling approaches. Similarly, an equation is developed (in SI §8.1) which provides a relationship between OEW and GTOW of Jet-A and/or 100% SPK from the present study and aircraft in service.

4.4 Discussion

4.4.1 Modifications to aircraft and aviation sub-systems

100% SPK and LH_2 are the only two alternative fuels (quantitatively) identified from this study that enable a long-range air travel with a tube-wing LTA aircraft. In terms of modifications required to the aircraft sub-systems, LH_2 use requires significant changes to the aircraft sub-systems which primarily include installation of cryogenic tank (negative effect on aerodynamic and structural performance as observed in §4.1), modifications to fuel lines and engine/combustor (improve flame characteristics and reduced emissions of oxides of nitrogen), and installation of a heat exchanger (for enabling phase change of hydrogen before injecting it into the combustor and component cooling). These modifications and the aspects such as LH_2 aircraft safety and refuelling, and changes to airport infrastructure for hydrogen powered aviation are reviewed in other studies (Khandelwal et al., 2013; Rondinelli et al., 2017; Schmidtchen et al., 1997; Svensson, 2005b).

Compared to LH_2 aircraft, 100% SPK requires insignificant modifications (due to similar fuel properties as that of Jet-A) such as minor increase in fuel tank volume, change of seals in the high-pressure fuel systems (due to absence of aromatic content), etc. The effect of fuel properties of 100% SPK and required modifications are reviewed in other studies (Jagtap, 2016; Lokesh, 2015). Due to the significant modifications required for the LH_2 aircraft, its acquisition cost is expected to be more than Jet-A and 100% SPK.

4.4.2 Fuel and life-cycle costs

100% SPK and LH_2 should be manufactured from less carbon intense or renewable energy pathways (considering life-cycle effects) that will enable truly climate-neutral air travel (further elaborated in SI §9). Additionally, effects of contrails and other non-CO_2 emissions need to be considered. In the use phase, LH_2 combustion theoretically emits zero emissions except water vapour and oxides of nitrogen whereas combustion of 100% SPK emits similar quantity of greenhouse emissions as that of Jet-A. The boundary of analysis should be extended beyond the use-phase to the fuel lifecycle. The pathways and/or feedstocks used for manufacturing both these fuels would determine their benefits in terms of lifecycle emissions and fuel costs. The fuel costs also depend on the scale of manufacturing, technology advancements, efficiency and effectiveness of the fuel supply chain, and governmental incentives (Dray et al., 2022).

4.4.3 Airline decision-making

It is observed in this work that for a long-range tube-wing LTA aircraft, compared to Jet-A, a LH_2 aircraft consumes more energy for all range and payload combinations. Purely based on the energy performance, it is observed from the off-design performance (in §4.2) that for a given payload, LH_2 aircraft offers a stable SEC at greater range (>10,000 km). However, for Jet-A the SEC for a given payload decreases with increasing range and minimises at ~7,000 km and thereafter it increases with increasing range. This is an important observation for airline operations, that may favour LH_2 aircraft for long-haul flights, but this will ultimately be driven by fuel costs and aircraft availability.

4.4.4 Aircraft design

Firstly, the significant increase in the LH_2 aircraft fuselage length observed in this work could be a potential challenge associated with the use of LH_2 in the conventional tube-wing architecture, as this likely has structural and stability implications. Secondly, longer tube-wing LH_2 aircraft might not be readily compatible with the current airport design and layout, which may require modifications to airport aprons, in addition to new refuelling infrastructure. Lastly, for a significantly lighter LH_2 aircraft observed in this work (~15% GTOW reduction), aircraft design optimization is necessary considering that a lighter aircraft would have reduced thrust requirement for maintaining the same thrust to weight (*T/W*) ratio, which could further decrease the SEC of the LH_2 aircraft. The above aspects are further elaborated in SI §9.

4.5 Limitations of the present research

The present work is a low-order modelling of aircraft performance characteristics using Breguet's range equation for different fuels. The *L/D* ratio during cruise is based on the average aircraft weight during cruise. Also, in the estimation of the drag coefficient, wave drag is considered to be negligible which are typically considered in high-fidelity analysis. The effects of headwinds/tailwinds are not considered in this work and the range calculated assuming constant speed and angle of attack. The evaluation of the aircraft performance characteristics in this work is limited to the aircraft use-phase only and these include the aerodynamic, weight and energy performance. The (quantified) effects of the aspects in §4.4.1 to §4.4.4 (except the cryogenic tank) on aircraft performance or operations are not considered in this work as they are out of the scope of this work and need a separate higher order analysis. Life-cycle effects and the fuel cost (dependent on the feedstock and/or pathway used to produce fuel) are not considered in this work. In addition, flight/mission cost and examination of flight economics (comparison for different fuel cases) is not conducted in this work. Low carbon fuels with more hydrogen content compared to Jet-A fuel, such as LNH_3, LH_2, LNG, etc. are expected to produce more water vapour at typical cruise altitude and could increase contrail formation, which are known to have a net warming effect on climate. However, significant uncertainties remain as to the contrail induced climate effects of hydrogen aircraft, and it might be possible to implement operational avoidance strategies, such as avoiding ice-supersaturated regions(Svensson, 2005b; Teoh et al., 2020). The emissions and contrail performance, and effect of varying altitude on LH_2 aircraft, are not included in this work. Additionally, aircraft structural/stress and stability examination are not considered in this work (particularly resulting from increase in fuselage length), and these could be crucial for LH_2 powered aircraft where the aircraft fuselage length increases significantly (~30%). The present work does not conduct rigorous design and optimization of aircraft employing different fuels and the analysis is only limited to a tube-wing aircraft architecture. Lastly, 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 both internal and external mechanical and thermal stresses.

5. Conclusions

The aviation sector is responsible for 3.5% of the total anthropogenic radiative forcing, and the use of low-carbon alternative energy vectors is critical to significantly reduce aviation's climate impacts. This research evaluated low-carbon energy vectors for long-range LTA passenger aircraft and used the standard Breguet range equation to perform a comparative assessment for the characteristics of six alternative liquid fuels (methanol, ethanol, 100% SPK, LH_2, LNG, and LNH_3). Considering the impact of both gravimetric and volumetric energy densities of the different fuels, we find that LH_2 and 100% SPK are the only alternative liquid fuels that could enable typical long-range flight of approximately 14,000 km (or 7,500 nautical miles) in a conventional tube-wing aircraft for a 366 passenger-payload within the MTOW limit of the baseline Jet-A LTA aircraft. Additionally, by using present-day aircraft technology, the SEC (MJ/tonne-km) of the aircraft powered by LH_2 and 100% SPK (separately) could change by +11.0% and -0.2% respectively, compared to the baseline Jet-A aircraft.

Our off-design point analysis, using different range and payload (load factor) combinations for aircraft powered by LH_2 and 100% SPK, shows that for any given load factor and range, the SEC of LH_2 aircraft is higher than SEC of Jet-A aircraft. The SEC of LH_2 aircraft decreases with increasing range but is less sensitive to range beyond 10,000 km. Additionally, the difference in SEC between LH_2 and Jet-A aircraft decreases with increasing range for all load factor cases, and this reduction is greater at higher load factor. Overall, 100% SPK can be used across all range and load factor combinations with similar SEC as that of Jet-A, whereas the SEC of LH_2 is lower at higher range and greater load factor combination though it is always greater than the SEC of Jet-A for all load factor cases.

Finally, we show that the OEW and GTOW for LH_2 aircraft at design point from the present work and previous literature, can be related by a power law equation. This equation will facilitate low-order modelling or weight sizing of LH_2 aircraft. The aircraft energy consumption estimation in this work for both 100% SPK and LH_2 fuel should inform future studies on the estimation of: (i) feedstocks and/or pathways that could decarbonise long-range civil aviation on a lifecycle basis; and (ii) ticket pricing as the fuel cost is dependent on the energy consumption of aircraft and fuel manufacturing process.

Challenges associated with the use of LH_2 in the conventional tube-wing architecture include the significant increase in the fuselage length (~30%), which could have structural and stability implications, and compatibility with current airport configurations.

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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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